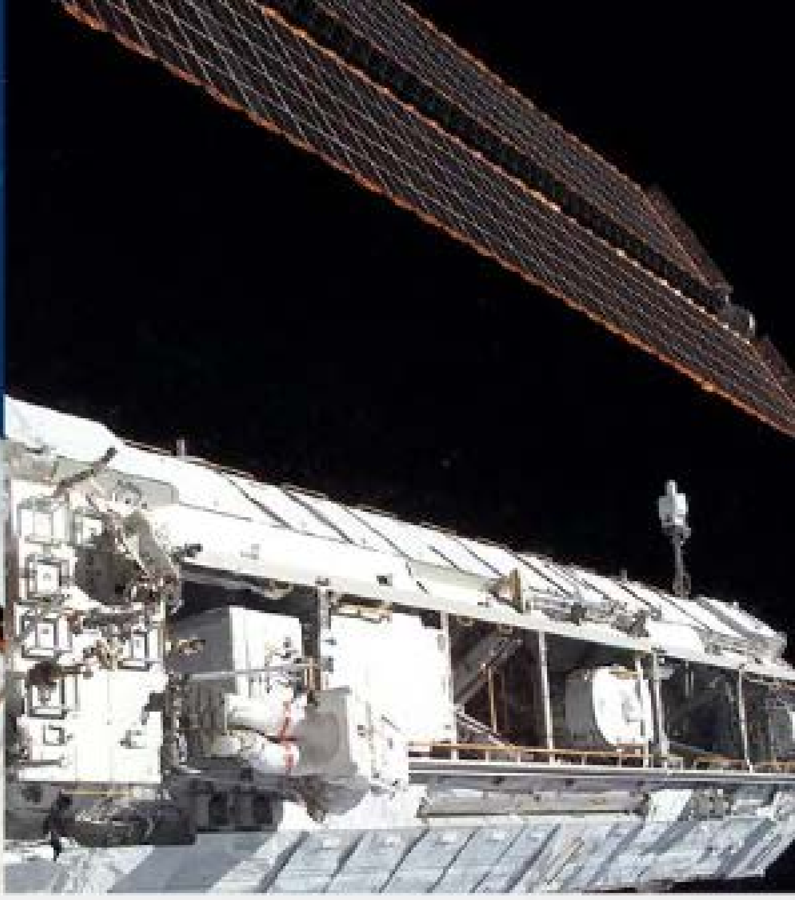

U.S. Spacesuits

Second Edition

Kenneth S. Thomas
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PRAXIS

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Honeywell Corporation's Torrance, CA, U.S.A. Division[1] with its AiResearch and AlliedSignal Heritage was the extravehicular life support provider for Gemini and Skylab suit systems.

Arthur Iberall Family[1] who is preserving the memory of an early pressure suit pioneer.

ILC Dover, LP[1,2] of Fredrica, DE, U.S.A. is a pressure suit provider for the Apollo, Skylab, and Shuttle extravehicular mobility units.

Dr. Joseph P. Kerwin, MD[1] is an esteemed physician, 22-year-career NASA astronaut, author, retired U.S. navy captain and President of Wyle Laboratories' Life Sciences Division.

Doug Lantry[1] is a historian/researcher with the U.S. Air Force Museum, Wright Paterson Air Force Base, OH, U.S.A.

Dr. Cathleen Lewis[2] is the National Air and Space Museum Space History Division Specialist responsible for Apollo era and Russian space artifacts.

Nikolay "Nik" Moiseev[2] is a former lead designer and project manager for Zvezda, the Russian spacesuit provider, spacesuit entrepreneur, and a co-founder of Final Frontier Design.

Dr. Story Musgrave[1] is a respected 30-year-career veteran NASA astronaut with degrees in mathematics, business, chemistry, medicine, physiology, and literature.

Dr. A. Ingemar Skoog[1,2] is a career aerospace engineer, historian, formerly Dornier/ESA European spacesuit system manger, co-author of *Russian Spacesuits*, and member of the International Academy of Astronautics.

Smithsonian Institution National Air and Space Museum[1,2], Space History Division, Washington, D.C., U.S.A.

Ted Southern[2] contributed U.S. materials and processes knowledge to his teaming with Moiseev to take second place in NASA's 2009 Astronaut Glove Competition and subsequently co-founded Final Frontier Design.

William E. Spenny[1] is an extravehicular mobility unit (EMU) subsystem manager and 26-year-career NASA engineer.

U.S. Air Force Museum[1], Research Division, Wright Paterson Air Force Base, OH, U.S.A.

Dr. Paul Webb, MD[1] was the Founder of Webb Associates of Yellow Springs, OH, U.S.A. and creator of the (mechanical counter pressure) space activity suit.

Dick Wilde[1] is a career engineer supporting (among other efforts) the Apollo Lunar Module and the Shuttle extravehicular mobility unit.

Amanda Young[1] retired as the Space History Division Apollo Era Spacesuit Specialist at the National Air and Space Museum.

Note: [1] First Edition contributor and [2] Second Edition contributor.

Preface

Ken Thomas and Joe McMann have produced a magnificent treatise on spacesuits, spacewalking, life support systems and escape systems. *U.S. Spacesuits* is historical, massively comprehensive, precise, informative, relevant, and readable.

As an astronaut I spent 30 years in their world and in their suits. My life was in their hands. I trained on the Apollo and Skylab systems; I assisted in the development of the Skylab extravehicular activity (EVA) procedures and was a capsule communicator (capcom) on six of the Skylab walks. I helped them in the development and testing of the Shuttle suits, escape systems and all the spacewalking equipment. Together with Don Peterson, I was the first astronaut to test the material in space and I was the lead walker in the initial repair of the Hubble Space Telescope. In this book I am able to relive a lot of my 30 years in that world and gain new insights and perspectives on those experiences.

This book is an accurate and detailed history. It is a comprehensive chronology but it is also much more. It not only tells and shows what happened but it deals with how and why things happened. It addresses the hardware and processes that came into fruition and, very importantly, also addresses the options that might have occurred, but did not. It deals with history as an evolutionary process and shows the selection and development system at work. Although it is a history, it also carries the reader into the future; one is able to derive future possibilities from the historical trajectories it builds.

Ken and Joe begin with the environment—what is space and what requirements are imposed on the hardware that must operate there. It is a wonderful place to start the book; it is so logical, that the reader need not even consider that it could have started elsewhere. The environment becomes the reference for everything else, as must be the case in the development process. In addition, the authors also deal not only with the hardware but with the physiology and the physiological consequences of different design specifications.

The book is about hardware, but again it is also much more—it is a history of United States spacewalking. It is a chronology, description and analysis of all American EVAs—the hardware in purpose and action.

The text is highly readable and accessible. It is a balanced mix of words, figures, illustrations, tables and indices. The language flows, the figures describe, the illustrations simplify concepts, the tables summarize, the indices point the way and the bibliography substantiates in a way that makes a massive amount of material digestible and understandable.

This book could only have been created by these authors—people immersed in the day to day details of suit development and operation, people whose heart, soul and bodies were in the business and in the hardware. Side by side with Joe McMann for 30 years, we worked, sweat, suffered and celebrated the victories, defeats and tragedies. The book is a monument to those who gave the most and were the best—just for the sake of being the best.

Story Musgrave

Foreword

One of my biggest thrills as a young Navy pilot in the early 1960s was the full pressure suit flight in the F-4H Phantom, then the Navy's latest and greatest Mach 2 fighter. We launched, climbed to 35,000 feet, hit the afterburners and accelerated to twice the speed of sound, than pulled the nose up to about 60 degrees and climbed. At about 65,000 feet the afterburners quit (not enough oxygen), and at 80,000 we were as high as we were going to reach—still barely supersonic but down to 200 miles per hour, and pushing the nose over to avoid stalling. We were several miles offshore east of Norfolk, Virginia, on a clear day. I could see north to New York and south to Florida—it was breathtaking.

That's when we deliberately dumped the cabin pressure. The Goodrich Mark 4 full pressure suit inflated properly (thank goodness!) and there I was sitting in the front ejection seat, just able to move my arms. There was enough mobility to move the control stick with my fingers, and keep the Phantom wings level until we descended below 35,000 again, where the denser air made its way into the cabin and the suit gradually relaxed its grip. We were getting low on fuel, and returned immediately to NAS Oceana to land.

I thought the suit was fine. It had done its job, keeping us alive and functioning long enough to get our aircraft down. Mobility and visibility weren't great, it was a pain to don, and was warm and bulky in the cockpit. Nevertheless, we respected its protection, and acknowledged that this was the cutting edge of pressure suit technology. That suit was what the engineers at NASA and the various aerospace companies had to start with as they developed a spacesuit good enough to get humans to the Moon. The spacesuit was one of the astonishing developments that made the mission possible.

A spacecraft has been described as a little world—a microcosm that must contain all the things of Earth that humans need to live and work—air, under the right temperature and pressure and cleaned of contaminants, water, food and all needed arrangements for work, sleep and communication. A spacesuit is also a microcosm—smaller, but nearly as complete. For several hours it must protect and sustain its occupant while allowing that person to see, reach and work in the vacuum and temperature extremes of space. It must be extremely reliable, with backups for almost every possible failure. It must be light and compact enough to pack on your trip to the Moon. And, yes, it even contains a little food and water. This prescription seemed impossible to some, and dangerous to many. I clearly remember the reluctance of some NASA managers to send crew members on EVAs in spacesuits unless it was absolutely necessary. Of course, in the early 1960s the men and women charged with developing these suits didn't know what the suits would encounter, or if they would be successful.

This book tells the story of how successful they—the people and the suits—really were. The history of the spacesuit is one of the best parts, in which the book reviews the earliest attempts to protect pilots at high altitudes, both in airplanes and balloons. Great old names like Wiley Post and Scott Crossfield are remembered and honored. The tremendous task of progressing from the aircraft pressure suit to the Moon and the Shuttle is then told in living detail.

Some of you will read the book from end to end, as I did. Others will use it as a textbook and reference to the engineering breakthroughs and the lessons learned, and will become better engineers as a result. You'll see how quickly materials wear and fail. You'll learn of the tradeoffs between shoulder width (to fit three crew members side by side in the Apollo Command Module cabin) and mobility, of how to cool a hard-working human body in such a suit, of how much extra oxygen is required to get the astronaut back into the spacecraft if the fan fails, or if a micrometeoroid puts a small hole (you can forget about a large hole) in the pressure layer of the suit. You'll read the names (not as many as should be mentioned) of the engineers who solved all these problems and produced a product that never failed when needed.

When I came to NASA in 1965, I was fortunate to be assigned as one of the astronauts who monitored spacesuit development. I was privileged not only to meet these great young engineers at NASA, at Hamilton Standard, at ILC and at David Clark and other companies, but I was also able to watch them work, and to test the results in the lab, in altitude chambers, and eventually in space. I've never had so much fun in my life. I made friends with people whose talents, dedication and results I honor to this day. I wish we could start again together, on a suit in which to roam the hills and valleys of Mars.

Joe Kerwin

Acknowledgments

We found that assembling the history of U.S. spacesuits was a daunting task. Thousands of people in over a dozen government and industry organizations have been involved over the decades. Although one might surmise that uncovering the story of U.S. spacesuit development would involve a relatively simple review of organized documentation, the opposite turned out to be the case. Official documentation is seldom retained longer than seven years after the conclusion of a program. The personal records of the personnel participating in the various efforts often tends to be fragmented and difficult to obtain. Much of the early documentation relating to the Apollo suit was classified, and the process of declassification, along with retention and storage is expensive and difficult for businesses to justify. In addition, business relocation, mergers and transition of organizations out of the space industry also contributed to loss of records. The inevitable loss of key individuals due to death has also robbed us of valuable sources of information.

Nevertheless, we were able to tap into an impressive reservoir of information, both official and personal, that does exist thanks to the dedication and discipline of many past and present members of the spacesuit community. By drawing on the aforementioned contributors and referenced bibliographical sources, we have attempted to assemble as accurate and fair a representation of U.S. spacesuit history as possible.

For their dedication and contributions to spacesuit system development, the authors wish to express their appreciation to all the men and women, past and present, involved in spacesuit systems. These people have frequently faced personal sacrifice to make this subject possible.

Two spacesuit documentation pioneers also deserve recognition. Lloyd Mallen wrote a book in the late 1960s that provided an excellent first attempt at the subject. Lillian Kozloski, while working at the National Air and Space Museum, recognized that suit history was being lost and attempted to capture it by producing a significant

book. Both would have an effect on many of the contributors and on one of the authors of this text.

For support of preceding documentation efforts utilized in this manuscript, the authors wish to thank Bill Ayrey,[2,3] Earl Bahl,[2] Bob Balinskas,[2] Dan Barry,[2] Jack Bassick,[2] Jim Clougherty,[2] Charlie Flugel,[2] Dennis Gilliam,[3] John Granahan,[2] Dave Graziosi,[2] Gary L. Harris,[3] Bob Herman,[2] Andy Hoffman,[2] the family of Arthur Iberall,[2] Tom Iles,[2] Jack Kelly,[2] Dr. Joseph P. Kerwin MD,[1] Joe Kosmo,[1] Lillian Kozloski,[3] Doug Lantry,[3] Bill Maas,[2] Michael Marroni,[2] Jim McBarron II,[1] Dan McFarlin,[2] Dr. Story Musgrave,[1] Bill Rademakers,[2] Mike Reddig,[2] Kevin Rusnak,[3] Tom Sanzone,[2] Ray Shuey,[2] Dave Slack,[2] Dr. A. Ingemar Skoog,[2] Hubert C. "Vic" Vykukal,[1] Dr. Paul Webb MD,[2] Dr. Walter Wiechetek MD,[2] Dick Wilde,[2] and Amanda Young.[3]

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Appreciation is also expressed to all who contributed in any way to the illustrations used in this text. The authors are particularly grateful for the assistance (in alphabetical order) of: David Clark Company; William Elkins; Brand Griffin; Hamilton Sundstrand Div. UTC; Gary Harris; Honeywell Corporation; the Iberall family; ILC Industries; Dr. Pascal Lee; NASA; A. Ingemar Skoog; Smithsonian Institution National Air and Space Museum; University of Maryland; U.S. Air Force Museum; and Dr. Paul Webb.

Lastly, the authors wish to thank the families of all the above, without whose indulgence this book would not have been possible.

Note: Past or present—[1] NASA spacesuit system personnel; [2] contractor spacesuit system personnel; [3] historian or museum specialist; and [4] spacesuit system organization.

Editorial notes

As people who have found themselves attempting to explain this subject countless times to the general public, we (the authors) recognized the difficulties. This text was crafted with the intent of providing enlightenment into the world of spacesuits.

A spacesuit is a system that keeps an astronaut or cosmonaut alive and permits that person to perform useful work. This system includes a pressure suit assembly to provide atmosphere retention with personal mobility and a life support system to keep the enclosed atmosphere capable of supporting life. With intravehicular (IVA) activity spacesuits that support launch, entry and rescue after landing, the spacecraft provides the primary life support. Such suit systems frequently have backup life support equipment for activity independent of the craft and to enhance survival. Extravehicular activity (EVA) spacesuits allow humans to venture outside the spacecraft to work or explore. These can derive life support by umbilicals from the vehicle or be totally autonomous by suit-carried systems for greater range and freedom from encumbrance.

In the last quarter century, U.S. spacewalking-type suits have worn a rather unique patch on the right shoulder. It has a Da Vinci-like figure in a spacesuit on a blue field that now has five stars. The five stars represent U.S. extravehicular activity milestones, which are:

- Gemini IV—Ed White, first U.S. EVA
- Apollo 11—Neil Armstrong and Buzz Aldrin, first lunar EVA
- Skylab 2—Joe Kerwin and Pete Conrad, repair EVA that saved Skylab
- STS-6—Story Musgrave and Don Peterson, first Space Shuttle EVA
- STS-104/ISS 7A—Mike Gernhardt and Jim Reilly, first EVA initiated from the International Space Station.

The Preface and Foreword to this text were provided, respectively, by Dr. Story Musgrave and Dr. Joseph P. Kerwin, MD. As these two gentlemen are also mentioned in the above list of U.S. EVA stars, we are honored by their support.

Most of the illustrations used in this book were originally created by NASA or USAF-funded efforts. Many of the pictures are no longer available or available only if the original negative is known. The courtesy acknowledgements reflect the person or organization that provided the copy that was used. The illustrations without courtesy acknowledgements were created by Thomas J. Reddie who produced detailed depictions of suit models to show the layers of suit systems, design evolution, and permit comparison of features. Without his artistry, many models would have been depicted by crude design sketches or photographs of flat, lifeless, incomplete, or tattered surviving artifacts.

The world of spacesuits has its own language in the form of technical terms that are shared with other disciplines and in spacesuit-specific acronyms as provided in the next section. Acronyms are abbreviations for longer terms that facilitate writing and talking about subjects without tedious or distracting repetition. The majority of acronyms are pronounced as a string of letters. Examples are Extravehicular Life Support System (ELSS, e-l-s-s), Extra-vehicular Mobility Unit (EMU, e-m-u), Extra-Vehicular Activity (EVA, e-v-a), Intra-Vehicular Activity (IVA, i-v-a), Life Support System (LSS, l-s-s), and Pressure Suit Assembly (PSA, p-s-a). However, many acronyms are pronounced like words. Such acronyms used in this text include BLSS (bē-les), ESA (ē-sa), EVVA (ē-va), FIDOE (fīdoe), HUT (hut), IMLSS (im-les), JAXA (jax-a), LEVA (lē-va), MAG (mag), MOL (mōl), NASA (nasa), NASDA (nasda), PLSS (pliss), PRE (prē), SAFER (safer), SUT (sut), WETF (wet-ef) and WIF (wiff).

This text was written in the American dialect of English. While this may seem an odd statement to a U.S. reader, this text was published by a British literary division that typically produces books in the Queen's English. The two dialects have differences in spelling and traditions that reflect the political and cultural separation of over two centuries. This was a deliberate act by mutual agreement of authors and publisher because this is an American story. The authors wish to acknowledge that the writer-accessible and friendly culture of British publishing was a positive experience. We enjoyed our interactions with our British colleagues. We also tried to include some anecdotal insight in addition to the mass of technical detail, and we hope you find this book interesting and useful. Second Edition copies of this book benefit from additional 1964–1965 era Apollo suit development information that became available to the authors as a result of publishing the First Edition. The Second Edition also includes next-generation suit development activities that occurred after the First Edition was submitted for publication.

Acronyms and abbreviations

AATE	*Asociación Argentina de Tecnología Espacial* (Argentine Association for Space Technology)
ACES	Advanced Crew Escape Suit
AEMU	Advanced Extravehicular Mobility Unit
AES	Advanced Extravehicular Suit—an Apollo Applications Project effort
A-L	Air-Lock Incorporated, Milford, CT was co-founded in 1951 by Mr. David M. Clark to design and manufacture pressure suit and anti-G suit hardware for DCC. A-L is now a wholly owned subsidiary of David Clark Company
ALSA	Astronaut Life Support Assembly—a Skylab LSS system
AMU	Astronaut Maneuvering Unit—a USAF system, planned for use during Gemini
ARG	Anthropomorphic Rescue Garment
ASEM	Assembly of Station by EVA Methods
ASMU	Automatically Stabilized Maneuvering Unit—a Skylab system
ASTP	Apollo Soyuz Test Project
atm	One atmosphere pressure at sea level, equivalent to 14.7 psi
BFG	B. F. Goodrich (now Goodrich Corporation)—makers of the Mercury spacesuits
BLSS	Buddy Life Support System—part of the Apollo 15–17 EMU system
btu	British Thermal Unit—a measurement unit of thermal energy
CCA	Communications Carrier Assembly
CCC	Contaminant Control Cartridge
CEE	Crew Escape Equipment—a Shuttle IVA suit system
CEI	Contract End Item
CES	Crew Escape System
CEV	Crew Exploration Vehicle

CFM	Cubic Feet per Minute
CMP	(Apollo Program) Command Module Pilot
COTS	NASA's Commercial Orbital Transportation Services
CSD	Crew Systems Division—the suit system technical unit of the MSC
CSM	Command and Service Module
CSSS	Constellation Space Suit System program
DCC	David Clark Company Incorporated, Worcester, MA
DCM	Display Control Module—a Shuttle EMU subsystem
DCS	Decompression sickness
DL/H-1	(Pablo) de León and (Gary) Harris Number One prototype (DL/H-1B is a subsequent revised configuration)
ELSS	Extravehicular Life Support System—a name used in Gemini and by OSS
EM-ACES	Enhanced Mobility-Advanced Crew Escape Suit—a pre-competition, CSSS study contract prototype
EMU	Extra-vehicular Mobility Unit
EOS	Emergency Oxygen System
ESA	European Space Agency
EST	Exploration Systems and Technology—an HS and ILC consortium that competed for the CSSS
EV	Extra Vehicular
EVA	Extra Vehicular Activity
EVVA	Extra-Vehicular Visor Assembly—a Shuttle EMU subsystem
FCS	Fecal Containment System
FFD	Final Frontier Design
FIDOE	Fully Independent Delivery of Operational Expendables—the robotic support vehicle of a 1998 Lunar-Mars suit system prototype
FSA	In April 2004, the Russian Space Agency was renamed the Russian Federal Space Agency (FSA), which is also called Roscosmos
g	Acceleration of $32.2\,\mathrm{ft/s^2}$ ($9.8\,\mathrm{m/s^2}$) due to Earth's mass
GAO	Government Accounting Office
GFE	Government Furnished Equipment
HHMU	Hand Held Maneuvering Unit
HMD	Helmet Mounted Display
HMP	Haughton Mars Project
HS	Up to 1970, Hamilton Standard Division of United Aircraft Corporation 1970–1999, Hamilton Standard Division of United Technologies Corporation After 1999, Hamilton Sundstrand Division of United Technologies Corporation
HSSSI	Hamilton Standard Space Systems International
HST	Hubble Space Telescope
HTS	Hard Torso Shell
HUT	Hard Upper Torso—a Shuttle EMU subsystem

IEVA	Acronym has two meanings: (1) Intra/Extra Vehicular Activity—a generic type of space suit; and (2) Integrated Extra Vehicular Activity—a specific HS advanced suit designed in 1967–1968
ILC	Acronym has two meanings: (1) Up to 1969, International Latex Corporation, headquartered in New York City, spacesuit facility located in Dover, DE; and (2) 1969 to the present, the ILC Dover subsidiary of ILC Industries Incorporated located first in Dover and later Fredrica, DE
IMLSS	Integrated Maneuvering Life Support System—a specific model of an HS spacesuit designed and made in 1968–1969
IS3	Industrial Suborbital Space Suit—an OO suit model
ISS	International Space Station
IVA	Intra-Vehicular Activity
JAXA	Japanese Aerospace & Exploration Agency—formerly NASDA
JSC	The Johnson Space Center—formerly MSC, at Houston, TX
km	Kilometer
kPa	KiloPascal—a metric unit of pressure
kph	Kilometers per hour
LCG	Liquid Cooling Garment
LCVG	Liquid Cooling Ventilation Garment—a Shuttle EMU subsystem
LES	Launch Entry Suit
LEVA	Lunar Extra-vehicular Visor Assembly
LMS	Lunar-Mars Spacesuit
LRV	Lunar Roving Vehicle
LSS	Life Support System
LSSI	Life Support Systems Incorporated
LSU	Life Support Umbilical
LTA	Lower Torso Assembly—a Shuttle EMU subsystem
MAG	Maximum Absorbency Garment
MCP	Mechanical Counter Pressure—an alternative approach to traditional pressure suits for space use
MEEP	Mir Environmental Effects Payload
METOX	Metal oxide—a CO_2 sorbent
MIT	Massachusetts Institute of Technology
MMU	Manned Maneuvering Unit
MOL	Manned Orbiting Laboratory—the U.S.'s space station program before Skylab. This was a USAF program
MSC	Manned Spacecraft Center, NASA Center in Houston, now Johnson Space Center
MWC	Multiple Water Connector
MX-2	Maryland Experimental #1 prototype (University of Maryland Space Systems Laboratory)
NACA	National Advisory Committee for Aeronautics

NAM	Suit prototype named for its creator Nikolay Alexandrovich Moiseev
NASA	National Aeronautics and Space Administration
NASDA	Japan's national space agency until 2004—this agency is now JAXA
NBL	Neutral Buoyancy Laboratory
NBS	National Bureau of Standards
NDX-1	North Dakota Experimental #1 prototype (NDX-2 = prototype 2)
OES	Orbital Extravehicular Suit
OO	Orbital Outfitters
OPS	Oxygen Purge System
ORU	Orbital Replacement Units
OSS	Oceaneering Space Systems
OSS	Oxygen Supply System
OWS	Orbital Workshop
PCU	Pressure Control Unit—a Skylab LSS component
PCV	Pressure Control Valve—an Apollo LSS component
PECS	Portable Environmental Control System
PGA	Pressure Garment Assembly
PLSS	Acronym has two meanings: Portable Life Support System in Apollo Primary Life Support System in Shuttle
PMA	Pressurized Mating Adapter—an ISS component
POS	Portable Oxygen Subsystem
PPA	Pilot's Protective Assembly
PRE	Personal Rescue Enclosure
PSA	Pressure Suits Assembly
PSC	Pressure sealing closure—a Shuttle CEE feature
psi	Pounds per square inch—unless otherwise noted, the pressure is the delta (psid) from the outside of the pressure vessel, which is usually the vacuum of space, to the inside
psia	Pounds per square inch above an absolute vacuum—this has significance where there is some level of atmosphere outside the spacesuit. The pressure measurement that reflects physiological atmosphere for the wearer is psia, where the pressure loads subjected to pressure suit assembly are a lesser delta pressure
R&D	Research and Development
RCU	Remote Control Unit
RFP	Request For Proposal
RMS	Remote Maneuvering System—an ISS component
RSA	Russian Space Agency (in Russian RKA). In April 2004, this organization was renamed the Russian Federal Space Agency (FSA)
RTV	Room Temperature Vulcanizing—a type of silicon rubber compound
SAC	Space Age Control Incorporated
SAFER	Simplified Aid For EVA Rescue

SCU	Service & Cooling Umbilical
SEVA	Standup Extra-Vehicular Activity or where the astronaut only partially leaves the spacecraft
SOP	Secondary Oxygen Package
SPCA	A model of primate suit developed under the monitoring of the Society for the Prevention of Cruelty to Animals
SSA	Space Suit Assembly
SSER	Space-to-Space EMU Radio
SSF	Space Station Freedom
SUT	Soft Upper Torso
TCV	Temperature Control Valve
TEES	Texas Engineering Experiment Station of the Texas A&M University
TMG	Acronym has two meanings: (1) Thermal Meteoroid Garment in Apollo; and (2) Thermal Micro-meteoroid Garment in Shuttle
UCTA	Urine Collection and Transfer Assembly
UND	University of North Dakota
USA	United Space Alliance
USAF	The United States Air Force
VCM	Ventilation Control Module
WETF	Weightless Environment Test Facility—originally named the Water Immersion Facility (WIF), this NASA-JSC facility was eventually renamed the Weightless Test Facility (WETF)
WIF	Water Immersion Facility
WLVTA	Water Line Vent Tube Assembly
WWI	World War I
WWII	World War II
ZPS	Zero Pre-breathe Suit

1

Introduction

People who venture out in cold weather equipped with a coat, gloves, and hat have something in common with the astronauts and cosmonauts who don spacesuits before undertaking a journey into the harsh environment of space. Both the winter traveler and the spacewalker recognize that nature can be hostile, and to accommodate this hostility they wear garments for protection and survival. Suit protective systems provide for comfort, size variation, life support, mobility, dexterity, and safety.

Selecting cold weather clothing involves tradeoffs. Layers of garments can be added and shed to provide comfort during varying levels of winter environment and activity, but this approach has drawbacks in weight, bulk, and ultimate thermal protection. For example, trading a coat and hat for a parka increases warmth, but limits visibility; and mittens may be warmer than gloves, but inhibit manual activity.

If we consider biological and chemical protective suits, it is not possible inside an enclosed suit to add clothing in cold weather; and, when working in a hot climate or in direct sunlight, cooling must be provided to allow even moderate activity. The enclosed suit also necessitates a life support system that adds oxygen and removes carbon dioxide and humidity.

High-altitude exploration shares many of the considerations of Earth-bound biological/chemical protective suits and adds the need for providing a pressure envelope. On Earth, the weight of miles of air above us causes pressure around and through our bodies, while higher altitudes result in lesser surrounding pressure. If we removed all surrounding pressure from around our bodies, we would perish. Although pressure suits provide the necessary surrounding pressure, they also pose another challenge: mobility. As the pressure inside a suit pushing outward tries to make the suit immobile, this necessitated the development of mobility elements in early pressure suits. However, the degree of sophistication of the mobility elements has to be based on need, and then weighed against comfort, bulk, and cost.

K.S. Thomas and H.J. McMann, *U. S. Spacesuits*, Springer Praxis Books,
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Spacesuits potentially add another dimension to the technical challenges to keeping humans alive in space. Space pressure suits require greater consideration for pressurized fit and use. Development is very dynamic, and minor changes can have surprising results. Complex shapes and effects from pressure load make the use of structural fabrics a "black art". Unlike most other engineering applications, there are effectively no textbooks with empirical tables to allow the selecting of materials, system architectures, and volumetric/mass attributes to effectively design, certify, and produce an effective spacesuit system for an application with minimal development. Thus, spacesuit design and development are very iterative processes.

While launch/entry/emergency "intravehicular activity" (IVA) spacesuits that are never used outside the spacecraft can be very similar to equivalent high-altitude aviation pressure suits, there are differences. Spacecraft exit and subsequent survival is more challenging. To date, IVA spacesuits that have reached flight service have been derivations of existing high-altitude aviation pressure suits. This may change in the future.

Spacesuit systems that permit people to venture out into space and perform activities have to address even more challenging environments. These challenges include greater need for low-effort mobility, extreme thermal conditions, higher levels of radiation, protection of the eyes from blinding direct sunlight, and resistance to impingement from limited levels of micrometeoroids and space debris. The response to these challenges has varied in approach and ultimate success. This book is intended to provide insight into these challenges and the technical responses.

2

Reaching upward and outward

As humans attempt to reach higher into the atmosphere, a host of physiological challenges emerge. First, as one travels upward, the familiar sea level atmospheric pressure lessens. In fact, air pressure drops by about half for every 3.4 miles (5.5 km) of altitude increase. For those traveling to higher elevations, this means that, although the percentages of oxygen, nitrogen, and trace gases remain the same, the actual amount of oxygen available to the lungs is decreasing drastically. For example, the altitude of Denver, Colorado, in the U.S.A. is 5,300 ft (1,600 m) above sea level. Denver's elevation causes a reduction in air pressure of over 4 psi from that at sea level. The partial pressure of oxygen, or the amount of oxygen present to support life, is correspondingly reduced from just over 3 psi (21 kPa) at sea level to just over 2 psi (14 kPa). Those who have exercised at elevated locations such as Denver may have noticed the need to breathe more deeply. If breathing harder does not provide enough oxygen, the level of oxygen in the blood becomes reduced, resulting in a condition called hypoxia.

Hypoxia is insidious; it is not like suffocation, where there is a desperate struggle to take a breath. Hypoxia symptoms vary from individual to individual, but some common symptoms include blurring of vision, slight shortness of breath, dizziness, and possibly vague weakness. However, sometimes, these symptoms are so slight as to go unnoticed, which may be an indication of another potential symptom of hypoxia: impaired judgment.

Decrease in oxygen due to increase in altitude is a significant consideration in aviation. U.S. pilots are recommended not to fly above 10,000 ft (3.1 km) without supplemental oxygen during the day and not above 8,000 ft (2.4 km) at night. However, understanding the relationship between oxygen and altitude is not new, and was learned in early aviation. Until World War I, the internal combustion engines that powered aircraft lost power as the aircraft gained higher altitudes. This, rather than impaired human function, imposed limits on the altitude that aircraft could attain.

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Figure 2.1. Circa 1918 German Imperial Flying Corp oxygen pipe system (courtesy Hamilton Sundstrand).

World War I (WWI), which was fought between 1914 and 1918, brought aviation inventions that included the supercharger. A supercharger compresses the air going into an engine to compensate for the atmosphere becoming thinner with altitude. This made the human crew the limiting factor to achieving higher altitudes. Another WWI invention, "oxygen pipes" with nose-clips (Figure 2.1), proved to be an effective solution. However, this had drawbacks such as clip discomfort over time and decreased efficiency that provided limitation to the altitude advantage. Higher altitudes brought yet another challenge: colder temperatures with altitude. For every 10,000 ft (3.1 km) increase in altitude, the temperature tends to drop approximately 28°F (16°C). This was also realized at the time of WWI, but was more easily solved by providing pilots with appropriate clothing. Thus, the ability to effectively provide supplemental oxygen was the main constraint to ascents to higher altitudes.

Exposure to European aviation technology in WWI was an awakening for a U.S.A. that had envisioned itself as an aviation-leading nation. This epiphany was reinforced by its having to purchase French aircraft for U.S. aerial combat forces. As a consequence, President Wilson established the National Advisory Committee for Aeronautics (NACA) in 1918 to close the aviation technology gap.

Figure 2.2. 1920s' NACA/U.S. Army Air Corp oxygen mask and thermal protection suit (courtesy Hamilton Sundstrand).

The 1920s brought the development of flying suits (Figure 2.2) with tight-fitting oxygen masks and effective thermal protection garments for altitude record attempts. However, the oxygen mask was only effective to about 35,000 ft (10.7 km), at which point the amount of oxygen in the lungs would become insufficient to support adequate human function.

Pressure suits were also considered as a potential solution to humans functioning in high altitudes; however, their development would take much longer. The world's first high-altitude pressure suit concept appears to have been the vision of Fred M. Sample, who conceived a "suit for aviators" that would provide a compressor-fed atmosphere to an enclosed suit to permit "flights at high altitude … or travel in a rarified atmosphere" (U.S. patent 1,272,537 filed on March 20, 1917). It is unknown what sort of fabrications, if any, may have accompanied this patent effort. The earliest known creation of an aviation full pressure suit prototype occurred in Russia in 1931, and was the product of an engineer named E. E. Chertovsky. While the Chertovsky Ch-1 suit had essentially no mobility when pressurized, it was but a first development in pressure suits for Russian balloon records and, later, programs for military aviation suits.

In parallel to Sample and Chertovsky, a British professor named John Scott Haldane was exploring the challenges of high altitude, and saw pressure suits as a solution. Haldane, who developed staged decompression for deep sea divers to prevent the bends, traveled to Pike's Peak in the U.S.A. to conduct extensive studies on the physiological effects of high-altitude, lower air pressure on humans. His 1920 published studies included a concept for a fabric high-altitude, full pressure suit. In 1931, an American daredevil named Mark Ridge became obsessed with breaking the world's altitude record in an open gondola balloon using a fabric pressure suit. Ridge recognized that the challenges included oxygen deprivation and temperatures of −60°F to −70°F (−51°C to −57°C), and his quest ultimately took him to the U.K. to see Dr. Haldane in the summer of 1933. Haldane shared Ridge's interest in pressure suit development, and sought the assistance of Sir Robert H. Davis, DSc and a member of Siebe, Gorman & Company (a pioneer deep sea diving suit manufacturer). With the Haldane and Davis resources, a prototype suit was created. Ridge tested the suit in a simple low-pressure chamber to a simulated 50,000 ft on November 16, 1933. However, as he got no British support for further activities, he never made his record attempt. On September 28, 1936, Royal Air Force Squadron Leader F. R. D. Swain set an official world's altitude record at 49,967 ft (15.4 km) in a similar Haldane–Davis suit. This, however, was not the world's first operational pressure suit.

In the U.S.A., aviator Wiley Post recognized the west-to-east speed advantages of high-altitude wind currents and the need for a pressure suit system to support manned flight at those altitudes. In 1933, he conceived a suit system that combined excess pressure from the engine's supercharger and excess heat from the engine's exhaust with a fabric suit for pressure enclosure, and supplemental oxygen to provide a lightweight/compact high-altitude life support system. In March 1934, Post secured B.F. Goodrich (BFG, now Goodrich Corporation) to make the suit. Supporting this project was Russell Colley, who would be a key participant in Goodrich's pressure suit developments during the decades that followed. Goodrich made three prototype suits before a successful suit emerged. On September 5, 1934, suit No. 3 (Figure 2.3), with an operating pressure of 3 psi (21 kPa), successfully supported flight at 42,000 ft, but subsequent flights to 50,000 ft (15 km) and over were never officially recognized due to documenting instrument failures. Between 1934 and 1935, Post made five attempts to use what is now known as the jetstream to set a new U.S. transcontinental record. All attempts failed due to mechanical difficulties; however, the difficulties were with the aircraft and not with the suit system.

Significant effort was put into high-altitude pressure suit development during World War II (WWII), and in the U.S.A. many companies and organizations competed in this wartime endeavor. While Goodrich (Figure 2.4) was among those at the U.S. forefront, the field of participants included Arrowhead Rubber Company, Goodyear Tire & Rubber, U.S. Rubber Company, University of Minnesota teamed up with Bell Aircraft, and the U.S. National Bureau of Standards. The Bureau of Standards and the University of California acted as clearinghouses to disseminate information to all the pressure suit companies of the

Figure 2.3. The Post/B.F. Goodrich Suit No. 3 of 1934 (courtesy G. L. Harris).

Figure 2.4. 1943 BFG XH-5 prototype suit (courtesy G. L. Harris).

period. While effective pressure suit mobility was not obtained in WWII, this effort provided the groundwork for future development.

With the conclusion of the war, the U.S./Soviet "Cold War" competition resulted in continued funding of aviation development. This included high-altitude, high-speed applications such as the X-1 rocket plane developed under the auspices of the National Advisory Committee on Aeronautics (NACA), which would later be absorbed into the National Aeronautics and Space Administration (NASA). In this area, the David Clark Company (DCC) came to prominence with the development of a partial pressure (mechanical counterpressure) suit system for high-altitude aircraft. This started with the association of Dr. James Henry of the University of Southern California and David M. Clark, founder of the DCC while working on acceleration/anti-*g* suits during WWII. Dr. Henry conceived a system where a gas mask provided pressurized oxygen to the face and lungs. Gas pressure also expanded "capstan tubes" running down the torso, arms, and legs, which tightened the garment and provided external counterpressure. DCC provided resources and technical support to Dr. Henry, and the resulting prototype (Figure 2.5) was tested to an equivalent of 90,000 ft (27 km) at Wright Field, Ohio, in 1946. DCC then developed Dr. Henry's design into the S-1 flight suit that supported the

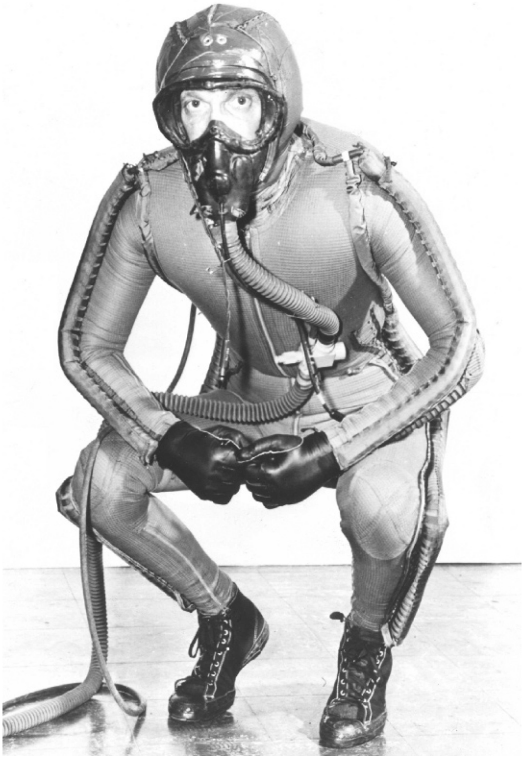

Figure 2.5. 1946 Dr. Henry in his partial pressure suit prototype (courtesy David Clark Co.).

X-1 rocket plane's record-breaking flights above 50,000 ft (15 km). The Henry/DCC capstan partial pressure suit design in subsequent DCC models was used routinely in high-altitude activities until 1989, and the overall principle of mechanical counterpressure suits remains a potential future spacesuit technology.

The X-1 plane was followed by D-558-2, another NACA rocket plane program. The objective was to break Mach 2, and a better pressure suit system was therefore sought. In 1951, DCC won the development contract with its first operational full pressure suit. The resulting design featured an arm scye (shoulder) bearing and a waffle weave fabric restraint layer with integrated webbing and chord restraints to form highly effective mobility elements (Figure 2.6). This full pressure enclosure required less effort to reach and operate controls, and the pilot's protection was no longer a barrier to progression into the fringes of space.

Other perceived Cold War needs were U.S. surveillance aircraft—such as the U-2 to fly at extremely high altitudes to avoid missiles—and U.S. fighter aircraft to reach high-flying Soviet bombers. In the 1950s, the U.S. Navy was tasked with the development of a full pressure suit. For this system, the Navy utilized Goodrich &

Figure 2.6. 1951 DCC D-558-II full pressure suit with "Link-net" (courtesy, left and right, David Clark Co. and G. L. Harris, respectively)

Figure 2.7. 1959 era BFG Mark III/IV-type full pressure suit (courtesy Hamilton Sundstrand).

Arrowhead Rubber for pressure suit development and produced a variety of models, culminating in the late 1950s with the Goodrich Mark III and IV designs (Figure 2.7). While these suits were exclusively for aviation applications, NASA subsequently used the Goodrich Mark IV with minor modifications to support its first manned space program, Project Mercury (see Section 4.2).

In 1954, NACA led the development of the X-15 experimental aircraft that would progressively break speed and altitude records to ultimately reach 6.72 times the speed of sound and 354,200 ft (108 km). The X-15 application also required the full pressure suit to provide not only hypobaric (low-pressure) protection but also windblast protection in the event of a high-speed ejection. This resulted in the development of a pressure suit system in parallel with that of the Navy. The David Clark Company won the contract for the design, development, and manufacture of X-15 suits (discussed in Section 4.1), and as the rocket engine–powered X-15 was intended to set altitude records reaching into suborbital space, these X-15 suits qualified as the first U.S. spacesuit design.

3

The basics of spacesuits

Mankind's quest for ever higher altitudes resulted in finally reaching into space itself. However, the Moon, planets, and vast expanses of open space present even greater challenges. While space shares demands with high-altitude aviation such as proper oxygen level, removal of carbon dioxide and humidity control, space additionally requires protection from greater thermal extremes, radiation, and direct sunlight. In addition, operating in space adds greater challenges to communication, mobility/fit, and any operation in which one must use one's hands. Approaches for satisfying these more stringent requirements have varied through the years with varying degrees of success. As experience has been gained, new techniques and technologies have emerged.

This chapter supplies basic information to permit appreciation and understanding of spacesuits and the challenges faced by their designers. The information falls into two areas: "types of spacesuit" and "space challenges to humans". This chapter offers an introduction into the panoply of spacesuits.

3.1 TYPES OF SPACESUITS

Thus far, basically three types of spacesuit have been produced (Figure 3.1.1). These are intravehicular activity (IVA), exclusively extravehicular activity (EVA), and combined intra/extravehicular activity (IEVA), which are described in the discussions that follow.

Crew escape/rescue/launch/entry IVA suits

The functions of IVA spacesuits include keeping the astronaut (or cosmonaut) alive if the spacecraft loses internal pressure, providing a safe haven if the cabin atmosphere becomes contaminated, supporting escape in case of emergency, and aiding

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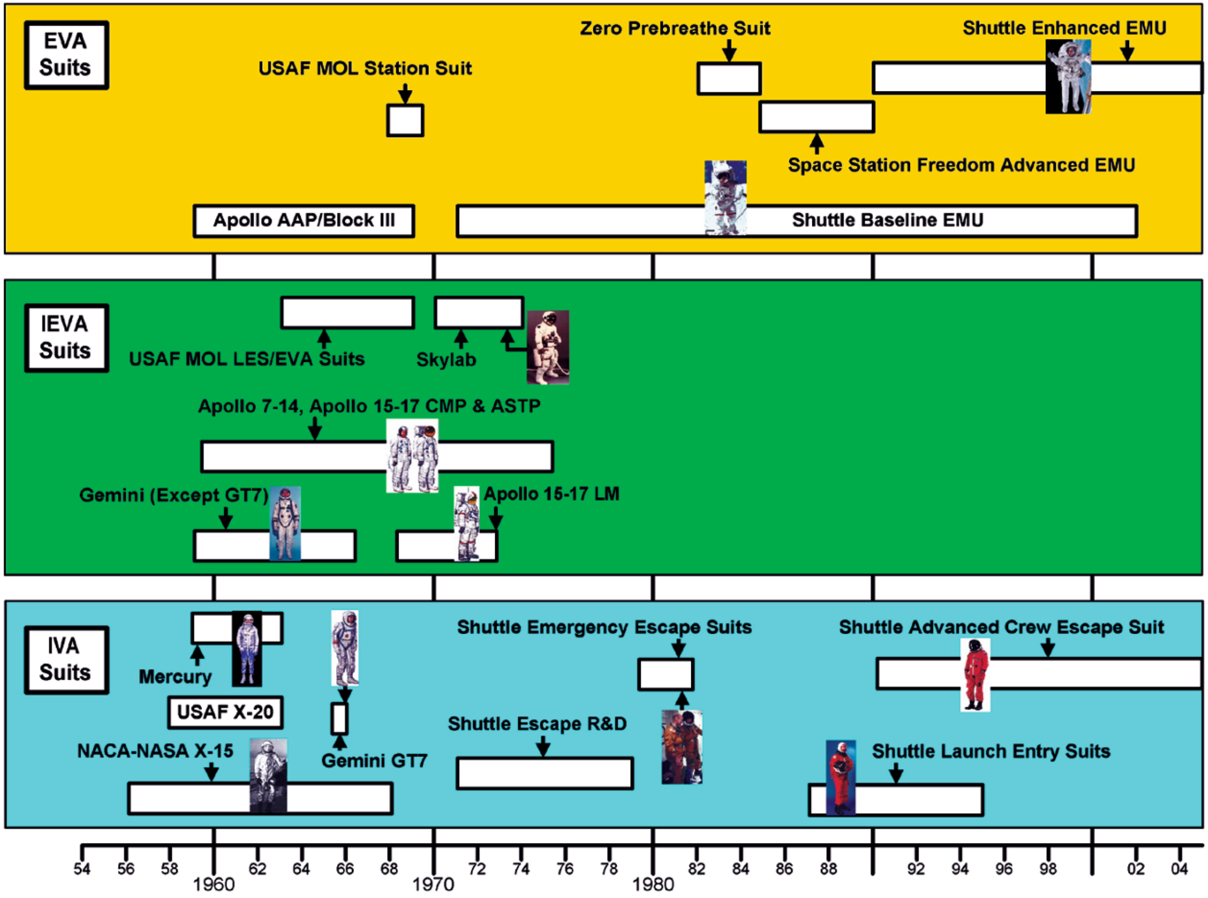

Note: Timeline starts at first related study for the program. Illustration location on timeline denotes first space use.

Figure 3.1.1. Types of spacesuit used by U.S. programs with timelines.

survival after successful egress. The first Russian, U.S., and Chinese spacesuits have been IVA suits, since these first steps to space have been an attempt to go into space and return without going outside the vehicle. However, IVA suit facilities have continued to be a part of all space vehicle systems because these suits enhance crew survival. This is especially important during launch and entry. During these phases of the flight, multi-g loads and significant vibration are placed on the crew and spacecraft. Under these conditions, minimum weight, minimum bulk, and no hard contact with suit components are as important to human function as comfort. These factors are also important during pre-launch periods. Prior to launch, an astronaut can be constrained in the launch position for hours. Thus, freedom from contact with hard and unfriendly shapes is critical. Minimal weight and bulk are also important in the event of a launchpad disaster to ensure that an astronaut's ability to exit the vehicle and launch area quickly is not inhibited.

Both Russian and U.S. IVA suit systems carry basic survival equipment, including an emergency oxygen system for life support during emergency conditions, flotation systems for water landings, comfort padding, liquid-cooling garment(s), communications and biomedical systems, waste management systems, drinking water, flares/flashlight/lightsticks, radio, knife/shroud line cutter, and exposure clothing. In recognition of these safety features, the Russians have traditionally called their IVA suits "rescue suits". U.S. IVA suits additionally carry, or interface with, a parachute system for leaving the spacecraft after launch or before landing.

Extravehicular activity spacesuits

An EVA spacesuit system allows a cosmonaut or astronaut to perform activities outside the vehicle in the vacuum of space, be it in orbit, on the Moon, or on a planetary body. While requirements may vary according to operational scenarios, an EVA suit system provides protection from radiation, temperatures as high as 250°F (121°C) or as low as −250°F (−157°C), blinding light, and microscopic particles potentially traveling faster than 17,500 mph (28,158 kph). The EVA suit system is usually also expected to provide lighting and tool attachments for working under any conditions while allowing low-effort mobility to permit many hours of effective work. For working in space, two approaches have been followed in EVA spacesuit system development. One approach features a dedicated EVA system that is optimized for working in space but does not support launch and entry. The second is an intra/extravehicular activity (IEVA) dual-purpose suit that serves both as a launch/entry suit and as an EVA system, when conjoined with a life support system.

Both the U.S. and Russian space agencies currently use EVA suits exclusively. These EVA spacesuits utilize hard upper-torso "shell" structures, bearings, and mobility joints with elements that allow low-effort mobility, but these features introduce mass and potential contact points that would be unacceptable in an IVA application. Also, without the constraints of IVA requirements, the EVA system can be optimized for tool attachment and control plus tether attachments for zero-effort position retention during EVA. In zero gravity, the weight of such systems that may have significant "Earth weight" is of little consequence. In lunar and planetary conditions, an EVA suit might be optimized for walking, riding in/on vehicles or reaching desired exploration sites. Given the cost of putting humans in space to perform work, making those humans as effective as possible in performing work tends to favor the (exclusively) EVA suit approach.

The first exclusively EVA suit system to see space usage was the Russian Orlan D system on December 20, 1977. This EVA system was used to perform an external inspection on the Soviet space station Salyut 6. The equivalent U.S. milestone came on April 7, 1983, with the first EVA of a Shuttle extravehicular mobility unit (EMU) to test EVA equipment and systems on Space Shuttle mission STS-6.

Intra/extravehicular activity dual-purpose spacesuits

The first Russian and U.S. spacesuits to be used outside a vehicle were IEVA-type dual-purpose designs that served as both a launch/entry suit and an EVA system. This was due to the volume and launch weight limitations of the early space vehicle systems, and such early suit systems resulted in functional compromises compared with single-purpose IVA and EVA systems. EVA thermal garments place distracting and uncomfortable additional weight on the chest during multi-g launches, and the bulk of the thermal garments also provide encumbrance in emergency egress. Also, systems that provide the best capacity for EVA mobility have hard details and surfaces that would cause unacceptable contact during launch and entry, and optimum EVA mobility systems tend to add mass and bulk that, like the thermal garments, would be inhibiting in some emergency egress conditions. The effective performance of work in space requires tool control/storage and positioning attachments, but this additionally adds weight and potential obstructions that would be a constraint in many emergency activities. As a result, the U.S. (Figure 3.1.1) and Russian space agencies both adopted separate IVA and EVA suit systems as soon as lift vehicle development allowed the weight and volume of separate systems to be developed.

However, the IEVA suit approach saved volume and launch weight that made possible the first ventures outside the spacecraft. Such suits accrued a distinguished service history supporting EVA activities in the Voskhod, Gemini, Apollo, early Soyuz, and Skylab programs. As humanity considers a return to the Moon and onto Mars, launch weight and volume will again be significant considerations supporting a potential return to the IEVA approach. This will have to be traded against launch comfort, emergency egress, gravitational weight considerations, and EVA effectiveness. In solar system exploration, planetary gravity becomes an increasingly important consideration. The gravity of the Moon is one sixth that of Earth, and Mars has gravity that is three eighths that of Earth. While, current U.S. and Russian EVA suit systems weigh 250 lb to 275 lb (112 kg to 125 kg) on Earth, they essentially weigh nothing in orbit where they are normally used. However, these all day EVA work systems would weigh about 40 lb to 46 lb (18 kg to 21 kg) on the Moon and 96 lb to 106 lb (44 kg to 48 kg) on Mars.

3.2 CHALLENGES TO SPACESUIT DEVELOPMENT

Space is deceptive. The vacuum of space, while devoid of breathable air, has many extreme hazards. Without the filtering of Earth's atmosphere, sunlight is so intense that it can literally be permanently blinding. Without insulation for protection, people would be baked on one side and frozen on the other. Without a protective pressure envelope, the water-based fluids in the human body would boil or freeze on their way to the vapor state. To promote an understanding of what a spacesuit provides and the technical evolution of these suit systems, the subjects listed below are addressed in the discussions that follow:

- Space vacuum vs. the human need for surrounding pressure
- The dynamics of a pressure enclosure and effects on joint mobility
- Pressure selection and decompression
- Thermal and radiation protection and control
- Human-friendly spacesuit environments
- Protection from direct sunlight in space
- Space debris
- The cost of space hardware.

Space vacuum vs. the human need for surrounding pressure

On Earth at sea level, the body functions in a 14.7 psi (1 atm) environment. This results in uniform pressure all over and all through our bodies. The U.S. Space Shuttle and the International Space Station operate at 14.7 psi. If a spacecraft cabin failed and a person decompressed to space vacuum, all air would be expended from the lungs, the body would expand, blood vessels would rupture, and the blood would eventually boil.

However, humans can operate in lower pressure environments. Millions of people live in higher elevations where the air pressure is two thirds that of sea level pressure or less. If decompression is adequately slow, people can operate in a pure oxygen environment down to almost one fifth of sea level pressure without harm. As higher suit pressures typically result in increased effort and user fatigue, it would seem that the spacesuit design goal would be to operate at the lowest pressure possible. However, the need to decompress to use low-pressure spacesuits adds yet more hazards. Being surrounded with pressure is therefore a necessity and a source of conflicting challenges.

The dynamics of a pressure enclosure and effects on joint mobility

The advantage of a human in space over a robot is the ability to see, touch, and adapt instantly to real-time conditions. This is an advantage only if the astronauts are able to effectively use their hands, arms, legs, eyes, and brains. At least 3 psi (pounds per square inch) or 21 kPa (kilopascals) pressure are needed to support life. An average size pressure suit has over 3,000 in.^{2} (1.9 m^2) of internal surface area. So, even minimum pressure can make fabric pressure suits hard to the touch and potentially immobile. The ideal pressure suit mobility system would allow the suit user to move in any possible direction with negligible effort and without impediment of movement, injury, or increased risk to safety. But this has yet to be achieved. The most common approach thus far has been the strategic location of constant or near constant volume mobility joints. Constant volume is the ideal, because having to compress the internal volume of the suit to bend a finger, arm, or leg requires effort. Without mobility systems, the effort to compress the volume is beyond human ability. However, mobility systems that nearly retain constant volume during bending tend to have accompanying features that add weight, bulk, and hard elements that frequently conflict with other requirements of the suit system. Higher operating pressures not only increase the challenges to mobility, but also increase the structural requirements, adding bulk to impair mobility.

A common element of the previously mentioned U.S. high-altitude pressure suits is that they were capable of providing a pressure increase up to 3.5 psi (24 kPa) above the surrounding atmosphere. While spacesuit mobility technology improvements have made higher operating pressures possible, fatigue over an 8-hour typical workday has been a key factor in keeping U.S. spacesuit operating pressures low. One disadvantage of lower operating pressures is the need to remove dissolved nitrogen in the blood and tissues before decompressing to the suit operating level. This lowering of pressure increases the likelihood of decompression sickness (DCS), commonly called the "bends". The Shuttle extravehicular mobility unit (EMU) has an operating pressure of 4.3 psi (30 kPa) and the Shuttle crew escape/launch/entry suit operates at a maximum of 3.5 psi (24 kPa). All Russian spacesuits, in comparison, operate at 5.8 psi (40 kPa) to minimize or avoid decompression sickness or other risks.

The dynamics of pressure are most noticeable, and the greatest technical challenges still lie, in hand dexterity, tactility (touch feedback), and comfort. Gloves pose unique problems such as accommodating small hands, the bulk from stitching and seams, heat loss (high surface area), differences in hand configuration between individuals (contact pressure with time can result in injury) and wear/abrasion protection vs. tactility. Effective use of hands and fatigue are the limiting factors to higher pressure suit systems, which offer the benefit of no pre-breathing. Using lower operating pressures equals lower user fatigue, technical challenge, and cost. However, lower pressures add further challenges, which are discussed in the next topic.

Pressure selection and decompression

The U.S. Space Shuttle and the International Space Station both use Earth-like nitrogen/oxygen atmospheres pressurized to 14.7 psi (1 atm). As the current U.S. EVA spacesuit operates at a nominal 4.3 psi (30 kPa), this requires a controlled rate of decompression from the station or Shuttle cabin pressure to avoid decompression sickness (DCS). The importance of controlling the rate of decompression was first learned in deep mining and underwater construction applications in the 19th century where mystery illnesses commonly called "the bends" sickened, crippled, and killed workers.

DCS is now understood to result from making too rapid a transition from high pressure to low pressure. Atmospheric nitrogen is very soluble in certain body tissues such as fat, scar tissue, and cartilage. When the body is depressurized rapidly, the nitrogen tries to leave these tissues. Nitrogen bubbles expand within the poorly vascularized cartilage and scar tissue surrounding certain joints. The results can range from minor discomfort to physical disability. Nitrogen bubbles forming in the bloodstream can also overwhelm the lungs' ability to degas the blood. When this occurs, symptoms range from breathing discomfort to lethal embolisms, depending on whether the gas bubbles lodge in blood vessels supplying critical organs such as the brain, lungs, or heart.

There are safe decompression rates that can minimize the chances of DCS. Ridding the body tissues and blood of nitrogen before reducing pressure is another method of guarding against DCS. In the U.S. Space Shuttle, cabin pressure is reduced to 10.2 psi (70 kPa) for 24 hours prior to an EVA. The suited astronaut then pre-breathes pure oxygen in the airlock for 45 minutes prior to decompressing the airlock to the Shuttle extravehicular mobility unit (EMU) operating pressure of 4.3 psi (30 kPa). In the International Space Station, the protocol does not involve lowering the airlock pressure, so the astronaut or cosmonaut must pre-breathe oxygen for approximately 4 hours prior to decompressing the airlock.

U.S. studies have indicated that people could rapidly decompress from 14.7 psi (1 atm) to 8 psi (55 kPa) with minimal risk. Similar Russian studies viewed decompression sickness risk slightly differently. From 14.7 psi, a Russian suit pressure of 5.8 psi (40 kPa) is judged to be sufficient to avoid decompression sickness after half an hour of breathing pure oxygen, which is approximately how long it takes to perform a suit checkout before going out to do an extravehicular activity. As a result, all Russian spacesuits feature a 5.8 psi operating pressure.

Human-friendly spacesuit environments

Humans require environmental parameters to be within prescribed limits for comfort and to effectively perform work. One significant parameter is oxygen concentration. In a sea level atmosphere of 14.7 psia, the oxygen partial pressure is 3.08 psia (21.2 kPa). This results in an oxygen partial pressure within the alveoli of the lungs of 2.0 psia (13.7 kPa). NASA selected this as the lower limit of alveolar pressure for nominal human space operations. To maximize spacesuit joint mobility and to minimize leakage and loads on the pressure suit, spacesuits are designed to operate at the lowest pressure consistent with other requirements. Hence all spacesuit systems provide a breathing atmosphere of 100% oxygen (discounting small amounts of carbon dioxide and water vapor). However, because breathing efficiency decreases as pressure decreases, the normal operating pressure for U.S. spacesuits in the 1960s and early 1970s was established at 3.7 psi (25.5 kPa).

Humans can also exist at oxygen partial pressures at or slightly above 17.7 psi (1.2 atm) for periods of up to several weeks before incurring oxygen toxicity. Early space programs sought to take advantage of this. By placing astronauts or cosmonauts in pure oxygen atmospheres of 14.7 psi for a few hours prior to launch, nitrogen would dissolve from body tissues and the crew could safely decompress rapidly when launched. This also permitted spacecraft to use simple, single-gas (pure oxygen) life support systems and cabin pressures of 5 psi (34.5 kPa) for U.S. or 5.8 psi (40 kPa) for Soviet designs. With these cabin pressures, EVAs could be initiated without any pre-breathing to avoid decompression problems. The lower pressures also reduced structural requirements, and thus the weight of the spacecraft. However, this approach brought significant other hazards such as increased flammability and toxicity.

The Soviet Union learned this first on March 23, 1961, with the loss of cosmonaut Valentin Bondarenko. Bondarenko was in a pressure chamber filled with pure oxygen at 14.7 psi for a long-duration experiment. A medical alcohol wipe accidentally hit a hot plate, and the wipe not only instantly caught fire, but also resulted in the ignition of many other materials in the chamber, including clothing. Bondarenko was rescued from the chamber but died soon afterward. This tragedy made the Soviet space program aware of the danger and spacecraft cabin atmospheres and procedures were revised averting any further losses. Unfortunately, the Soviet Union elected not to share this loss with the world, and so the United States would go on to repeat the tragedy.

On January 27, 1967, a fire during a capsule checkout claimed the lives of what was to have been the first Apollo crew, astronauts Chaffee, White, and Grissom. It was not only learned that materials became surprisingly more combustible in a higher pressure of oxygen, but also that the combusting materials off-gassed potentially toxic chemicals. This led to the creation of more stringent new requirements and safer space travel for those who followed. However, the safe introduction of oxygen is just one of many spacesuit system considerations.

In a sealed environment without any supplemental life support, carbon dioxide (CO_2) will cause incapacitation or result in loss of life before oxygen deprivation. There are many chemical sorbents that can remove CO_2 from the atmosphere, but weight and volume are premium considerations in space applications. From the beginning of manned space flight, lithium hydroxide (LiOH) was favored by space programs for its ability to absorb CO_2 and become lithium carbonate. However, LiOH is not a regenerable material. It is also a potent irritant if released into the atmosphere. Once it has reached its capacity for absorption, it must be discarded. Space stations have brought the need for a CO_2 removal system that can effectively function for durations of months and even years. This has fostered the development and use of other chemical systems that are regenerable but perform the same function. The "CO_2 removal" cartridges in the last three U.S. EVA suit systems have been named contamination control cartridges because they contain particulate

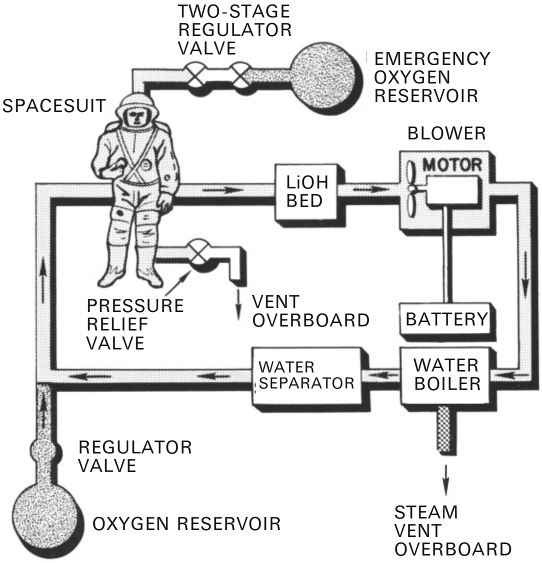

Figure 3.2.1. 1962–1963 Apollo schematic showing a "basic system" (courtesy Hamilton Sundstrand).

and charcoal odor filters, in addition to the chemical that removes CO_2 (see Figure 3.2.1). One version, used for Shuttle EVAs, still uses LiOH. On board the International Space Station, however, a metal oxide lattice adsorbent is used and regenerated by driving off captured CO_2 by means of a heated airstream in an oven.

Control of odors in spacecraft (and, as a consequence, spacesuits) received significant attention in the U.S. space programs of the 1960s. Natural materials like leathers and natural rubbers were designed out of the systems in favor of synthetics. One of the changes resulting from the Apollo capsule fire was the formalized process of evaluating odors in the U.S. material acceptance process for all manned space applications. This resulted in spacesuits without noticeable smell in contrast to the Russian suit systems, which continue to use natural materials and have their own unique, but not objectionable aroma.

Humidity is also important. Humans perspire and exhale molecular water. In a closed environment such as a spacesuit, this quickly causes extremely humid conditions that not only cause discomfort, but can also adversely affect the function of systems within the spacesuit. Thus, a spacesuit system must remove humidity. But removal of the humidity in the ventilation stream can cause yet further difficulties. An atmosphere that is too dry can adversely affect the eyes and nasal passages of the suit user. Over 8-hour periods and repeated usage, this can affect the mission and the wellbeing of the astronaut. An excessively dry atmosphere can also result in hazards from electrostatic discharge. Even with material selections and oxygen safety–minded procedures, ignition sources are deliberately designed out of the pure oxygen environments of spacesuits. Should a static electricity discharge occur within a spacesuit, it could involve tens of thousands of volts, but only microamps of current. This could shock, but not harm, the crewmember. However, as this could damage sensitive electronic components, suit systems must remove excess humidity while maintaining at least minimum levels of humidity for both comfort and safety.

Ventilation is yet another spacesuit consideration. The flow of gases through the suit must be adequate to wash out CO_2, prevent fogging of the visor, and remove user odors. Early spacesuits also relied on ventilation flow to cool the astronaut. So, the fastest ventilation flow possible would probably seem ideal, but the ventilation flow requires energy, enlarging batteries or adding other devices that add weight and volume. Early high-flow suit systems also had ventilation noise difficulties; thus, sizing the ventilation flow for the application is one of the many spacesuit arts.

Another spacesuit art is addressing the nutritional and waste disposal needs of the users. From the time a user dons a spacesuit until it is doffed is typically 9 hours or more. Leaving the suit to eat or to make use of the lavatory are not options. To provide food during Apollo, the U.S. used a slurry mix injected through a port in the helmet, and the same helmet port allowed the astronaut to drink fluids. Today, the astronaut has a food-stick positioned inside the suit helmet. Also, an in-suit drink bag is mounted inside the upper torso with a drink valve positioned near the mouth. While these modern day systems have drawbacks, such devices allow the astronaut to have a bite to eat or something to drink during the workday.

In Apollo, all the astronauts were male. A urine collection and transfer assembly was provided for control and removal of liquid waste, and worked only for male personnel. Apollo spacesuits also had a fecal containment system—essentially an adult sized diaper—which addressed the potential for solid waste. The Shuttle EVA suit system uses a maximum absorbency garment (MAG) for both liquid and solid waste for both sexes of spacewalker. The MAG works and looks like adult "pull-ups". As crews typically use the Shuttle or station facilities before going EVA and exercise timing in the consumption of in-suit water, the principal function of such systems is to provide peace of mind as they are rarely, if ever, used.

Thermal and radiation protection and control

Effectively, space has no temperature; yet, in space, heat and cold can be experienced beyond any Earthly possibility. At an altitude of 53 miles (85 km), the temperature decreases to about −120°F (−85°C). After this, at about 398 miles (640 km), the temperature actually increases but not in an effective way. In this layer of space the small amount of residual oxygen absorbs highly energetic solar radiation, so the temperatures of these oxygen molecules can reach 4,500°F (2,482°C) in the "day-side" of an orbit. However, these temperatures essentially have no effect. The gaseous atmosphere around us on Earth is not only dense enough to support life, but it also allows thermal energy to move and attempt to equalize. That is why you feel warmer when you walk from an air-conditioned building out into the summer's heat. The air around you is literally trying to heat you up. The oxygen in this layer of space is, for all practical purposes, negligible. At 47 miles, the pressure is less than 0.001 of 1 psi (0.007 kPa). Thus, the rarity or extremely low density of these gases renders convection insignificant to heating or cooling.

In space, heat is transferred through radiant energy in the form of direct or reflected sunlight. The temperatures of objects in space, including astronauts and cosmonauts, when exposed to solar radiation coupled with reflected energy from surrounding surfaces, can exceed 250°F (121°C). Without any radiant energy from the Sun, a totally shaded condition such as the cold void of space itself is roughly −387°F (−233°C). The result is that an object may absorb solar radiation and become heated on one side and radiate heat away on the shaded side. Exactly how much heat is absorbed or lost depends on the surface characteristics of the object and the use of insulation. Designers make use of this in selecting material layers of spacesuits.

On the Moon, radiation is also the mode of heat transfer. Lunar craters facing the Sun may reach 250°F (121°C), while areas facing deep space may reach −250°F (−157°C). On Mars, the presence of a slight atmosphere with winds and dust presents a different set of challenges. The temperature extremes are less than in space or on the Moon, ranging from about −120°F (−84°C) to a high of about +13°F (−10°C). The very thin atmosphere of approximately 0.0145 psi (0.1 kPa) gives rise to heat loss or gain due to wind action. Therefore, the type of insulation to be used in space or on the Moon will vary from that used on Mars.

The very beginning of manned space programs saw the development of highly effective insulation for the vacuum of space. This was aluminized Mylar. A dozen or less layers of spaced aluminized Mylar can effectively insulate in space. But this solution brings yet another problem, which is getting rid of body and electrical component heat. This problem has two facets: the first is the removal or collection of heat within the suit; the other is rejecting that collected thermal energy to space.

Without a cooling system, the inside environment of a spacesuit would stabilize somewhere above the user's temperature, which is nominally 98.6°F (37°C). This produces an unfavorable climate for activity. As the user performs work, more thermal energy is created. As the body sweats to cool itself, the environment would become excessively humid making sweating ineffective. The user's body would soon overheat or become dehydrated. Given the small enclosed atmosphere around the spacesuit wearer, spacesuit system designers soon learned that cooling and dehumidifying the ventilation gases was not effective for either keeping the wearer comfortable or being able to perform meaningful work. The solution was the invention of the liquid cooling garment. This garment is laced throughout with water tubes to remove metabolically generated heat. The water loop is also used to cool electronics, as well as condition the ventilation loop by cooling it and condensing out water vapor.

The collected thermal energy then has to be rejected to space. As space is a vacuum, an Earth-type "radiator"—such as one might use in an automobile—would be useless as there is no air to provide thermal transfer. Therefore, evaporative cooling by boiling or sublimating water at low pressure has been uniformly selected as the first approach. By evaporating water to space, the cooling water loop can be reduced to about 40°F (4°C). Each pound of evaporated water can remove over 1,000 Btu (252 kcal) from the spacesuit. This evaporation can be accomplished through wicks or microscopically fine mesh screens, provides effective cooling, and works well for limited duration missions such as spacesuit use, but requires the transport of water into space. In the future, as humankind looks to routinely work in space or travel to planets and moons in the outer reaches of the solar system, new regenerable, low-mass, compact ways of rejecting thermal energy to space will have to be developed. This is not the only energy challenge that is posed by solar system exploration.

Space has forms of radiation that can be harmful. On Earth, the atmosphere acts as a filter protecting people from the most injurious parts of solar radiation. Space has minutely spaced but highly energized hydrogen, helium, carbon, nitrogen, silicon, calcium, iron, and oxygen atoms. It also has solar ultraviolet and visible radiation, solar flare X-rays, cosmic rays, and electron and proton radiation. These present varying hazard levels as one leaves Earth orbit and travels into deep space. The category of dangerous radiation, called "ionizing" radiation, causes damage by disrupting the chemical and physical processes that are necessary to health. The Earth's atmosphere provides some protection, and the Earth's magnetic field captures certain high-energy particles in the Van Allen belts. As the Sun emits high-energy particles during solar flares, spacesuits and space vehicles must provide enough shielding to prevent accumulated radiation dosages from causing harm to astronauts and cosmonauts. Limiting exposure is another way of minimizing dosage. For example, spacewalks can be scheduled around absences of solar flare activity. The absence of appreciable atmospheres on the Moon and Mars means that no protection is afforded from radiation. Providing required shielding in the spacesuit system itself would present designers with a significant challenge to maintain the required degree of mobility and visibility.

There are yet other thermal challenges: cold hands and feet. In orbit, essentially half of the orbit is in direct sunlight and half is in the shade of the Earth. In the shade, items in space can reach a temperature of −250°F (−157°C), while in sunlight, equipment temperatures as high as +250°F (121°C) are not uncommon. Foot restraints and grasping items provide a thermal path to conduct thermal energy (warmth) away from or towards the hands and feet. Of the two thermal conditions, providing protection from cold surfaces has proven to be the more demanding challenge. Providing adequately thick insulation material in boots is relatively easy to accomplish, but hands have to be able to perform work. The bulk of insulation in gloves becomes an encumbrance. For the assembly of the International Space Station, U.S. EVA spacesuits have been equipped with electrically heated gloves as a solution.

Protection from direct sunlight in space

As previously mentioned, Earth's atmosphere filters the light from our Sun. Sunlight in space is far more intense, and can make a person instantly and permanently blind. It can cause "Sun burn" on skin in seconds where scores of minutes or hours are required for the same effect on Earth. This was understood from the beginning by manned space programs. The solution was, and is, sunvisors. Like sunglasses, sunvisors attached to helmets permit vision but reduce the light levels and filter out harmful portions of the spectrum of light that is present in space.

As you look at a suited person performing work in space, you frequently see a gold reflective visor pulled down over the face. The gold color arises from a thin film—approximately 0.00001 in. (0.3 µm) thick—of gold-plating vapor deposited onto the visor. Of all the coatings tried in early experiments, a very thin layer of gold proved to be ideal in blocking harmful segments of the spectrum of light in just the right amounts while not adversely affecting color perception. Only in recent years have alternative metallic alloy visor coatings been certified for U.S. space use.

Space debris

The planets, stars, comets, meteors, and particles all combined still leave space mostly empty. That said, astronauts and cosmonauts in Earth orbit face an increasing challenge of impact damage, due not only to naturally occurring micrometeorites but also from ever increasing levels of orbital debris from past space vehicles and jettisoned waste. The gravitational acceleration imparted to these particles and debris by the Earth and other celestial bodies provides them with tremendous energy.

Looking at the Moon, one sees craters from meteor impacts. The surface of Mars has similar scars. Meteor collisions are part of our ongoing solar history and, when these collisions occur, some surface materials are thrown forcefully enough into space to overcome the bonds of gravity causing fragments to float throughout our solar system until they become trapped in yet another gravitational field like that of Earth. This provides a natural form of orbital space debris. Comets and meteor-to-meteor collisions are other natural sources. From this, we get "shooting stars" and common house dust as these fragments are drawn in by the Earth and consumed by frictional heating in the atmosphere. However, not all fragments are destroyed in this way. Some meteorites survive atmospheric entry and strike the Earth, which is how we have found lunar and Martian rocks on Earth.

Beyond man-made debris resulting from spacecraft and satellite activity, additional debris is formed when naturally occurring micrometeoroids collide with man-made items in orbit. Close tracking and avoidance is used to minimize these risks to humans in space, and measurements taken on orbiting spacecraft specifically designed for gathering data on micrometeorite and orbital debris impacts are used by spacesuit engineers to design protection from these hazards. However, these provide formidable challenges. Even if a particle in space were barely moving, a spacecraft with a spacewalking human may be traveling at 17,500 mph (28,158 kph) or more around the Earth and even faster in interplanetary space travel. What is important is the relative velocity of the particle and the spacewalker. The typical solution has been to position the spacecraft ahead of the spacewalker in the orbital path, but this is not practical in Space Station applications. So, as humankind moves forward into space, other solutions to the problem of particle impingement will require development.

The cost of space hardware

In commercial industry, typically 50 or more units are made and evaluated in pre-production development. Production runs may number in the thousands or even millions over a period of years. Such large numbers provide a statistical basis for predicting the life of the item and provide good data for calculating failure rates. In space exploration, 50 units over two decades represent significant "production". To obtain safety and reliability given the limited experience base, NASA normally follows a process of design and manufacturing in compliance with NASA specifications. This process includes a preliminary design review, a critical design review, design verification testing, and certification of one or more early production items (which usually involves more testing) to rigorously identify and eliminate (if possible) design deficiencies and hazards before a product is used in space.

This also invokes a rigorous documentation and record-keeping system on every part of a space item to permit every aspect of manufacture to be traced and to identify all out-of-specification occurrences, together with the reasons for failure, so that corrective actions can be implemented and lessons can be learned. NASA then incorporates this knowledge into their specifications to avoid recurrence on space programs in the future. While this makes NASA products of high quality, it also tends to make these products very specialized with limited manufacture runs. As the cost of placing items in orbit is in thousands of dollars per pound, space items tend to be extensively designed to difficult-to-manufacture tolerances for the lowest possible weight and volume. These factors all contribute to cost.

The high costs tend to work against the development of new systems. Programs tasked with delivering a space vehicle or station within a given timeframe and budget usually do not have funding for developments that are not considered essential. Design and operational costs associated with the introduction of a new system, coupled with the inevitable "learning process" of new technologies and limited program budgets, have played a significant role in limiting U.S. spacesuit development.

4

Launch/entry spacesuits: Past, present, and possibly future

The world changed on October 4, 1957 when the Soviet Union successfully launched the world's first artificial satellite, Sputnik I, into Earth orbit. In reaction, the U.S. created the National Aeronautics and Space Administration (NASA) by the Space Act of October 1, 1958. The new agency inherited the National Advisory Council on Aeronautics (NACA) and other government organizations. NASA initiated America's first manned exploration program, Project Mercury, within its first week of existence. However, Mercury was not the first U.S. program to develop a pressure suit for use in space. Both the X-15 rocket plane and the U.S. Air Force X-20 space plane (see Chapter 8) programs had preceding suit activity. These first suits were to keep the astronaut or pilot alive if the spacecraft cabin lost pressure anytime in their journey. Mercury also introduced integrated flotation systems.

The Gemini, Apollo, and Shuttle programs featured launch and entry-specific suit systems. Gemini and Shuttle included parachute systems and survival gear. By the end of the 1960s, the number of U.S. organizations offering operational launch and entry type spacesuits had effectively dwindled to two, where it stayed for the remainder of the 20th century.

The new millennium brought change. In April 2001, a private citizen named Dennis Tito became the first space tourist. With this milestone, low Earth orbit (LEO) became a recreational destination. 2004 brought the first private manned spacecraft, named SpaceShipOne, to fly into space twice within 14 days to claim a $10 million dollar prize. While SpaceShipOne had but a thin graphite composite pressurized shell and the pilot was not provided a spacesuit or backup life support system, this benchmark meant commercial human spaceflight was coming and that commercial space travel would be required to back up life support. In March 2010, the Obama administration elected to cancel Project Constellation in favor of private industry spacecraft to transport goods and people to the International Space Station. As LEO becomes a place where people are transported to work or play by private industry, safety will most likely require launch and entry spacesuits. This recognition

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has already brought new groups into the spacesuit community mix as this chapter will illustrate.

4.1 THE NACA/NASA X-15 PROGRAM (1954–1968)

The need for U.S. launch and entry spacesuits started in 1954. The National Advisory Committee on Aeronautics (NACA) joined the U.S. Air Force (USAF) and Navy in a joint experimental aircraft/spacecraft named the X-15. The X-15 program's mission was to expand significantly the horizons of aerospace research. Operating as an aircraft, the X-15 ultimately reached Mach 6.72. However, the X-15 was designed to resist the heat and friction of atmospheric entry. Powered by rocket engines that were not dependent on air for propulsion, the X-15 was also intended to be a suborbital space plane. Thus, X-15 pressure suits were also intravehicular activity (IVA) spacesuits.

Development and selection of X-15 suits started when the USAF invited several companies to provide pressure suit designs for consideration. Prototypes from International Latex Corporation (now ILC Industries), Rand Corporation, and David Clark Company were among the suits funded by and evaluated at Wright–Patterson Air Force Base in Ohio in 1957.

This evaluation saw the debut of International Latex Corporation as a pressure suit design and fabricating organization. Having combined internal resources with recruitment of B. F. Goodrich personnel, International Latex took a molded convolute joint approach that was pioneered by Goodrich (Figure 2.4) and developed it into a more effective mobility system. A curious feature of the International Latex prototype (Figure 4.1.1) was that it was not equipped with pressure gloves as the X-15 evaluation was for mobility elements and providing pressure gloves with the suit prototype was not a requirement.

Perhaps the most technically interesting facet of the X-15 evaluations was that the two most mobile of the competition prototypes might have evolved from a common technology concept. The first evolutionary trail is clear. The National Bureau of Standards (NBS) provided technical support to the commercial and defense sectors that included pressure suit technology. Starting in 1947, the NBS funded research headed by Arthur S. Iberall that resulted in a "netted" bladder restraint concept. Iberall explained this system with a theory that he called "lines of non-extension". The theory recognized that if you were to mark the human anatomy with lines, there are areas where the skin stretches with the movement of joints and there are areas where it does not (lines of non-extension). These are now typically called the "flex" and "non-flex" areas of spacesuits, but those words would come later. The NBS funded two prototypes of this concept. The second prototype was completed by 1951 and was capable of 2 psi (14 kPa) pressurization. In 1954, Iberall left the NBS and secured a position with the Rand Corporation. At Rand, Iberall resumed pressure suit development to create a sophisticated multi-restraint layer, full pressure suit design that was Rand's entrant in the X-15 suit competition. While the Iberall/Rand prototype (Figure 4.1.2) displayed excellent mobility for the

Figure 4.1.1. 1957 International Latex XMC-2-ILC X-15 prototype (courtesy ILC Dover LP).

period, the USAF judged the suit to be too heavy, the donning process too complex, and the design incompatible with the specified USAF helmet. After the competition, Rand funded a follow-on design and prototype to rectify the evaluation findings. This last Iberall suit design was completed before the end of 1958 but never found a program use.

The Iberall influence on the David Clark Company (DCC) entrant is less clear. Both Dr. Iberall and Mr. Clark left memoirs and supporting documents regarding the conception of the DCC Link-net pressure suit restraint system. However, these remembrances do not agree. Mr. Clark recounted that the idea for Link-net stemmed from a WWII pressure suit attempt by Dr. Nicholas Wertheson of Clark University

Figure 4.1.2. 1957 Rand–Iberall X-15 prototype (courtesy Iberall family).

that was supported by a very talented DCC-supplied seamstress named Rose Arlaukas. This predated Iberall's NBS suit work. Mr. Clark indicated that the Wertheson–Arlaukas fish net restraint weave concept was the genesis for the sliding mesh restraint technology that would later be called Link-net. In Mr. Clark's account, this WWII mobility system did not work and neither Wertheson nor Arlaukas would most likely recognize the similarity between their work and the subsequent Link-net design. In Mr. Clark's lengthy accounts, he constantly referenced anyone involved and gave generous recognition to the contributions of others, yet Iberall does not appear to be mentioned.

In Dr. Iberall's memoirs, the then Mr. Iberall first met Mr. Clark while providing technical support on the valving system for a DCC partial pressure suit that predated the NBS suit effort. According to Iberall, the second (1950–1951) NBS prototype was fabricated by DCC. Surviving letters from Clark to Iberall indicate that they knew each other well and had worked together on projects before 1954. So, DCC having fabricated the second NBS prototype and DCC being intimately familiar with the details of the NBS technology seems credible. By NBS's charter, the rights to the 1947–1951 Iberall-led full pressure suit research was free to any U.S.

manufacturer. Iberall, being a paid researcher for the NBS, could not patent the concept or system. Thus, Mr. Clark was under no obligation to acknowledge Iberall if he had influenced the DCC X-15 suit design. The 1954 Clark–Iberall letters also indicate that Mr. Clark helped Iberall gain his position with the Rand Corporation. Iberall's subsequent leading of Rand into becoming a suit competitor to the DCC may have contributed to the historical differences. Regretfully neither Iberall nor Clark is alive to help resolve this dispute. However, in 1957 both the Rand and the DCC X-15 prototypes appear to have utilized a woven restraint system for mobility featuring the same size and weave orientation as had been specified in the 1951 NBS final report.

In spite of their differences, there is one historical point on which both Iberall and Clark agreed. This was that DCC drew on the experience and active participation of Scott Crossfield in the development of the X-15 suit. Crossfield was a veteran test pilot and would be the initial pilot for the X-15. He probably contributed greatly to the ultimate DCC X-15 design.

The winner of the X-15 suit evaluation and subsequent contract was the DCC XMC-2-DC suit. The XMC-2-DC suit differed from the preceding NBS designs in many ways including the NBS second prototype having utilized the sliding mesh in just the flex (joint) areas of the pressure suit. The DCC produced a greatly simplified design where the restraint system was one layer of Link-net over the entire torso (patent 3,081,459, inventor David M. Clark). The resulting base mobility technology would continue to be used in the X-20, Gemini, Apollo (Block I portion not flown), and Shuttle (crew escape suit) programs because it provides a simple pressure garment that is free of hard details that can cause extreme discomfort or injury during launch and entry. It also provides an element of multi-directional motion capability, albeit at the penalty of required effort. In derivations, the DCC would develop load-bearing webbing integrated into the restraint system to reduce effort in specific directions.

The X-15 program started flight using David Clark MC-2 full pressure suits (Figure 4.1.3), which were "production" versions of the XMC-2-DC prototype. The MC-2 suits were custom made for each pilot. The first X-15 and MC-2 flight came in March 1959 with Scott Crossfield in the cockpit. At an altitude of 35,000 feet (10.7 km), while still attached to the B-52 "mothership", Crossfield decompressed the X-15's cabin to test the suit system. Crossfield found "my movements were slightly constrained and slightly awkward" but he was able to reach and operate all controls. This suit checkout was implemented as standard procedure in the X-15 flights that followed. While the MC-2 was adequate, it was not popular amongst the pilots. Many found the MC-2 bulky, slow donning, and uncomfortable. While the suit system included attachment of an emergency oxygen supply and harness system that interfaced with a parachute package, most of the typically 30-minute donning time was assembly of the pressure garment. Donning the pressure garment required carefully folding of the upper and lower torso rubber bladders to form a pressure seal before final attachment of the restraint slide fastener (Figure 4.1.3, left). The suit then had to be pressurized to verify bladder folding had produced an adequate seal. This was a very slow process. Only then did the pilot don the thermal covers,

Figure 4.1.3. Scott Crossfield in David Clark Co. (DCC) MC-2 X-15 suit (courtesy David Clark Co.).

harness, and emergency life support (Figure 4.1.3, right). These MC-2 characteristics resulted in the early development of a second X-15 pressure suit.

The second X-15 suit design was similar to the standard Air Force A/P 22S-2 full pressure suit, but with the addition of a *g*-suit. This suit was externally similar to the MC-2 and was also custom manufactured for each pilot. The new pressure garment and helmet resolved the MC-2 issues plus added improved durability and pilot visibility. Improvement in vision range came from relocating the barrier separating the head and torso cavities from the neck ring area to inside the helmet at the edge of the face. The use of a face seal barrier eliminated the neck dam, which had placed the pilot's head further back in the helmet. The A/P 22S-2 helmet had a head suspension system with double contoured face seal that placed the pilot's face comfortably in the

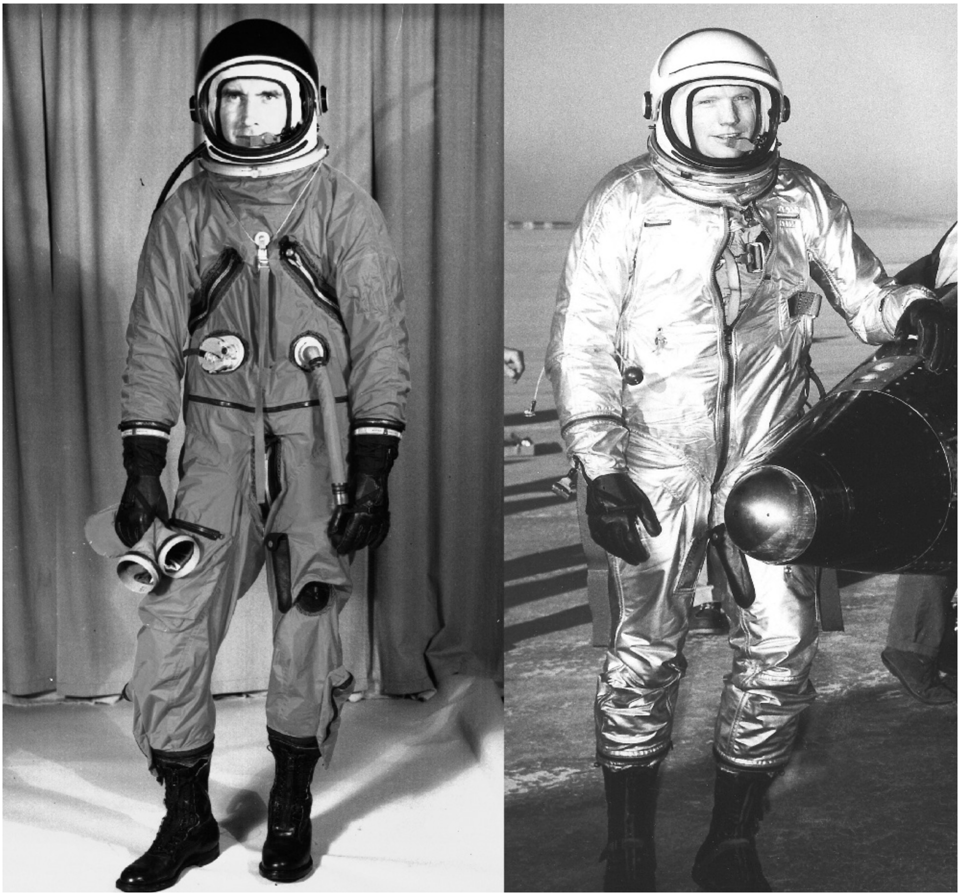


Figure 4.1.4. The DCC A/P 22S-2 improved X-15 aviation/spacesuit (Pilot Neil Armstrong, right) (courtesy David Clark Co.).

front of the helmet. The pressure garment gained a cover over the Link-net to provide abrasion protection (Figure 4.1.4, left). Bulk and slow donning were both eliminated by the addition of a pressure-sealing zipper in addition to an outer restraint zipper. Comfort was successfully improved by a redesign of the shoulder areas. The A/P 22S-2 additionally featured glove disconnects that aided donning and improved comfort as gloves did not have to be donned until needed which aided in providing ventilation, thus improving comfort. The X-15 A/P 22S-2 (Figure 4.1.4, right) suit reached flight service in March 1961. Further improvements led to the development of the USAF A/P22S-6 suit in the mid 1960s, based upon the model S-901J suit developed for the SR-71 Blackbird high-altitude reconnaissance aircraft. The A/P22S-6 suit was used for the later X-15 flights.

The X-15 program's mission was to significantly expand the horizons of aerospace research. Starting in 1962, eight X-15 pilots would take an X-15 on 13 missions over the 50-mile altitude limit to qualify as space flights. Thus, these later X-15 suits were also spacesuits (an X-15 suit summary is provided in Appendix A). The X-15 additionally flew 188 "aviation altitude" flights before the program ended in 1968.

4.2 MERCURY PROGRAM (1959–1963)

The Mercury program spacesuit was part of an astronaut survival system where the astronaut remained in the capsule from the time the hatch was closed until the capsule splashed down in the ocean. There were no provisions for emergency egress such as an ejection seat. In case of launchpad fire or malfunction after liftoff, the capsule could be pulled free of the booster vehicle by a nose-mounted rocket system for a suborbital water landing. Except for a solid Earth landing rather than in water, the Russian Soyuz uses a similar system. On September 26, 1983, a pre-launch fire destroyed a Russian booster vehicle and launchpad. However, the emergency capsule rockets lifted Cosmonauts Vladimir Titov and Gennadi Strekalov to a safe landing.

In Project Mercury, the pressure suit would be utilized only if the capsule lost pressure during the mission. Although such an event would cause many of the electronics to overheat and fail, the Mercury capsule was equipped with a pilot viewing window and manual controls designed to function in space vacuum. During Mercury development, the need for a pilot's window, manual flight control ability, and a pressure suit was questioned based on the expectation that the reliability of the system would make such items unnecessary. That view did not prevail and the aforementioned safety systems were included in the design. While no cabin decompression was ever experienced on Mercury, an electronics failure of the guidance system did occur on the last flight of the Mercury series, MA-7. Astronaut Gordon Cooper performed a visual land sighting and timed the firing of the entry rockets by his wristwatch. Faith 7 splashed down closer to its recovery ship than any of the preceding flights, proving the effectiveness and value of human piloting as a backup system.

The Mercury program evaluated the existing pressure suit technology at Wright–Patterson Air Force Base in 1959. This evaluation included pressure suits from B. F. Goodrich, David Clark Company, and International Latex Corporation. This was not a formal competition by later NASA standards due to time constraints and lack of previous experience. The David Clark and the International Latex prototypes were serious contenders and demonstrated the base technologies that later won contracts in the Gemini and Apollo programs, respectively. The Goodrich design, which was a slight modification of Goodrich's U.S. Navy Mark IV pressure suits (Figure 2.7), was selected to be the Mercury suit in July 1959. The function of the Goodrich Mercury suits was to provide reasonable unpressurized comfort and support emergency atmosphere retention in the event the cabin decompressed, while consuming minimal volume. The suits (Figure 4.2.1) utilized a rubberized bladder with an integral bias ply construction (similar to the lay-up

Figure 4.2.1. Mercury astronauts in BFG program suits: front row, left to right, Walter M. Schirra Jr., Donald K. Slayton, John H. Glenn Jr., and M. Scott Carpenter; back row, left to right, Alan B. Shepard Jr., Virgil I. Grissom, and L. Gordon Cooper (courtesy NASA).

used in automotive brake lines) without convoluted mobility joints. There were no hard details or unfriendly shapes to cause uncomfortable contact points. The outer layer was aluminized and provided bladder protection and structural restraint. The suits were tight fitting and custom made to minimize pressurized volume to be overcome for movement and to fit better in the cramped cabin of the Mercury capsule. Additional zippers were added for easier donning and removal. Astronaut

Schirra's suit (bottom row, end left in Figure 4.2.1) included an improved mobility element in the right shoulder (as worn) showing some of the suit development that occurred during the program.

The helmet moved with the head via restraints, which allowed down/up mobility for improved visibility. However, the system did not have a pressure-sealed neckring bearing. Thus it allowed no side-to-side movement once pressurized. The helmet pressure visor was movable and used a tiny oxygen bottle to provide a pressurized seal when lowered.

Life support for this IVA suit system was provided by inlet and outlet ventilation umbilicals connected to the capsule's environmental control system. Heat discomfort and helmet-fogging problems on the fourth and fifth Mercury flights were traced to contamination of the vehicle life support system. No other life support systems were considered necessary.

Mercury suits were not "rescue suits" and did not carry survival gear (a Mercury suit summary is provided in Appendix A). The Mercury suits originally did not have provisions for flotation other than a neck dam to keep the suit from filling with water should an astronaut find himself in water. Shortly after the second Mercury water landing, a malfunction caused the hatch to be jettisoned prematurely and the capsule began to sink. Astronaut V. I. "Gus" Grissom was forced to exit the craft. His suit partially filled with water and he had difficulty remaining afloat. While Grissom was rescued, his capsule sank (later recovered in July 1999). As a result, subsequent Mercury suits were equipped with a mini-flotation device for additional buoyancy. Flotation devices and additional accommodations for water rescue would be included in Gemini and Apollo suit system designs.

Mercury suit evolution was not limited to flotation. For the third Mercury flight, John Glenn's gloves were equipped with fingertip lights. This proved to be such an asset in dim lighting conditions that similar finger light systems would be used or at least tried in the Gemini and Apollo suit programs. There were also improvements to enhance comfort for the last Mercury flight with Gordon Cooper and his 22 orbits of the Earth. Specifically, Cooper's suit was equipped with boots, gloves, and suit shoulder areas that incorporated enhancements for comfort plus a helmet-mounted thermometer, improved helmet microphones, and improved pressure visor seal for better and more reliable performance.

4.3 DUAL-PURPOSE SUITS FOR GEMINI, APOLLO, AND THE U.S. AIR FORCE

NASA's Gemini and Apollo both had one model of exclusively intravehicular activity (IVA) suits (Gemini G5C and Apollo A1C). Gemini G5C suits were made and flown for Gemini VII. The Apollo A1C was never flown. Essentially, the Gemini, Apollo, and Skylab programs all took the approach of using dual-purpose intravehicular and extravehicular activity (IEVA) suits that could support both crew survival and extravehicular activity. For clarity, the suits of these programs are addressed in Chapters 5, 6, and 9, respectively. For similar reasons, the initial suits of the U.S. Air Force's Manned Orbiting Laboratory (MOL) program used the same approach. MOL suits are addressed in Chapter 8. For the Shuttle, NASA would use separate intravehicular and extravehicular spacesuits to support U.S. space needs.

4.4 SHUTTLE CREW ESCAPE SYSTEMS RESEARCH AND DEVELOPMENT (1971–1979)

In 1971, NASA completed the requirements study for the Shuttle spacesuit systems. At that point, there was a strong element within NASA that desired one spacesuit system to do both intravehicular and extravehicular activity (IEVA) like the ILC A7L and A7LB had done for Apollo. Hamilton Standard won the competition for the "Shuttle Requirements Study" that was delivered in 1973. The study recommended two suit systems with an 8.0 psi (55 kPa) operating pressure. The 8.0 psi operating pressure was based on U.S. studies for avoiding decompression sickness (DCS). These results differed from Soviet studies that had arrived at a value of 5.8 psi (40 kPa) due to variations in the way the separate tests were run and the subjective nature of early symptoms signaling the onset of decompression sickness.

In the same period or slightly before, other elements within the U.S. spacesuit community recognized the limitations of the IEVA approach and desired two separate systems. In 1970–1971, NASA funded development of some 3.75 psi (26 kPa) exclusively IVA prototypes to explore how light and compact such a suit could be. The first prototype in this series (Figure 4.4.1, far left) was an ILC Industries (ILC) suit that utilized existing Apollo mobility systems. With its "soft helmet", this prototype could be stowed in a very limited volume. However, this was not the optimum but rather a baseline for the prototypes that would follow. The next suits investigated both gathered tucked fabric and flat pattern mobility systems to reduce stowage volume, reduce cost, and improve mobility. For this, NASA funded ILC (Figure 4.4.1, center left) and Space Age Control Incorporated (Figure 4.4.1, center right and far right) for a second round of prototypes. The ILC suit best demonstrated the advantages of flat pattern joints. This led to a further step in IVA suit exploration.

In 1972, NASA funded ILC for another emergency IVA prototype that would feature a safer, more reliable, faster closing, and lower leakage entry/closure system and also support reasonably rapid decompression from a 14.7 psi (1 atm) cabin pressure without risk of decompression sickness. This resulted in ILC being funded for a next IVA prototype (Figure 4.4.2) utilizing Kevlar as the restraint fabric with a hard ring body seal closure. This was designed to operate at 8.0 psi (55 kPa). Due to extensive experience at lower operating pressures plus budget, weight, and volume constraints, NASA elected to implement a 4.0 psi extravehicular suit system and not to include a launch/entry/escape system in the Shuttle once it became fully operational.

Eight approach and landing manned flights were made during 1977 using the Space Shuttle *Enterprise*. These were conducted without pressure suits, with the two-

Figure 4.4.1. 1971 Shuttle IVA prototypes (ILC, left and left center; SAC, right) (courtesy ILC Dover LP, Hamilton Sundstrand, and G. L. Harris).

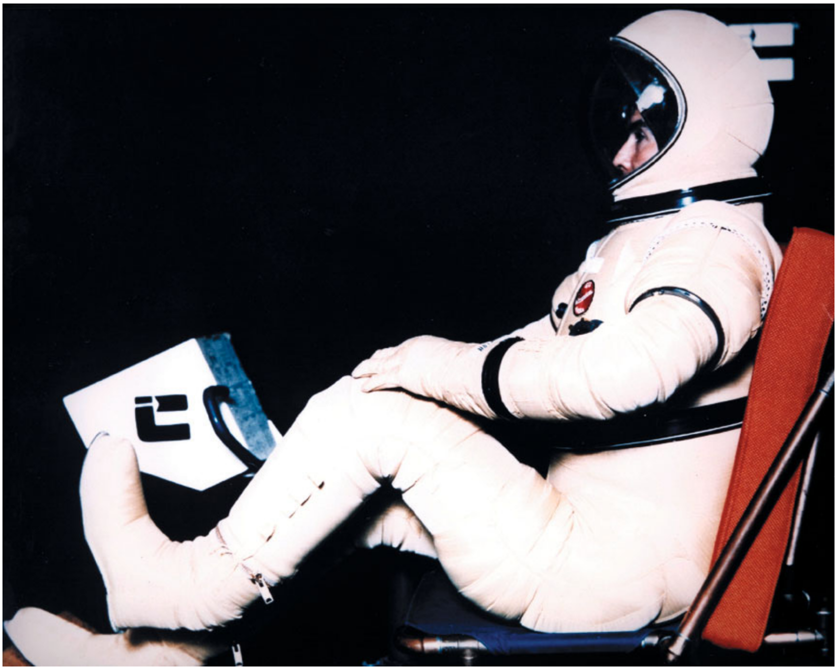


Figure 4.4.2. 1972 ILC 8 psi IVA prototype (courtesy Hamilton Sundstrand).

person crews using just helmets and oxygen masks. Surplus oxygen tanks from the Skylab EVA emergency oxygen system provided the oxygen supply, and suit ventilation was provided by a system using a Skylab fan.

In the early to mid 1970s, funding for a Shuttle extravehicular activity (EVA) spacesuit system was in question as many considered it as an option rather than a requirement. What made the presence of an EVA suit a necessity was concern that the cargo bay doors might malfunction. Without the ability to go EVA to investigate or perhaps manually close the doors, the orbiter would be unable to return. Consequently, this provided not only an EVA capability, but also a place of refuge for two crewmembers in case of loss or contamination of the Shuttle cabin environment. As part of the EVA system, there would also be two portable oxygen subsystems (POSs) that normally would support pre-breathing of pure oxygen during preparation for an EVA. That would place two compact autonomous life support systems on board.

In the late 1970s, NASA started implementation of a crew survival system that built on planned, already designed, and certified pre-breathers with the addition of a simple, compact fabric structure called the personal rescue enclosure (PRE) or "rescue ball" (Figures 4.4.3 and 4.4.4). The PRE was a 34-inch (0.86 m) diameter fabric sphere, outfitted with a window. To don the PRE, a non-EVA crewmember

Figure 4.4.3. PRE transfer concept (courtesy Hamilton Sundstrand).

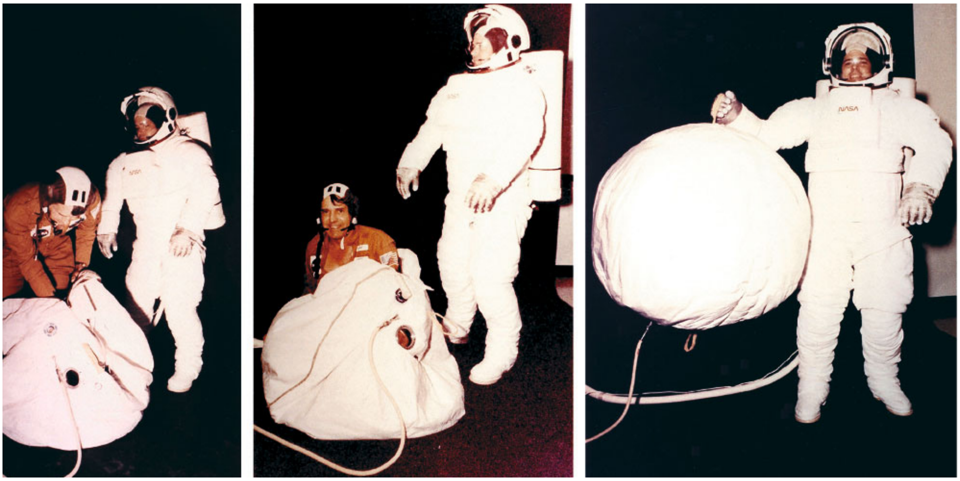


Figure 4.4.4. ILC-made PRE in don/use demonstration (courtesy NASA).

would open the zipper and enter wearing a portable oxygen system. Another crewmember would zip the PRE closed. The PRE had optional connection features to permit pressure and oxygen supply from the Shuttle until the portable oxygen system was needed. By carrying five highly compact PREs, three more portable oxygen systems, and using the two EVA suits, an emergency environmental haven could be provided for all crewmembers. In the event that a Shuttle was stranded in space, a second Shuttle could be launched and the EVA crewmembers could ferry PRE-enclosed colleagues to the rescue vehicle for return to Earth.

An alternative to the PRE was also explored briefly in 1976–1977 with the anthropomorphic rescue garment (ARG). Crewmembers wearing a portable oxygen system could don the ARG and perform some level of self-help tasks during emergency, rescue, or transfer operations. NASA funded ARG prototypes from DCC (Figure 4.4.5, left and center) and ILC (Figure 4.4.5, right), and NASA carried out evaluations of both concepts. However, before the Shuttles became operational, this overall rescue concept was found not to be practical. The schedule lead time for taking an orbiter from the pad, returning it to the vertical assembly building, installing a rescue kit, returning to the launchpad, and launching made an orbital rescue scenario unrealistic. Keeping an orbiter on standby strictly for rescue was also deemed to be programmatically unacceptable. Thus, the PRE concept never reached flight. However, the PRE lives on as an evaluator of astronaut capabilities in the selection process for astronaut candidates.

4.5 SHUTTLE EJECTION ESCAPE SUITS (1981–1982)

The first four Shuttle launches were test flights conducted with the orbiter *Columbia* between April 1981 and July 1982. For these flights, the orbiter had only a two-man

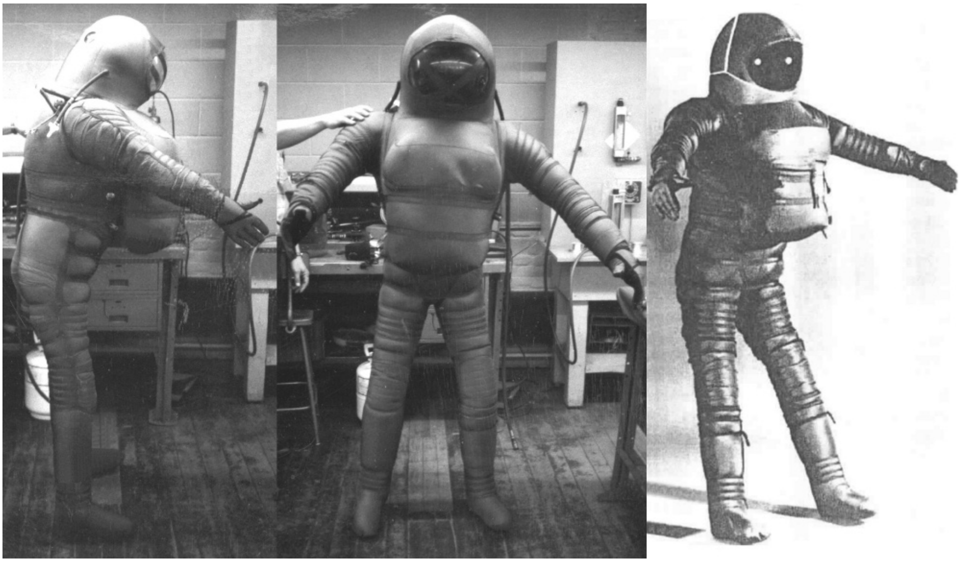


Figure 4.4.5. DCC (left, center) and ILC (right) anthropomorphic rescue garments (courtesy David Clark Co. and G. L. Harris).

crew. To provide the crew with the ability to escape, *Columbia* was equipped with ejection seats. The crew was outfitted with David Clark Company Model S1030A ejection escape suits (EES, Figure 4.5.1). These were 2.7 psi (18.6 kPa) full pressure suits that were a derivation of the U.S. air force model S1030 pilot's protective assembly then worn by crewmembers of the SR-71 high-altitude reconnaissance aircraft.

The ejection escape suit permitted emergency egress of the Shuttle crew at speeds up to Mach 2.7 and altitudes up to 80,000 feet (24,384 m) (see Appendix A for an ejection escape suit summary). The ejection system was installed for crewmembers in the upper deck. With the successful completion of flights STS-1 through STS-4, the Shuttle system was fully certified for flight and the ejection seats and pressure suits were removed from the vehicle system.

From STS-5 to the loss of *Challenger* in 1986, there was no in-flight escape system. Crew escape would have to be carried out either in pre-launch procedures or through emergency abort and early landing scenarios. Viewing this in the context of the time, commercial airliners similarly have no in-flight escape systems. The flying public accepts airliner risks as part of daily air travel in spite of aviation losses. The Space Shuttle was envisioned as a reusable, routine carrier of personnel and cargo into space. Thus, the 1982–1986 Shuttle architecture fit the paradigms of the times.

From 1982 to 1986, crewmembers launched, orbited, and returned in jump suits or conventional clothing. In place of a pressure suit, Shuttle crewmembers were provided David Clark launch/entry helmets (Figure 4.5.2). This "clamshell-type"

Figure 4.5.1. DCC STS-1 to STS-4 ejection escape suits (courtesy David Clark Co.).

helmet system was equipped with an emergency oxygen supply to provide an enclosed supplemental oxygen environment in the event of cabin contamination or slow reduction in internal pressure.

4.6 SHUTTLE LAUNCH/ENTRY SUIT (1987–1995)

The loss of the Space Shuttle *Challenger* in January 1986 caused NASA to review all safety-related procedures. With return to flight in 1988, Shuttle crewmembers were provided with a crew escape system that included an emergency pressure suit, a personal parachute assembly, and various survival items. The pressure suit (used until 1994) was the David Clark model S1032 launch entry suit (Figures 4.6.1 and

Figure 4.5.2. DCC 1982–1986 launch/entry helmets (courtesy NASA).

4.6.2). This was part of an overall system to provide an escape alternative if the orbiter was unable to reach a runway. In that event, the crew could equalize the cabin pressure with the outside atmosphere via the Shuttle's depressurization valve and pyrotechnically jettison the crew ingress/egress side hatch. The crew would then manually deploy an escape pole that would route exiting crewmembers away from the Shuttle's left wing. One by one, the crewmembers would attach their suit system's lanyard hook to the escape pole and egress through the hatch opening.

The S1032 launch/entry suit (LES) was a key element in the Shuttle's crew escape system (CES). The LES was a 2.8 psi (19 kPa) partial pressure suit that was based on a pre-existing suit system developed for the USAF. The primary design challenge was one of design integration with the Orbiter and other crew escape equipment. This was a fast-track development effort initiated to provide hypobaric protection to crewmembers during the launch and entry phases of flight as well as cold-water immersion protection in the event of a bailout over water. The LES coverall (torso assembly) restraint layer utilized Gore-Tex with strategic incorporation of Nomex webbing to enhance mobility.

The personal parachute assembly has two separable subsystems, the packed parachute container and the harness assembly. The packed parachute container

Figure 4.6.1. STS-26: First flight equipped with the crew escape equipment. Crewmembers: seated, Pilot Richard O. Covey and Commander Frederick H. Hauck (left and right); standing, Mission Specialists (left to right) John M. Lounge, David C. Hilmers, and George D. Nelson (courtesy NASA).

contains the "D" ring for attachment to the Shuttle egress pole, a parachute, a search and rescue beacon, and a life raft.

The harness assembly contained the torso harness, an emergency oxygen supply, an enhanced life preserver unit, a fresh-water pouch assembly, a carabiner, and emergency rescue packages. The torso harness was/is a multi-sized system that transmits all operational loads from the packed parachute container to the crewmember without injury or encumbrance. The emergency oxygen supply was a two-bottle, 2,850 + 50 psi (194 atm), purge-type system that provided 10 minutes of life support. The enhanced life preserver unit is a self-activating flotation system. The fresh-water pouch assembly provides drinking water to the crewmembers until they are rescued. Also included is a controlled descent device, which allows a crewmember to control his or her descent rate from the orbiter to the ground in the event of emergency. The two emergency rescue packages provide all the survival equipment such as flares, knife, and other items.

The familiar orange LES supported the preparation and flight of over 45

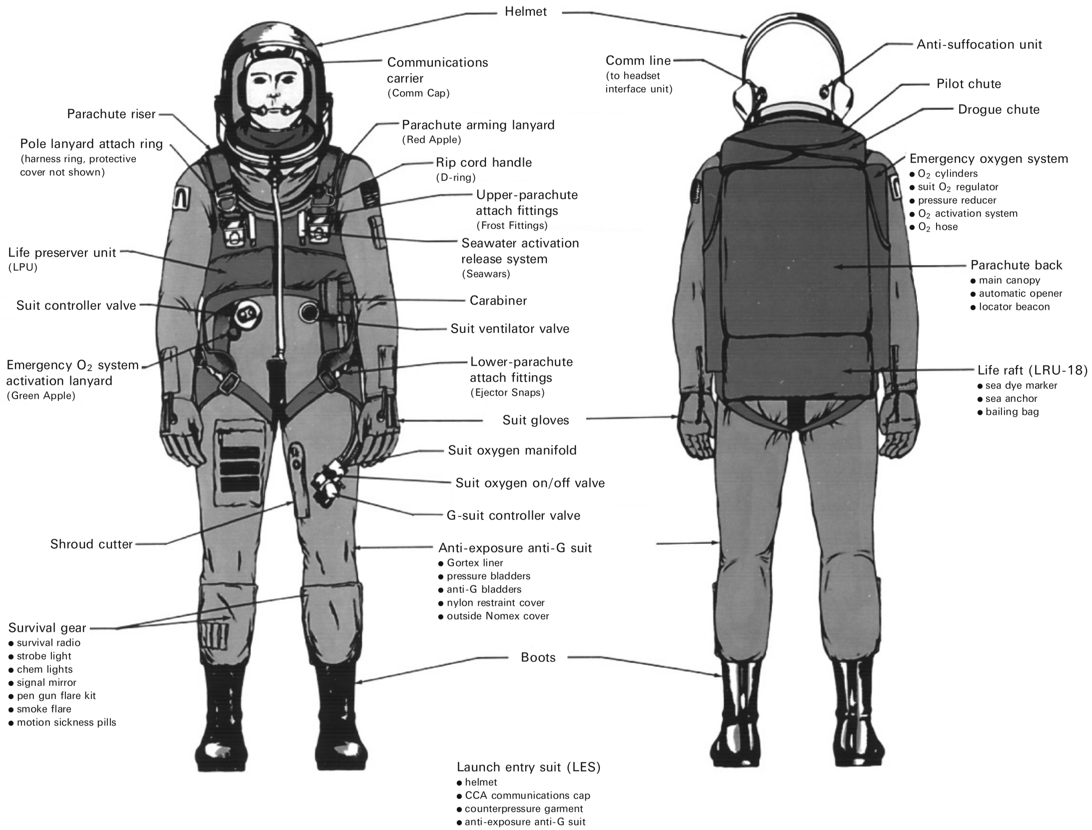


Figure 4.6.2. 1986–1995 DCC crew escape equipment system (courtesy David Clark Co.).

Figure 4.6.3. DCC CEE/launch entry suit in STS-26 training (courtesy NASA).

missions and hundreds of astronauts. However, not all LESs were orange (Figure 4.6.3). The initial lot (serial numbers 001–008) was fabricated in blue Nomex fabric because the LESs were envisioned as a replacement for the astronaut's standard issue blue flying suits. However, it was subsequently recognized that—in the event of a bailout—a high visibility color such as international orange would aid in search and rescue. Consequently, all remaining LESs were fabricated using orange Nomex coverings. The initial blue LESs were relegated to training where they saw prolonged service even after the LES had been replaced in flight by the advanced crew escape suit (ACES). The best attributes of the LES such as safety features to simplify crew reactions to emergency conditions were carried over into the ACES full pressure suit system. In 1994, the ACES was added to the flight manifest and, by the end of 1995, the S1032 launch entry suit was phased out as suits reached their certified lives (a LES summary is provided in Appendix A).

4.7 SHUTTLE ADVANCED CREW ESCAPE SUIT (1990–PRESENT)

The current Shuttle crew escape suit is the David Clark model S1035 advanced crew escape suit (ACES). The S1035 ACES (Figure 4.7.1) is a full pressure suit that was

Figure 4.7.1. STS-112: Astronaut Piers Sellers in emergency bailout training (courtesy NASA).

designed for simplicity, light weight, and low bulk. Its design facilitates self-donning/doffing and provides improved comfort with enhanced overall performance which helps reduce crewmember stress and fatigue. The S1035 ACES entered flight service in 1994 and operates at 3.5 psi (24 kPa) as opposed to the S1032 LES pressure of 2.8 psi (19.3 kPa).

Initiated in 1990, the ACES design utilizes proven manufacturing methods (Figure 4.7.2) with enhancements that include the use of a breathable material in the construction of the gas container to minimize bulk and reduce retention of humidity and body heat. This improves the overall comfort of the suited crewmember, especially during the period between securing the Shuttle and crew for launch and the actual launch.

Figure 4.7.2. Shuttle ACES spacesuit manufacturing (courtesy David Clark Co.).

Complete redesign of the coverall lower torso was accomplished to eliminate the separate restraint and exterior cover layers typical of previous full pressure suit designs. Additional improvements were made through the use of a dual-function pressure-sealing closure, redesigned glove disconnects for improved donning/doffing, easier operation, increased reliability, and redesigned glove softgoods to reduce thermal load, improve comfort, and maximize tactility and dexterity. These features of the S1035 ACES ensemble are summarized in Appendix A and in the discussion the follows.

Helmet assembly

The S1032 LES full pressure helmet use was carried forward for use in the S1035 ACES because it was able to meet the higher pressure requirements of the ACES and was respected by its users for its wide field of view, comfort, and elimination of headborne weight. This helmet design was originally developed and qualified for flight under USAF sponsorship in the late 1970s, with one prototype system having accumulated over 1,600 hours of use in high-altitude aircraft. There were two minor changes made to this helmet to accommodate specific NASA applications. The first being the addition of adjustable, formed wire supports under the helmet disconnect to provide helmet support and stability under varying *g*-loads. The second was the integration of automatic switches on the oxygen delivery system and the communications circuitry to mute the microphones during inhalation. This eliminated crew-breathing noises from the communications network. This microphone cutout system had previously been developed for use with the S1030A ejection escape suit, which supported Shuttle orbital flight tests, STS-l through STS-4.

The ACES helmet provides a complete head and neck enclosure with no direct body contact above the shoulders. This design allows crewmember comfort and (helmet-related) stress reduction. The large pressure visor provides excellent forward and peripheral vision. Side and rearward visibility is accomplished via manual helmet rotation. This is made possible by the coverall assembly having a pressure-sealed bearing at the neck permitting helmet and suit-side helmet disconnect rotation.

The helmet has additional features. A full sunshade is provided that operates independently from the pressure visor. An anti-suffocation valve is part of the system to permit an incapacitated crewmember to draw ambient air into the breathing compartment when the emergency supply of oxygen has been expended. Also, high-visibility tape is provided on the outer shell to assist in search and rescue operations.

Communications carrier assembly (CCA)

The CCA is a lightweight, headborne system worn by the crewmember under the helmet. This includes molded ear cups containing the electronics of the system and a softgoods ("Snoopy cap") assembly for retention of the system on the crewmember. This system features dual earphone receivers and two flexible boom-mounted microphones for operational redundancy, so the loss of one microphone or earphone does not affect mission performance. The CCA also incorporates head-buffeting protection padding, a large mesh area located in the top and back to minimize heat buildup and improve crewmember comfort. Moisture absorption padding is provided to prevent perspiration from getting into the eyes.

Coverall assembly

The general configuration change from a partial pressure S1032 LES to a full pressure S1035 ACES coverall resulted in simplified manufacturing, assembly, testing, and field serviceability methods. The S1032 LES incorporated air-filled, double-walled bladders between the wearer's body and the outer layer of the suit providing direct mechanical counter pressure to the body upon inflation. The ACES is a full pressure suit that encapsulates the wearer in an airtight anthropomorphic pressure envelope, which results in pneumatic pressure being uniformly applied to the body. This change enabled the elimination of one complete layer of the coverall.

Another ACES improvement was the complete redesign of the coverall hips and legs. A full pressure suit typically incorporates three layers. The layer closest to the wearer's body would be an air impermeable layer or bladder. The next layer would be the restraint garment, which prevents the gas bladder from distending upon inflation. A Link-net restraint system provided this layer in the S1032 LES and continues to support the upper torso and arms of the S1035 ACES (Figure 4.7.3). The restraint layer also causes the garment to conform to the wearer's body. The exterior layer would be a cover garment. The cover garment primarily provides flame and abrasion protection. In the design of the S1035 ACES legs, the functions of the restraint and exterior cover layers were incorporated into a single layer of high-temperature woven fabric. This integrated design approach allowed for the elimination of one entire layer, further simplifying the coverall design.

Additional improvements were made to the coverall design by the use of a "breathable" Gore-Tex material in the construction of the gas container layer.

Figure 4.7.3. ACES upper-torso Link-net restraint system (courtesy David Clark Co.).

The term ‘‘breathable’’ refers to the material’s ability to allow perspiration (in the form of water vapor) to pass from the inside to the outside, while retaining internal gas (air) pressure. This greatly improves comfort during lengthy pre-launch conditions. This material property also permitted the standard ventilation system to be greatly simplified and shortened with no perceptible change in comfort level to the wearer.

Finally, David Clark incorporated a pressure-sealing closure that functions as both a pressure-sealing mechanism and a restraint closure. This eliminated the need for two independently operated zipper systems, which further simplified the design of the coverall. This also improves the speed and ease of donning or doffing the suit system.

For ACES, the suit-side glove disconnect design was also improved with a locking mechanism that increased reliability and improved self-don/doff.

The improvements embodied in the ACES coverall or torso assembly also enhanced the ACES’ function as part of the crew escape system by reducing overall weight and encumbrance. This facilitates escape even when the suit is not pressurized.

Glove assemblies

The S1035 glove assembly was redesigned for improved comfort, mobility, and reduced bulk. This was achieved through outer-glove design improvements incorporating a combination of both flat and tucked patterning. Additionally, the fabrication of the glove wrist, palm, and backhand sections from breathable materials allows for reduction in heat loading, thereby improving comfort and reducing stress and fatigue.

Anti-*g* suit (AGS) assembly

The S1035 ACES AGS incorporates lightweight, low-bulk, high-comfort materials, like those used in the fabrication of the S1032 coverall, but is configured similarly to the (USAF standard) ‘‘five-bladder’’ cut-away AGS. Connection to the standard AGS pressurization and control assembly is accomplished via a coverall pass-through and hose interconnect. The coverall hose interconnect incorporates a self-sealing connector, thereby permitting the use of the coverall without the AGS. Additionally, the S1035 ACES AGS can be utilized without the coverall, via pressurization and control assembly integration directly to the AGS, for contingency operations.

Automatic safety features

The ACES, like the model S1032 launch entry suit before it, has a number of automatic safety features to simplify crewmember actions needed to respond to emergency conditions and enhance survivability should the crewmember become incapacitated. Figure 4.7.1 shows a crewmember training for a water landing

Figure 4.7.4. STS-101: Astronaut Mary Ellen Weber after a practice water landing (courtesy NASA).

before contact with the water. Upon contact with the water, the parachute lanyards release and the suit's flotation device, called the Mae West, inflates automatically, eliminating the need for manual activation. The Mae West is designed to assure the astronaut turns to and remains in a face up position even if the crewmember is unconscious. The raft also automatically inflates on water contact simplifying the process for the crewmember to climb into the raft to await rescue (Figure 4.7.4).

The ACES pressure controls are all automatic, incorporating redundant failsafe systems to maintain a minimum internal suit pressure of 3.5 psia, regardless of ambient pressure/altitude.

4.8 SHUTTLE CREW ESCAPE SYSTEM OVERVIEW

The Shuttle crew escape system greatly enhanced astronaut survivability (Figure 4.8.1) within the limitations principally imposed by the vehicle system. In a launchpad emergency, the minimal mass of the suit system permitted rapid departure from the vehicle and the area while providing a safe atmosphere.

Figure 4.8.1. STS-113: Suited and ready for the flight home, Expedition 5 ISS crewmembers (right to left) Astronaut Peggy A. Whitson (NASA ISS Science Officer); Cosmonauts Valery G. Korzun (Mission Commander) and Sergei Y. Treschev (Flight Engineer) (courtesy NASA).

In an abort after launch or once a Shuttle reentered Earth's atmosphere, the orbiters were gliders. If an orbiter were unable to reach a suitable runway, the crew's chances of surviving would have been remote. Thus, since 1987, Shuttle crews were provided the ability to perform in-flight egress from the vehicle. Crews train extensively for this and other contingencies. For in-flight egress, the vehicle first had to be depressurized to the outside ambient atmosphere. Crewmembers then bailed out the side hatch for a parachute landing. If the bailout was over water, Shuttle crew escape suits were equipped with an automatic flotation system (Figure 4.7.4) in addition to having a life raft stowed on the suit.

When a Shuttle landed, the exterior of the craft was still extremely hot. So, crews normally remained on board until all temperature and residual fuel hazards had been eliminated. As this was yet another period of risk to Shuttle crews, the orbiters were also equipped with emergency egress slides should an emergency evacuation be required. Under these conditions, crew escape suits provided safe atmosphere while still allowing mobility during evacuation from the area.

The Shuttle crew escape system did have limitations. Shuttle crew in-flight egress was premised on the Shuttle being able to maintain level and stable flight on a glide angle at or near minimum air speed at an altitude below 80,000 feet (24.4 km). The Shuttle controls and electrical systems depend on air convection for cooling and would fail if the crew cabin decompressed to vacuum or near vacuum conditions. The vehicle and suit systems were designed to address loss of cabin pressure only under very slow leakage conditions. The Shuttle IVA suit operating pressure was 3.5 psi (24.1 kPa). It inflated only when the ambient atmosphere dropped below its maximum operating pressure. A sudden loss of cabin pressure would induce hypoxia, which could cause loss of the crew. However, if there were time to don the launch escape suits, hypoxia could be avoided, but symptoms of severe decompression sickness could then occur. These symptoms could include difficulty breathing, dizziness, debilitating joint pain, unconsciousness, possible blindness, paralysis, permanent injuries, and loss of life. While this sounds severe, the vehicle systems were not designed to function with the crew cabin decompressed, which minimizes the reasons for having a higher IVA suit pressure.

The Shuttle will retire in 2011. Between the ejection escape suits, the launch entry suits, and the advanced crew escape suits, at latest 113 Shuttle flights and 689 human journeys will have been made more safe by crew escape suits. In 2009, the Obama administration changed the direction of space exploration (discussed in Section 11.4.2). While most elements of the Constellation program will be canceled, it appears the Orion spacecraft will continue in a lower cost form to support the International Space Station. In an effort to reduce expense, the continued use of existing inventory David Clark advanced crew escape suits is probably a consideration. Thus, this crew escape suit story may not be coming to an end.

4.9 ANSWERING THE CALL FOR FUTURE INTRAVEHICULAR SPACE SAFETY

In 1994, Weaver Aerospace had acquired an emergency escape capsule study contract with the Rotary Rocket Company of Mojave, California, and had developed pod mockups as part of that contract. The Rotary Rocket Company was to be the first all civilian launch vehicle, called Roton, to place crew and cargo into low Earth orbit. In parallel with the escape pod contract, and under internal funding, Weaver Aerospace also began spacesuit studies in an effort to place the company in a position to win possible space pressure suit and backup life support contracts that might result. To support these activities, Weaver Aerospace reassigned its principal engineer/designer Gary L. Harris, who had been working on cryogenic pressure vessel structures for the company. Mr. Harris also had 30 years of experience in aerospace and deep-water life support systems as well as experience in rigid and soft-pressure structure design. Previous to being assigned to the Roton project, Mr. Harris had built a testbed (Figure 11.3.1.2), in he early 1990s, for evaluation and comparison of various extravehicular spacesuit bearing and experimental fabric mobility joint configurations based on his preparation for a book. While the Harris–Weaver extravehicular suit demonstrator featuring a ridged, rear entry, hard upper torso, and looked like something more likely used on a spacewalk, it was designed and constructed to act as a research tool (test manifold) to support the design of an all fabric, launch, and entry suit. From this program various pressure suit joint, structure, and helmet configurations emerged as well as a proprietary suit system. After achieving several aerial tests of the Roton vehicle, the Rotary Rocket Company went out of business and opportunities faded for all civilian pressure suit development. Within a few years Lee Weaver died in an automobile accident; however, Mr. Harris persevered in completing his book and continuing his hands-on research. This set the stage for collaboration.

The Argentine Association for Space Technology (*Asociación Argentina de Tecnología Espacial* or AATE) is a private, non-governmental, non-profit organization based in Buenos Aires. It was formed by a coalition of academia (students and faculty), private individuals, and corporations actively involved in promoting Argentina's participation and growth in peaceful space exploration and development. Founded in 1987, the chief designer, project manager, and probably primary AATE financial spacesuit contributor in the 1990s was aerospace engineer Pablo de León. De León was responsible for space-related efforts that included the design and manufacture of a neutral buoyancy laboratory (NBL) equivalent of a spacesuit to explore the construction process of extravehicular activity garments and to gain insight into extravehicular activities. In 2002, de León emigrated to the U.S. establishing a business, De Leon Technologies LLC, in Cape Canaveral, Florida. De León and Harris soon met and elected to collaborate initially on biological/chemical protective systems and later spacesuits. A suit project that was later named the de León and Harris prototype number one (DL/H-1) started in 2004.

Even before their extravehicular suit developments for the University of North Dakota (UND) discussed in Chapter 11, de León and Harris started development of a launch and entry suit design. As this prototype was but one of many projects in flow, the DL/H-1 reached testing at the UND in 2008. The DL/H-1 was a full pressure suit developed under the auspices of De Leon Technologies. The DL/H-1 (Figure 4.9.1) was specifically developed to fulfill the needs for a full pressure suit for private spaceflight in case of decompression or in the need for bailout from the spacecraft. In February 2008, preliminary unmanned testing was conducted in the high-altitude chamber at UND. Also, in that month, human testing was performed in the UND Space Vehicle Simulator. The tests were undertaken with the suit in ventilation mode because that was deemed to be the normal ingress/egress mode. Full pressure testing was undertaken in the fall of 2008. The DL/H-1 configuration would be superseded by the DL/H-1B (see p. 56).

In 1986, two brothers started a movie prop and special effects company in a small garage in the Hollywood Hills. One brother, Chris Gilman, persevered. His interest in spacesuits resulted in the business growing into a major supplier of replica spacesuits, for the movies and television. Not satisfied with collecting and replicating spacesuits, Gilman looked for opportunities to participate in real

Figure 4.9.1. Harris (right), de León (left), and the DL/H-1 (less cover garments) (courtesy De Leon Technologies, Cape Canaveral, FL).

spacesuit development. The opportunity came with NASA's reconsideration of developing a small-size enhanced (Shuttle) extravehicular mobility unit (EMU).

In 1998, NASA elected to fund Gilman's company, Global Effects, Inc., for an "out-of-the-box thinking" small EMU hard upper torso (HUT) prototype. To avoid expenses associated with structural design, physical construction, and certification for user safety, the HUT was to be "vent pressure" (i.e., just enough internal pressure to support adequate ventilation flow—a small fraction of 1 psi—Figure 10.3.9).

For this small EMU project, Gilman solicited the collaboration of Dennis Gilliam. Gilliam's spacesuit background started as a researcher and suit restorer. His experience as an aerospace engineer/manager added technical depth to the project. In eight weeks, the Gilman/Gilliam team designed and manufactured a HUT prototype that explored alternative crewmember/life support interfaces and helmet HUT relationship. Due to funding limitations, Global Effects ultimately loaned NASA movie quality arms, gloves, and a lower torso assembly to complete the concept prototype allowing evaluation of the prototype. The resulting prototype spacesuit was delivered for evaluation in January 1999. While this resulted in minimal subsequent NASA development business, Gilman and Gilliam's interest in spacesuit development did not wane.

In 2006, Gilman helped found Orbital Outfitters (OO) becoming their Chief Designer. The stated vision of OO is to provide suits for private space travelers. A major step to realizing that vision was the 2007 debut (Figure 4.9.2) of the OO

Figure 4.9.2. The Orbital Outfitters (OO) industrial suborbital spacesuit (courtesy Global Effects, North Hollywood, CA).

"industrial suborbital spacesuit for crew" (IS3C). The name of the suit morphed to industrial suborbital spacesuit (IS3) with Gilliam joining OO as their IS3 Program Manager.

The OO organizational credentials were further enhanced in 2008 when the Texas Engineering Experiment Station (TEES) of the Texas A&M University elected to team with OO in the NASA-funded development of a "soft shoulder" concept for NASA's Constellation spacesuit program.

A third new entrant into U.S. commercial intravehicular spacesuits reflects global economics. Specifically, Russian experience coming to American shores. Nik Moiseev learned his trade as a spacesuit engineer for 20 years with Zvezda, the organization that has made all the Russian spacesuits from Sputnik to the present. His last 6 years were as Zvezda's Lead Designer and Project Manager. Of the "new-comers" to the U.S. spacesuit community, Nikolay "Nik" Moiseev had the technical advantage of having the experience of certifying suits and components to all the requirements associated with space use. A victim of difficult economic times, Nik temporarily found himself an ex-spacesuit engineer in 2006. However, his passion for the field caused him to explore other parts of the world spacesuit community. Coming to the U.S., Nik collaborated on teams competing in annual NASA Astronaut Glove challenges.

In the classic entrepreneurial spirit, Nik also personally funded the development of his intravehicular design. Two prototypes have been made and internationally demonstrated thus far. The model is called the NAM suit (Figure 4.9.3) for Nikolay Alexandrovich Moiseev, which is Nik's full name. Designed for low cost and light weight (15 lb), the suit aimed at suborbital and orbital space tourism, NASA's Commercial Orbital Transportation Services (COTS) and even "space jumps" (extremely high-altitude parachute record attempts). With a maximum operating pressure of 6 psi (41.4 kPa), the NAM suits would keep pilots, crewmembers, or tourists alive if the spacecraft lost cabin pressure in space.

In 2009–2010, Gary Harris and Pablo de León continued their commercial intravehicular suit activities under the auspices of De Leon LLC with modifications to their IVA prototype, which was subsequently redesignated the DL/H-1B. The DL/H1B (Figure 4.9.4) features an oval bubble helmet with a lower aluminum base, an enhanced suit seal closure, and soft boots to be worn inside a space vehicle. The new closure improves ease of donning and durability. The soft boots are a more comfortable and lighter alternative to the stiffer DL/H1 boot intended for parachute use.

In 2009, Nik Moiseev partnered with Ted Southern to compete in NASA's Astronaut Glove competition. The team won second place in the challenge and went on to form Final Frontier Design (FFD) to pursue spacesuit hardware development for commercial human spaceflight. On July 16, 2010 FFD debuted their first complete space pressure suit, the "Frontier Prime" (Figure 4.9.5). Weighing in at 13.4 pounds (6.5 kg), the Frontier Prime is intended to operate at 4 psi (27.6 kPa) and adjust to fit a person between 5′5″ and 6′1″ (1,651–1,854 mm). It is a front entry suit with wrist and neck disconnects and features improvements over the NAM suit in such areas as new easy-to-operate wrist disconnects, a new helmet visor shape for

Figure 4.9.3. A NAM suit in test (courtesy Nikolay "Nik" Moiseev).

improved visibility, more robust bladder design, and greater range of motion at reduced effort.

However, in addressing the IVA suit arena, newcomers to the community have an advantage over established spacesuit suppliers such as ILC Industries and David Clark Company. NASA has always required contractors to follow rigorous procedures to assure that potentially export-sensitive technical information is not placed into the public domain. This adds both time delay and reticence to releasing information on latest activities. In 2008–2010, ILC established a pressure suit fabrication capability in Houston to support NASA-JSC developments and also produced a commercial equivalent to the OO IS3C and FFD Frontier Prime suits. Both ILC and David Clark Company have produced space pressure suit models for NASA that have not been shared with the public. In contrast, new independent organizations are able to make instantaneous decisions as to whether a potential press release has technical export issues or not.

This flow of information has incurred potentially significant additional delays under the Obama administration in two ways. Specifically, spacesuits have been

Figure 4.9.4. The DL/H-1B configuration (courtesy De Leon Technologies, Cape Canaveral, FL).

placed under ITAR and EAR control. The Federal International Traffic in Arms Regulations (ITAR) has long been applied to space technologies such as rockets. A rocket can carry a nuclear warhead or support peaceful space exploration. However, ITAR being expanded to apply to spacesuits is new. Export Administration Regulations (EAR) fall under the jurisdiction of the Department of Commerce's Bureau of Industry and Security. EAR controls export of nationally strategic technologies.

Figure 4.9.5. The "Frontier Prime" suit (courtesy Final Frontier Design, New York, NY).

This too has been recently expanded to control spacesuit information. Under both ITAR and EAR, if a business has any question about whether ITAR or EAR applies to a public release of information, the business is required to apply for and gain approval from the Defense or Commerce departments before making the release. Spacesuit information will now be delayed potentially months if the business is willing to make the effort to go through the formal approval process. Otherwise, the delay could be years or even decades.

In 2010, the new administration also changed the overall direction of human space exploration by attempting to exclude Constellation program funding in the 2011 budget (see Section 11.4.2). Instead, the administration favored NASA funding for commercial orbital transportation systems. While this has yet to play out in Congress, it is likely to produce more vehicle providers needing IVA spacesuits. Recent events have already resulted in more potential providers. Who will be the winners of those suit contracts and the resulting models that reach space or the public domain remains to be seen.

The remnants of the Constellation program became "Orion Light". This was a minimum cost compromise to continue the space capsule but on a lower development budget. The need to minimize cost appears to have caused contingency extravehicular activity suit system ability to be dropped. The resulting "Orion Suit" will be exclusively intravehicular. The budget constraints may drive the Orion program to continue using the existing inventory of the last Shuttle launch and entry suit, the David Clark/NASA advanced crew escape suit (ACES) or perhaps a minimum cost, higher operating pressure intravehicular suit.

While the U.S. has never experienced cabin decompression, the Russians have had such experiences on the Soyuz and Mir programs. Hopefully, those lessons will be remembered by the Americans; so, if rapid cabin decompression is experienced on Orion, the crewmembers will be unharmed and able to respond to the emergency.

5

Gemini: The first approaches to exploring and working in space

Project Gemini's start actually came about because of Apollo. The first approach for getting to the Moon was a direct ascent technique, in which a gigantic rocket, the Nova, would launch an assembled vehicle that would travel to the Moon, land there, and return to Earth. A competing approach, use of lunar orbit rendezvous to permit only a small vehicle to land on the Moon, promised considerable weight savings and a shorter and less risky development time—less risky, that is, if the techniques of rendezvous and docking could be quickly and safely demonstrated. As stated in the Preface to *On the Shoulders of Titans: A History of Project Gemini*: "Gemini was first and foremost a project to develop and prove equipment and techniques for rendezvous."

It is uncertain how an EVA would have been accommodated on the Gemini vehicle if there had not been the decision to discard the escape tower approach used on Mercury and planned for Apollo. The escape tower was an externally mounted rocket motor that would lift the manned crew compartment free of the launch vehicle in the event of catastrophic failure. During a normal launch sequence, the tower would be jettisoned after the period of maximum risk had passed. Discarding the escape tower meant that several hundred pounds of weight and many troublesome failure modes were eliminated.

An ejection seat approach was selected as the means for effecting crew escape during a launch vehicle failure. The large door opening required to accommodate the ejection seat technique paved the way for an EVA, since it offered a "free" doorway to space; however, it was not until July 1961 that the spacecraft was officially changed from a single-occupant to a two-crewmember vehicle called "Mercury Mark II". The name was officially changed to "Project Gemini" in January 1962. Two crewmembers offered not only a number of advantages in spreading out tasks for longer missions, but also allowed the opportunity for EVAs.

EVA was not a high-priority Gemini objective, although it had been in the planning stages since 1962. The Gemini Support Office in MSC's Crew Systems

K.S. Thomas and H.J. McMann, *U. S. Spacesuits*, Springer Praxis Books,
DOI 10.1007/978-1-4419-9566-7_5,

Division (CSD) was formed by 1964 to formally carry out the development of hardware for a Gemini EVA; however, initial planning had gone on prior to the office formation in order to set in motion the processes to develop the spacesuit and associated life support system. In April 1964, Gemini EVA planning called for an EVA to commence on Gemini IV. The EVA program was to be phased, with EVAs on Gemini IV and V comprising Phase 1; those on VI, VII, and VIII were to make up Phase 2; and IX and subsequent missions, Phase 3. Maneuvering units were envisioned, as was an advanced life support backpack, called the portable environmental control system (PECS), then under early development with AiResearch (now Honeywell). This system would be used on a joint-funded NASA/Air Force mission called Gemini 14C. The PECS would feature, among other things, an Apollo program concept (discussed in Section 6.5) of liquid transport for rejecting metabolic heat—a design that would ultimately find its way into all U.S. spacesuits.

The requirements for the Gemini EVA program were threefold: (a) develop the capability for an EVA in free space; (b) use EVA to increase the basic capability of the Gemini spacecraft; and (c) develop operational techniques and evaluate advanced equipment in support of EVAs for future programs.

5.1 EARLY SAFETY WARNINGS

Much of the early concern for astronaut safety focused on the extremely critical and potentially dangerous launch sequence. The liquid oxygen and kerosene mixtures used for earlier flights were replaced by the Titan's hydrazine/nitrogen tetroxide combination, which ignited upon mixing. A primary Gemini concern was ejection through a fireball resulting from a launchpad explosion. Naturally, concerns for suit pressure retention as well as thermal control during an EVA were paramount in the minds of suit designers and builders. As future events would show, another and more insidious danger was inherent in all spacecraft then under design: the use of a 5 psia (34.5 kPa) pure oxygen atmosphere for orbital operations.

Although Mercury had operated at 5 psia (34.5 kPa) with no apparent problems, there was concern in the medical community for crewmember exposure for extended periods of time to elevated oxygen pressure. It was not until early July 1962 that a decision was made between a 7 psi (48.2 kPa) mixture—3.5 psia (24.1 kPa) oxygen/3.5 psia nitrogen—and a 5 psia (34.5 kPa) pure oxygen atmosphere for Apollo. The decision made was to use 5 psia for Apollo. Gemini had never really seriously considered any other pressure.

Studies related to 5 psia pure oxygen atmospheres were carried out by NASA to investigate the human effects over 14 days, and two of these studies suffered near catastrophic results due to factors other than those of physiology.

In late August 1962, in a collaborative test effort between NASA and the Air Force's School of Aerospace Medicine at Brooks Air Force Base in San Antonio, Texas, two Air Force officers were outfitted with pressure suits featuring removable arm and leg sections, in addition to having helmet faceplates that could be opened.

One suit was built by Arrowhead; the other by B.F. Goodrich (now Goodrich Corporation). The test subjects then entered an altitude chamber, where the suits were attached by inlet and outlet hoses to an environmental control system that would furnish cool ventilating flow, and remove carbon dioxide and expired water vapor. The cooling and condensing heat exchangers and the circulating fans of the environmental control system were provided by CSD, and featured Project Mercury ventilating compressors, along with cooling heat exchangers excessed from the "Big Joe" booster program.

The objectives of the 14-day test at 5 psia (34.5 kPa) pure oxygen included an evaluation of the partial don concept for the Gemini spacesuit as well as validation of the 5 psia pure oxygen atmosphere planned for both Apollo and Gemini. It was theorized that the ability to doff portions of the suit would aid in crewmember tolerance of a suited condition for 2 weeks. Fire broke out in the simulated space cabin on September 9, the 13th day of the test. One of the two Air Force officers was seriously injured due to smoke inhalation. The cause of the fire was determined to be a defect in an electrical circuit, called a "psychomotor", designed to monitor subject performance over the course of the test. The flash fire ignited foam-type insulation over cooling lines causing a toxic atmosphere that accounted for the injury to the one crewmember operating with his visor open. The other crewmember was fully suited, but lost ventilation due to subsequent power failure. Rupture of the diaphragm on an oxygen "walk-around" bottle fed additional oxygen to the blaze.

Another study involved unsuited subjects at 3.5 psia (24.1 kPa), 5 psia (34.5 kPa), and 7 psia (48.2 kPa) pure oxygen, with a control group at 14.7 psia (101 kPa) air—about 3.1 psia (21.4 kPa) oxygen partial pressure. Four naval officers were injured in November 1962, when an electrical spark ignited a fire in an altitude chamber, near the end of a 14-day experiment conducted by Republic Aviation for NASA at the U.S. Navy Air Crew Equipment Laboratory, Philadelphia, Pennsylvania.

In neither of these fires did the flammability of suit materials play a role; however, the susceptibility of a substance to burn, and burn vigorously, in the presence of an oxygen-enriched atmosphere plus the incredible speed of propagation presented a clear warning.

The philosophy that evolved seemed to be one of control of the sources of ignition, rather than make substantive changes in materials. It was not until after the disastrous fire of Apollo 1 in January 1967 that a sweeping change to materials selection was implemented, which affected suits as well as the other systems of the spacecraft.

5.2 GEMINI PRESSURE SUIT EVALUATION AND DEVELOPMENT

David Clark Company of Worcester, Massachusetts, won the Gemini suit contract in 1962, but this was not expected. As mentioned above, NASA had initially carried out design level evaluations with the B.F. Goodrich (GX1G) and Arrowhead (GX1A) partial don suits (i.e., suits with removable arm and leg sections to evaluate potential comfort enhancements during the planned 14-day Gemini

Figure 5.2.1. DCC Gemini rear-entry spacesuit (courtesy G. L. Harris).

missions). This resulted in a second design level of Goodrich GX2G and G2G suits that may have included equivalent Arrowhead models. Before a selection could be finalized, David Clark came in "off the street" with a rear entry prototype suit built with company funding. This suit design (Figure 5.2.1) utilized David Clark Link-net suit technology (Figure 5.2.2) that had been developed for the USAF X-15 program.

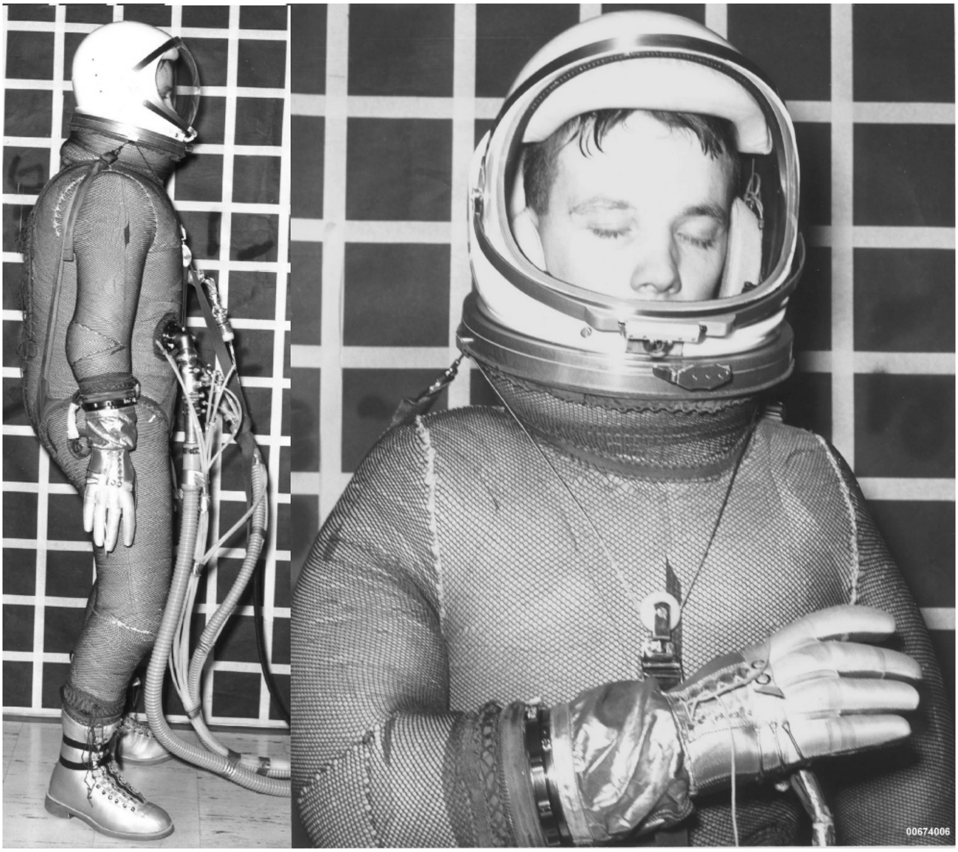


Figure 5.2.2. DCC Link-net views (courtesy Hamilton Sundstrand).

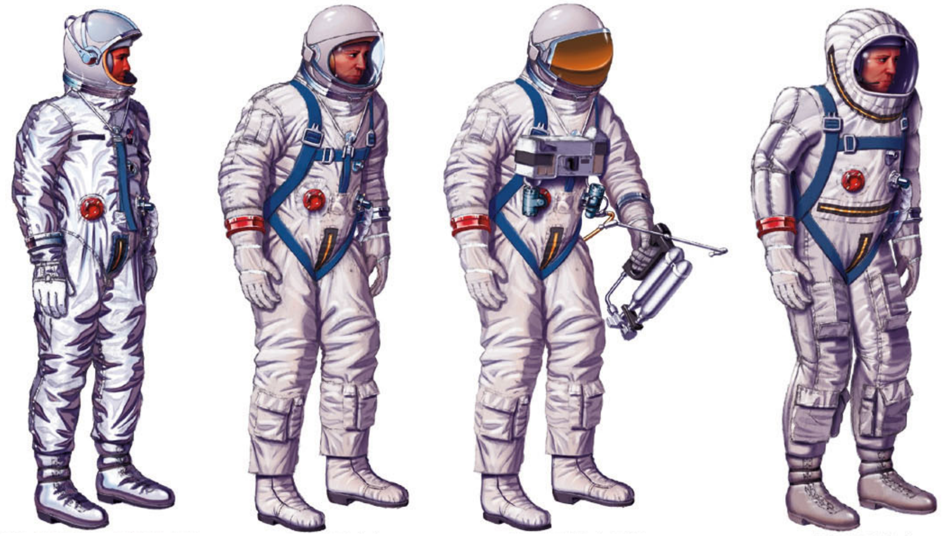
As the David Clark suit was deemed superior to the others, it was subsequently used for the Gemini program. David Clark G1C production suits soon replaced the GX1C prototypes to support evaluations. The G1C suit supported early vehicle interface evaluations that were critical to spacecraft production. The G2C training suit (Figure 5.2.3) followed, incorporating lessons learned from the G1C experience. The most noticeable feature of the G2C and earlier suits was the aluminized outer fabric that had been selected for space vacuum thermal properties (Figure 5.2.4A).

The Gemini G2C glove probably represented pressure glove state of the art before the demands for performing work in space brought new evolutions of design. The first pressure gloves—made for early, high-altitude aviation—were patterned for maximum comfort and dexterity unpressurized. While they provided the correct anthropomorphic shape unpressurized, they changed shape and provided limited manual mobility under pressure. These designs with minimum change became the intravehicular activity (IVA) gloves of the early space programs. The

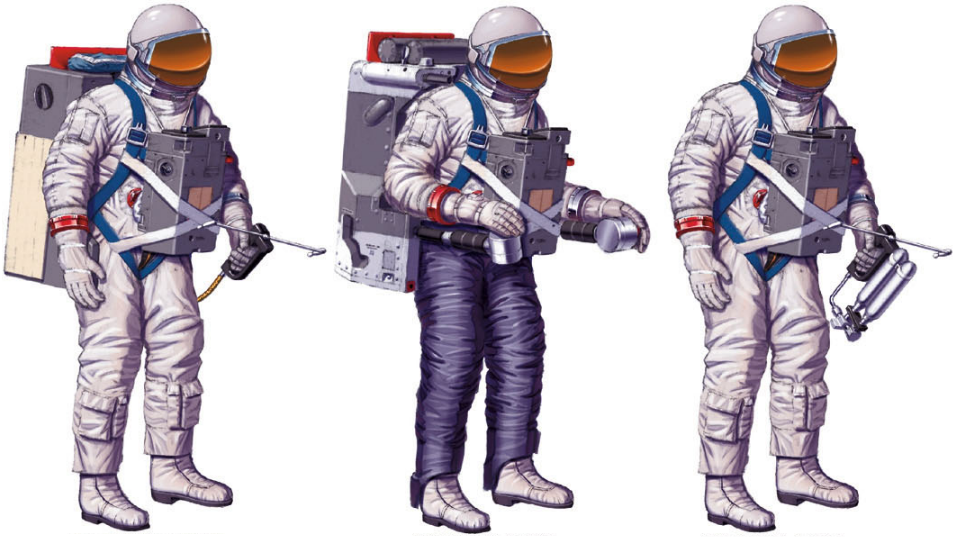
Figure 5.2.3. GT3's Gus Grissom (left) and John Young in David Clark G2C training suits (courtesy NASA).

early Gemini gloves used a lace-up restraint on the back of the hand. On the later Gemini gloves, including the EVA configuration, adjustable straps and adjustable palm restraint bars were used to retain the shape of the pressurized glove on the hand.

Gemini 3, the first manned Gemini flight, successfully utilized the G3C suit design for Astronauts Grissom and Young. Where the preceding Gemini suit utilized an aluminized outer layer, the G3C featured a natural (white) Nomex outer layer (Figure 5.2.4B).



(A) GX1C/G1C/G2C suits (B) G3C suit (C) G4C suit with VCM and HHMU (D) G5C suit



(E) G4C with ELSS, ESP and HHMU (F) G4C suit with ELSS and AMU (G) G4C suit with ELSS and HHMU

Figure 5.2.4. Derivations of the Gemini spacesuit system.

5.3 THE DEVELOPMENT OF EXTRAVEHICULAR SYSTEMS FOR GEMINI IV

Cosmonaut Aleksey Leonov's EVA of March 18, 1965 galvanized the fledgling NASA EVA community. Although the Apollo suit and life support system contracted efforts were proceeding as planned, Leonov's EVA sparked the Gemini Support Office of CSD to investigate the possibility of one of the Gemini crewmembers exiting the spacecraft on orbit.

The suit originally scheduled for Gemini IV was basically an intravehicular suit, but plans for "standup" EVA (i.e., have a crewmember open the hatch and stand up in the seat while attached to the spacecraft environmental control system) had been voiced as early as July 1964.

The possibility that a Gemini IV crewmember might "open the hatch and stick his head outside during the mission" had been considered. Such an operation would require modifications to the suit and require that the vehicle interior systems be able to operate satisfactorily during and after exposure to the vacuum and thermal environment of space. In November 1964, John Young had tested procedures for a "standup" EVA during the normal altitude chamber checkout of the spacecraft prior to the Gemini III launch. This exercise served to help to qualify spacecraft systems for EVAs planned for subsequent missions.

The David Clark G3C spacesuit had been baselined for the Gemini IV mission, but the plans for a standup EVA required some changes, resulting in the first G4C configuration. Originally intended only to protect crewmembers from loss of cabin pressure, the G3C suit's single outer protective layer was replaced with a cover layer of nylon felt for micrometeoroid protection, seven layers of aluminized Mylar superinsulation and an outer layer of high-temperature HT-1 fabric (Figure 5.3.1). The Gemini IV G4C cover garment featured a slipover jacket to minimize bulk during launch, entry, and closed hatch orbital operations.

The modified helmet used a two-lens visor assembly: the outer gold-coated lens attenuated visible and infrared energy and the inner lens provided impact protection and thermal control. Thermal overgloves protected against conductive heat transfer.

The EVA Gemini gloves had a molded neoprene bladder and a Nomex restraint layer. The fingers of the gloves had limited easement (extra material in the outside of the joints when bent) and, while this was an improvement on preceding pressure gloves, the pressurized volume had to be compressed to allow bending fingers to grasp objects. This challenge has been mitigated by further improvements over the decades, but is still a major hurdle in spacesuit design and manufacture.

On March 26, 1965, in parallel with pressure suit activities and with a launch less than 3 months away, James V. Correale, chief of CSD's Gemini Support Office, convened a small group of suit and life support system engineers to investigate all that would be required to provide an astronaut with a life support system for a full-scale EVA on Gemini IV.

This effort would be carried out in parallel with the definition and development of the Gemini EVA life support system planned for first use on Gemini VI (see p. 73). Correale appointed Larry E. Bell to head a NASA team to design, develop, certify, and provide not only a life support system to interface with the G4C suit, but also to utilize a handheld maneuvering "gun" that had been independently conceived by MSC's Harold I. Johnson to allow the EVA crewmember to direct his or her movements in space. This would give the U.S. EVA something extra to compare with the preceding Soviet accomplishment.

Figure 5.3.1. DCC Gemini IV suit materials (courtesy NASA).

The first order of business for the team was to perform the preliminary design of an open-loop purge system that would use oxygen from the Gemini spacecraft through an AiResearch-supplied 25 ft (7.6 m) umbilical that was gold-coated for thermal protection. The oxygen flow was throttled into the suit and exhausted through a demand regulator like those used on board the Gemini vehicle's life support system. The use of "Y" connectors permitted the EVA crewmember to be simultaneously connected to the vehicle environmental control system (ECS) and the EVA system. Upon disconnection from the vehicle ECS, the ports of the Y-connectors would automatically seal (Figure 5.3.2).

Upon accidental flow interruption from the umbilical, a small bottle of oxygen in the chest-mounted package would supply 9 minutes of O_2 to the demand regulator for automatic makeup or for manually actuated flow directed to the oro-nasal area of the helmet through the feed port. For national security reasons, the system was originally named the chamber vent system (CVS) but was later renamed the ventilation control module (VCM) for posterity (Figure 5.3.3). Only a few people at NASA knew of plans to use this system on Gemini IV in early June 1965.

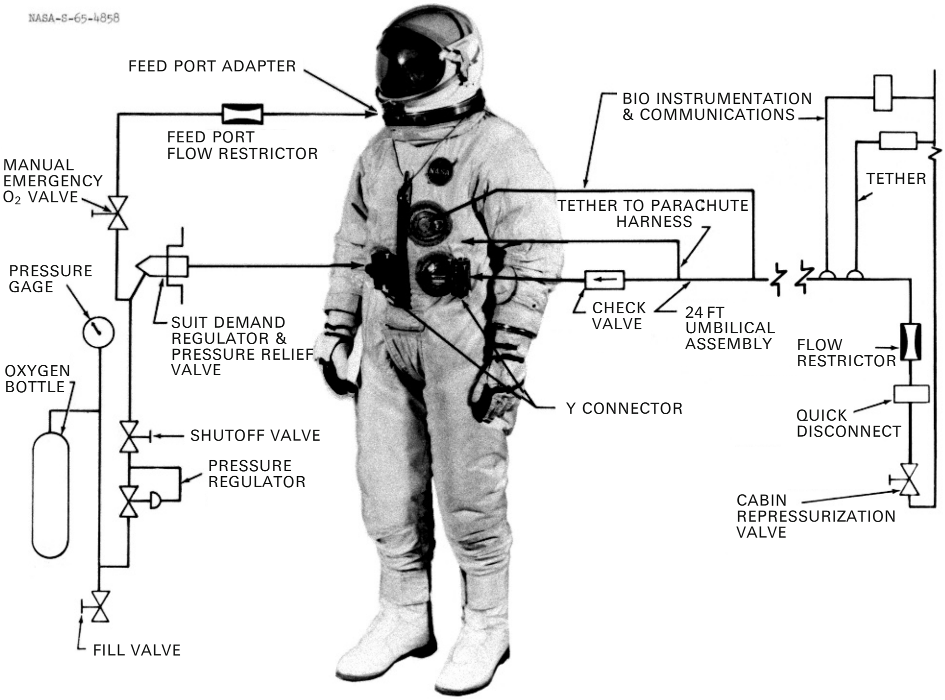


Figure 5.3.2. Gemini IV EVA suit system schematic (courtesy NASA).

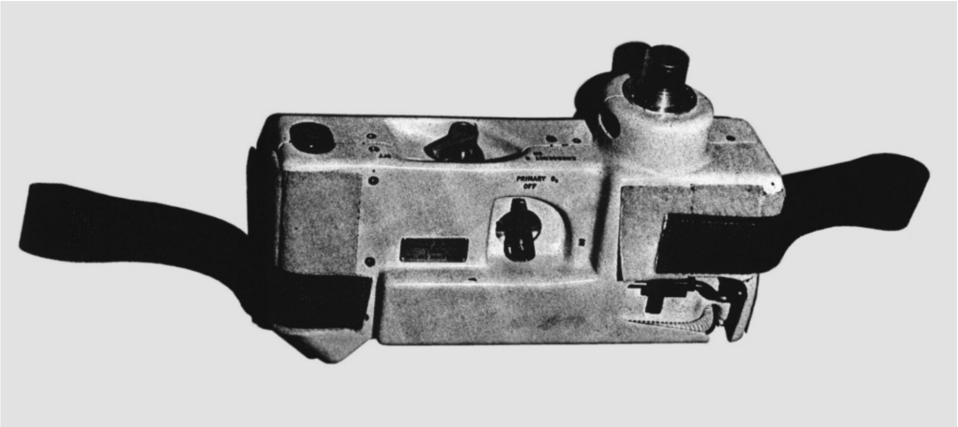


Figure 5.3.3. NASA/AiResearch ventilation control module (courtesy NASA).

The extremely compressed schedule required fast approval from MSC management. During a pre-flight briefing concerning the proposed Gemini IV EVA hardware made to MSC director Dr. Robert R. Gilruth and his senior staff, representative hardware items were passed around the conference table while Larry

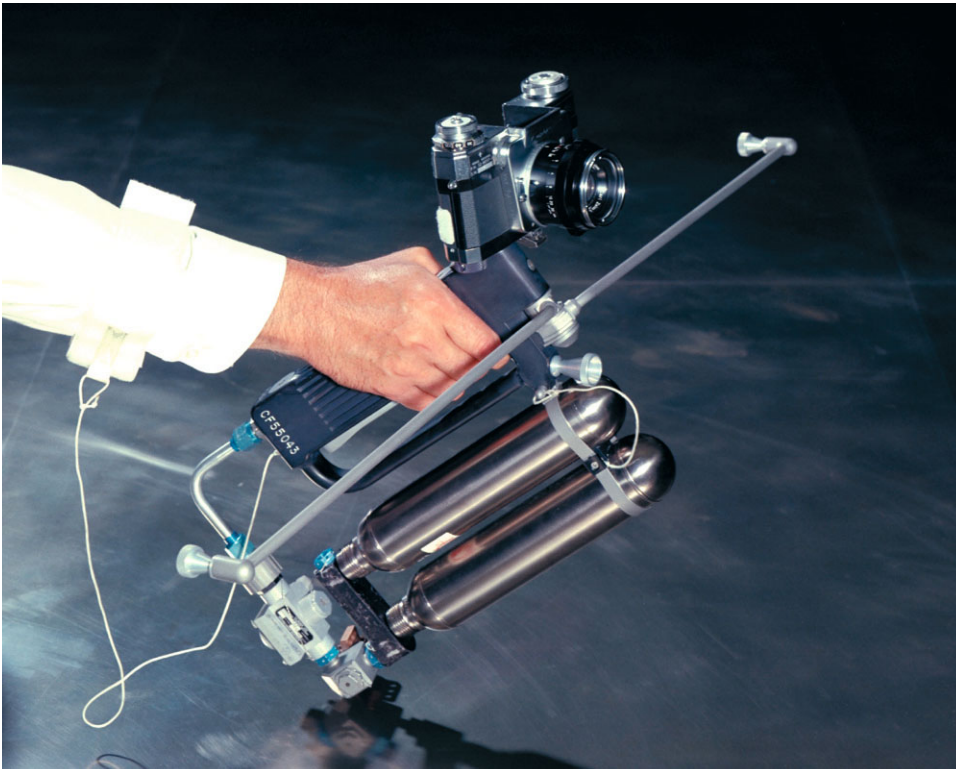


Figure 5.3.4. The world's first manned maneuvering unit (courtesy NASA).

Bell made the presentation. At one point, Dr. Gilruth was observed trying to jam open one of the Y-connector poppet closure valves with a folded paper match. He was unable to do so, and this was a tribute to the Air-Lock, Inc., design. Had he been able to lock the fitting open, this would have demonstrated a potential failure mode that, if encountered during vacuum operations, would have been fatal to the crewmember. Bell was unaware of this activity, which was probably fortunate for his presentation. However, as history will attest, the required approval was given.

Also developed by NASA for Gemini IV was the handheld maneuvering unit (HHMU, Figure 5.3.4). While some of the elements of the Gemini IV configuration would be mission specific (Figure 5.2.4C), subsequent versions of this compact foldup handheld propulsion system would also be carried on Gemini VIII, X, and XI. The Gemini IV HHMU was a self-contained system. Twin 4,000 psia (272 atm) oxygen bottles provided up to 40 lb-s of propulsive capability. HHMU evaluations were carried out only on the Gemini IV and X missions, due to spacecraft thruster problems on Gemini VIII and crew fatigue on Gemini XI.

5.4 GEMINI IV: THE FIRST U.S. SPACEWALK

Gemini IV astronaut Ed White conducted his historic EVA on June 3, 1965 (Figure 5.4.1), for a total of 36 minutes on umbilical flow. Of that, 20 minutes were spent outside the spacecraft. Early worries about disorientation were quickly dispelled, as he demonstrated the utility of the HHMU. The 25 ft (7.6 m) umbilical caused him to move back in the general direction of the Gemini spacecraft, but offered no help in body positioning or stabilization.

Reentering the spacecraft and closing the hatch proved to be substantially more difficult than anticipated. This resulted in an increase of Astronaut White's metabolic rate that soon overpowered the modest heat removal capabilities of the gas flow from the umbilical. His visor was fogged, and several hours were required on the vehicle ECS after repressurization before he regained thermal equilibrium. During the EVA, White exhausted all the HHMU propellant gas and, prior to closing the hatch, he jettisoned his thermal overgloves and the helmet overvisor.

Figure 5.4.1. First U.S. EVA: Ed White and his Gemini IV suit system (courtesy NASA).

This mission proved that EVA was feasible, but demonstrated that more time was needed for EVA preparation and that the life support equipment must be improved to accommodate the metabolic heat loads encountered. This mission also gave an indication that more attention must be paid to developing a means of stabilizing the EVA crewmember.

5.5 GEMINI V THROUGH VII GOALS AND SUIT SYSTEMS (1965–1966)

The goals of the Gemini V to VII missions did not include extravehicular activity. For the Gemini V and VI crews, G4C suits were used in an intravehicular capacity by replacing the EVA multilayer suit covering with a single IVA cover layer in addition to eliminating the gold EVA visor. Gemini VII also introduced a single-mission pressure suit configuration.

The Gemini V mission

Gemini V had the primary objectives of demonstrating that a human could function in a space environment over a period of 8 days, and that the Gemini vehicle systems would also operate satisfactorily over that period. With no real incentive to conduct another EVA on Gemini V, and the aim of operating in orbit for 8 days, the crew pushed to wear oxygen masks, goggles, and helmets instead of suits for increased comfort. They were overruled and were launched on August 21, 1965, wearing the G4C model suits that had been previously purchased. The success of the mission boded well for the ability of humans to travel to the Moon and return.

Gemini VII/VIA mission: Objectives and results

The need to demonstrate rendezvous was the overriding objective for this combined mission, and previous plans to conduct EVA on the flight were scrubbed.

The loss of the Agena rendezvous target vehicle on October 25, 1965 effectively negated the planned Gemini VI mission objective of rendezvous with this spacecraft. After some creative thinking and considerable study of how to accommodate two piloted spacecraft in orbit simultaneously, NASA revamped the Gemini VI and VII missions so that the planned Gemini VII 14-day mission would launch several days ahead of the renamed Gemini VI-A mission. Once on orbit, the Gemini VII vehicle would act as a rendezvous target for the Gemini VI-A spacecraft. Gemini VI-A astronauts Schirra and Stafford wanted to add EVA to the menu for the combined mission—and perhaps even perform a crew exchange to demonstrate crew rescue. However, Gemini VII astronaut Borman was emphatically against any EVA for his vehicle. Before the Agena problem, Gemini VI had once been scheduled for an EVA using the AiResearch-designed extravehicular life support system (ELSS) chestpack (see Section 5.6), but Schirra at that time had been against it and had managed to have EVA deleted from the flight. His subsequent efforts to have it reinstated were not successful.

Again, the question of whether or not a long mission such as Gemini VII should be conducted without suits was raised. Previously, successful tests had been performed by McDonnell in their altitude chamber with Astronauts Elliot See and Gordon Cooper wearing standard Air Force flightsuits with medical monitoring instrumentation, helmets, and oxygen masks. However, there was concern about the crew's ability to tolerate possible high cabin temperatures, and the inability to decompress to vacuum in the event of a fire. CSD's James V. Correale suggested using a lightweight version of the G3C intravehicular suit, and David Clark rose to the challenge by removing as many of the heavy components and as much complexity from the G3C as it could. The result was a 16 lb (7.3 kg) soft suit, which featured a soft cloth hood and flexible visor without a neck ring. The soft hood could be opened, and the entire suit doffed and put aside without having to be stowed. It could also be donned quickly in the event of an emergency. The suit, which Correale and others dubbed the "get-me-down" suit, was officially designated the G5C (Figures 5.5.1, 5.5.2, and 5.2.4D).

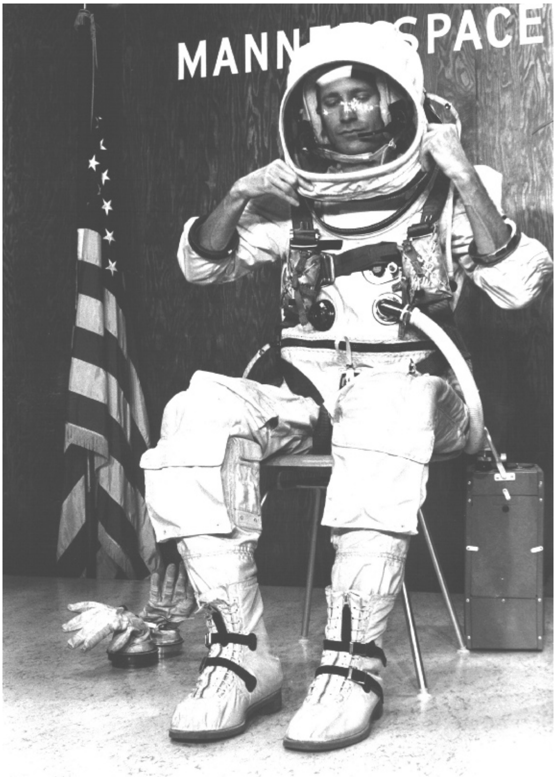


Figure 5.5.1. Donning the David Clark Gemini VII G5C suit (courtesy NASA).

Figure 5.5.2. Gemini VII astronaut Jim Lovell leads the way to a launch (courtesy NASA).

Gemini VII launched on December 4, 1965, and within 2 days Lovell began doffing his suit, but it took him more than an hour in the cramped vehicle interior. Borman complained of being warm, but it soon became obvious that even one unsuited crewmember improved general cabin comfort. The crew had planned that they would both doff their suits, but management disagreed, wanting one crewmember to be suited at all times. At one point, the crewmen switched conditions and, as Lovell donned his suit, Borman doffed his. Finally, both crewmembers received ground approval to proceed without suits.

Meanwhile, Gemini VI-A astronauts Schirra and Stafford in their G4C suits were launched on December 15, 1965, after a previously aborted attempt on December 12.

The combined Gemini VII/VI-A mission successfully demonstrated rendezvous, at one time achieving a separation of only 1 ft (0.3 m) between vehicles. Gemini VII was the only flight to use the G5C suit design.

5.6 SYSTEMS AND EXPERIENCES FROM GEMINI MISSIONS VIII TO XII (1966)

The Gemini VIII to XII missions had EVA goals. To support these activities, a modular system had been developed to facilitate exploration of various maneuvering system possibilities. The centerpiece of these optional configurations was the extravehicular life support system (ELSS). However, the suit system configurations for each mission were uniquely different, as illustrated in the remainder of Section 5.6. Some of the configuration experiments were not performed due to other mission difficulties, but the missions provided invaluable insights into the challenges of extravehicular activity.

Gemini VIII mission goals and system introductions

Next to docking with an orbiting Agena vehicle, EVA was the second most important part of the planning for Gemini VIII. Since EVA had been removed from the flights immediately after Gemini IV, there was a need to conduct a really meaningful space excursion to prepare for the flight of the Air Force astronaut maneuvering unit (AMU) on Gemini IX.

The primary objective for Gemini VIII's EVA program was evaluation of three pieces of EVA equipment (Figure 5.2.4E): (a) the semi-open-loop chest-mounted ELSS, which had greater cooling capability than the open-loop Gemini IV package; (b) further tests of the HHMU; and (c) a large backpack, called the extravehicular support package (ESP), which contained oxygen and maneuvering fuel. The extravehicular astronaut would be "sandwiched" between the ESP on his back and the ELSS on his chest. Transfer from the 25 ft (7.6 m) umbilical to a 75 ft (23 m) electrical cable with an integral tether would provide room for the crewmember to maneuver and acquire more experience with the HHMU.

Although similar to the G4C suit used on Gemini IV, the Gemini VIII version varied in the micrometeoroid lay-up and gloves. Two layers of neoprene-coated nylon were substituted in the suit cover layer for the previously used nylon felt and nylon fabric. Instead of overgloves, thermal and micrometeoroid protection were provided by a layer of silastic material on the palm (protection while grasping hot objects) and added layers of fabric to the back, respectively (Figure 5.6.1). The intravehicular crewmember used the standard gloves, without the added features. For non-EVA tasks, the pilot also used standard intravehicular gloves.

The first concept for the EVA life support system to be used on Gemini was not the Gemini IV system. When EVA was determined to be feasible for Gemini in 1963, engineers at CSD began work on a simple, open-loop purge system using excess Project Mercury environmental control system hardware. Two Mercury oxygen bottles and regulators were to be contained in a harness worn at the front of the EVA crewmember and these would provide about 15 minutes of purge flow to the suit, which would be exhausted through a relief valve.

CSD contracted with AiResearch Manufacturing Division of the then Garrett Corporation (now Honeywell) for the effort, which was mainly for assembling and

Figure 5.6.1. Gemini VIII and later EVA gloves (courtesy David Clark Co.).

testing the hardware. In January 1964, the concept was changed dramatically to an umbilical-fed, semi-open-loop system using an ejector powered by oxygen from the umbilical. The system, called the ELSS, had a self-contained, 30-minute emergency oxygen supply, an internal battery, and the controls, displays, and capability to operate from other oxygen and power sources, such as the Air Force AMU (Figure 5.2.4F).

The ELSS (Figures 5.6.2, 5.6.3 and 5.6.4) used an ejector that was powered by approximately 100 psia (6.8 atm) oxygen from an umbilical or other source to drive ventilation and cooling flow. The ejector provided the power to recirculate about two thirds of the total ventilation flow, with about one third (equal to the umbilical supply) being vented overboard through a relief valve. This overboard venting helped to control CO_2 and moisture levels in the recirculated portion of the ventilation stream. A water boiler heat exchanger using a small amount of stored water and reevaporating moisture, which was removed from the recirculating ventilation stream, cooled the remaining two thirds of the recirculated ventilation flow of about 16 lb/h (7.3 kg/h). The amount of oxygen with associated moisture and carbon dioxide vented overboard essentially controlled the carbon dioxide concentration in the helmet, since it was replaced with "fresh" oxygen from the spacecraft through the ejector. However, this also meant that, if activity levels exceeded design values, carbon dioxide concentration would increase. The ELSS design capabilities

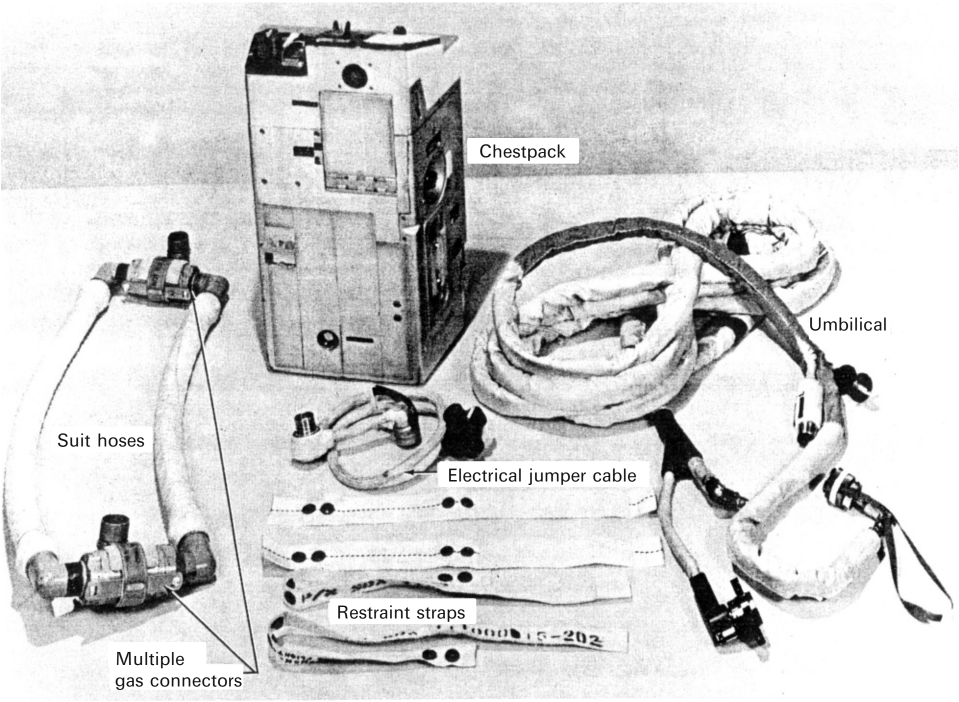


Figure 5.6.2. The component packaging of ELSS (courtesy NASA).

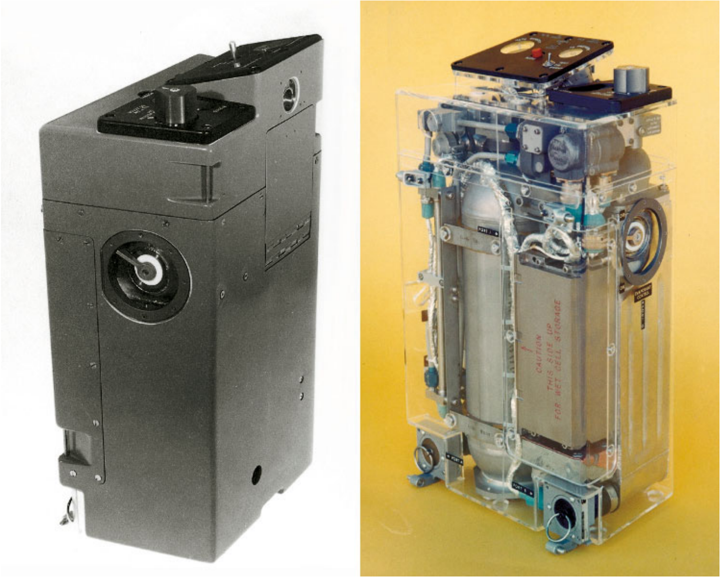


Figure 5.6.3. The AiResearch ELSS (courtesy Honeywell).

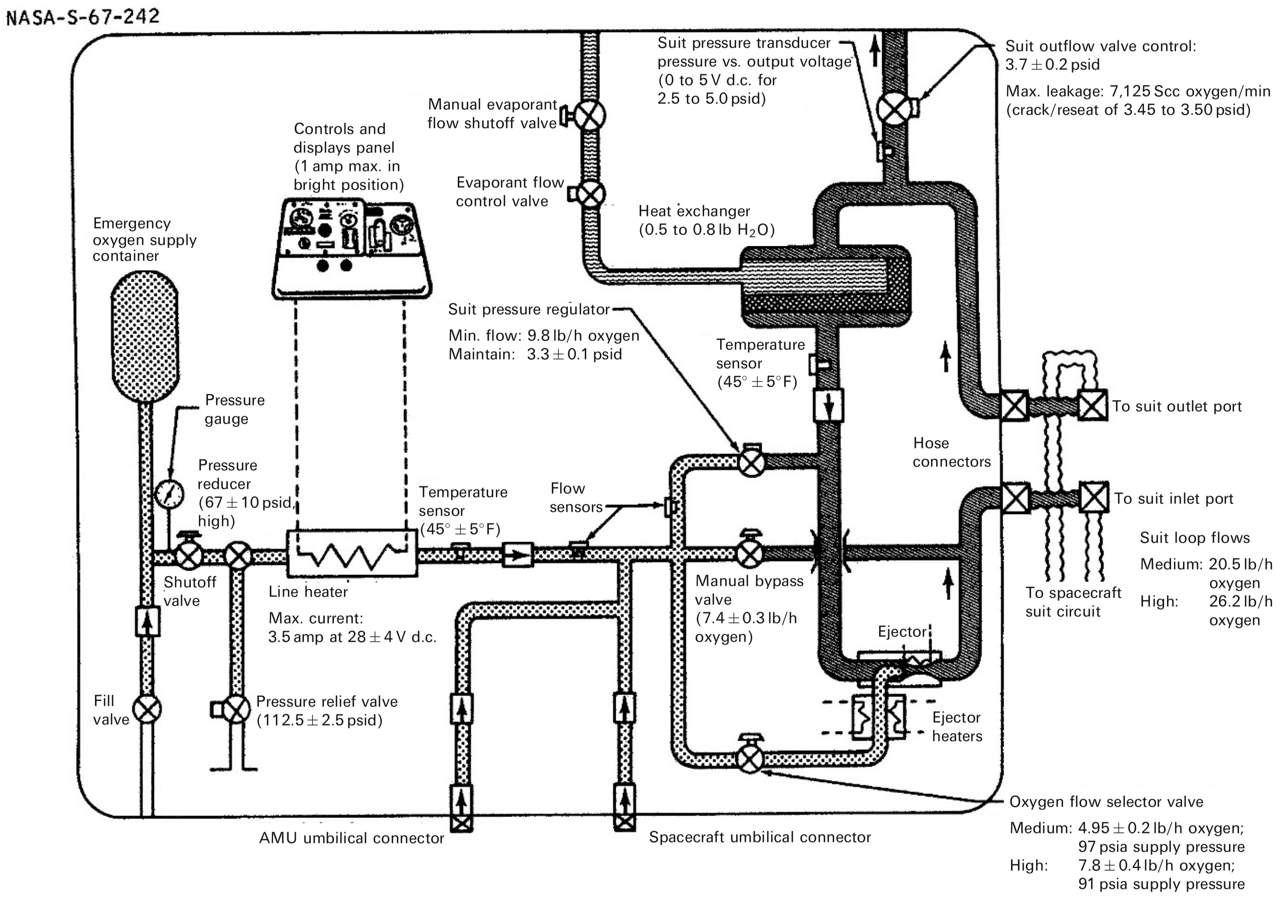


Figure 5.6.4. ELSS chestpack pneumatic subsystem schematic with nominal component performance values (courtesy NASA).

were 1,000 Btu/h (252 kcal/h) averaged over 71 minutes; 1,400 Btu/h (353 kcal/h) over 86 minutes; and 2,000 Btu/h (504 kcal/h) over 10 minutes. The nominal flow rates of the ELSS from the umbilical were 4.9 lb/h and 7.8 lb/h (2.2 kg/h and 3.6 kg/h) with an additional emergency bypass rate of 7.4 lb/h (3.4 kg/h), for a total of 15.3 lb/h (7.0 kg/h) in the bypass mode. Controls and displays enabled the EVA crewmember to vary ventilation flow and monitor emergency system status. As testing just prior to Gemini VIII showed that, under certain conditions, ice blockage of the ventilation passage in the ejector could occur, an electrical heater was added.

If umbilical oxygen was lost, the ELSS also contained 30 minutes of oxygen stored at 7,500 psi (510 atm) in a cylindrical tank, which was also the primary structure for the ELSS chestpack and provided the mounting points for stowage in the spacecraft. A battery built into the ELSS powered caution and warning and communications if spacecraft power was lost. The ELSS display panel was outfitted with six warning lights and an emergency oxygen pressure (quantity) gauge in addition to a gauge that would allow a hydrogen peroxide quantity display during operations with the AMU. Four of the warning lights dealt with the AMU status, and the other two indicated low suit pressure and flow from the emergency oxygen tank. An audible tone was used to draw the crewmember's attention to the display panel.

The ELSS chestpack had dual high-pressure oxygen inlet fittings, which would allow transfer from the spacecraft umbilical to other oxygen supplies, such as the ESP and AMU without interruption of supply. The ELSS electrical cabling arrangement allowed a similar transfer from spacecraft umbilical electrical services to those of the ESP or AMU; however, the astronaut would be temporarily disconnected from communications during the transfer.

Y-type connectors similar to those used on Gemini IV allowed simultaneous connection to the ELSS and spacecraft ECS. The EVA crewmember could disconnect from the ECS, with the self-sealing poppet valves of the Y-connector preventing suit depressurization. Upon reentering the spacecraft, the procedure was reversed.

The ELSS chestpack had a trapezoidal cross-section, in order to fit in a specific stowage location between the two crewmembers. In order to save weight on entry, the 40 lb (18 kg) chestpack was planned to be jettisoned, once the EVA crewman had reattached to the spacecraft ECS.

The 25 ft (7.6 m) umbilical differed from that used for Gemini IV in that a multilayer insulation wrap made of aluminized Mylar/Dacron scrim spacer was used instead of the gold coating. The insulation was covered by a Nomex nylon sheath. The umbilical carried oxygen at around 100 psia (6.8 atm); had electrical lines carrying bioinstrumentation, communications, suit pressure, and power; and a load-bearing tether. In order to prevent accidental loading of the oxygen or electrical lines, the tether was made shorter than these lines by about 2.3 ft (0.7 m). Thus, if the EVA crewmember happened to be moving rapidly and came to the end of the tether, the resulting energy-absorbing stretch would not load the oxygen and electrical lines.

Umbilical stowage was carried out by coiling the umbilical in a "figure 8" configuration in a bag that was held closed by hook-and-loop fasteners. The ends of the umbilical protruded from the bag, with one end attached to the spacecraft and the other end fastened to the ELSS. The umbilical could easily be deployed without kinking by just pulling on the ELSS end. Restowage was more difficult, as the EVA crewman and umbilical entered the spacecraft together.

The MSC extravehicular support package (ESP) was a backpack unit that contained a primary oxygen supply for the ELSS, supporting approximately an hour's worth of EVA. The ESP, designed and built by engineers and technicians at the Manned Spacecraft Center (MSC), now the Johnson Space Center, also supplied a freon 14–nitrogen mixture at 5,000 psia (340 atm) as a propellant supply for the HHMU and an ultrahigh-frequency radio package for independent voice communications. The ESP used existing Gemini spacecraft components to minimize development risk. Like the AMU, stowage of the ESP was in the Gemini spacecraft adapter which required donning to be conducted as part of EVA.

The ESP made use of the AMU peroxide quantity gauge on the ELSS display panel. The extravehicular crewman could read either propellant quantity or oxygen quantity by cycling a switch located on the ESP housing.

Along with the ESP, the Gemini VIII system featured a 75-foot (23 m) tether and electrical cable assembly to be used when operating on the ESP. In use, the 75-foot tether was connected between the 7.6-meter umbilical and the extravehicular crewman to allow 100 feet (30.6 m) of separation from the spacecraft.

The use of freon as a propellant increased the total impulse available to 600 lb-s (272.7 kg-s), as compared with the 40 lb-s (18.2 kg-s) of Gemini IV. However, the use of freon presented problems with low temperatures encountered during "firing". During testing, the temperatures of the expanded gas dropped to −150°F (−101°C) in the HHMU, which caused the poppet valves to stick open. Although a change to Teflon cryogenic seals solved the problem, redundant shutoff valves were added to the supply system to allow for a leaking hose or a stuck-open poppet valve.

The launch of Gemini VIII occurred on March 16, 1966. Near disaster struck shortly after docking with the Agena, when a Gemini vehicle thruster was determined to have failed in the "on" position. Undocking from the Agena and isolating the errant thruster allowed the crew to make an emergency entry. Obviously, any EVA was out of the question. From launch to landing, the flight had lasted less than 11 hours.

The emergency procedures leading up to landing had left no time to perform the normal jettison of the ELSS chestpack into space, planned for post EVA. This meant that the crew had to make a landing with the 7,500 psi (510 atm) emergency oxygen system of the ELSS fully charged. Instructions from CSD ELSS engineers to the recovery team in Naha, Okinawa, resulted in safe depressurization of the oxygen system.

Gemini IXA systems revisions and objectives

This mission focused on early rendezvous and extravehicular activity; the latter involving the Air Force AMU. To support these activities, the Gemini VIII system design was modified in critical areas.

Figure 5.6.5. The Gemini IX EVA suit system (courtesy NASA).

For Gemini IX-A, the pressure suits were revised from the Gemini VIII G4C configuration. The cover garment of Astronaut Cernan's suit had been redesigned to include a woven stainless steel outer fabric (called Chromel-R) in the lower-torso area (Figures 5.6.5 and 5.6.6) for protection from the potentially 1,300°F (705°C) AMU thruster plume. Underneath the cover layer, 11 layers each of aluminized H-film and fiberglass cloth spacer material replaced the aluminized 7 layers of Mylar and Dacron scrim, respectively, so that the high temperatures from the plume would not degrade the suit's insulation. The upper torso maintained the standard extravehicular cover layer lay-up. The intravehicular crewmember, Astronaut Stafford, wore a standard G4C suit.

The pressure-sealing visor was changed from Plexiglas to polycarbonate material, since the latter provided 10 times the impact resistance of acrylic. This change eliminated the need for the separate impact visor, and a single, gold-coated acrylic visor was added for visible and infrared light attenuation.

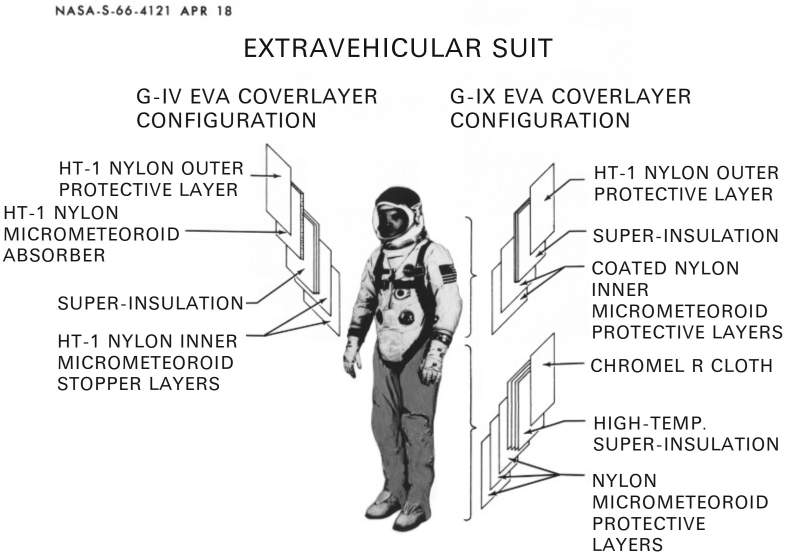


Figure 5.6.6. DCC Gemini IX suit materials (courtesy NASA).

The ELSS chestpack and umbilical flown on Gemini IX-A were similar in most respects to those flown on Gemini VIII. The chestpack was slightly modified to reroute an oxygen bypass line to provide supplemental ventilation flow downstream of the ejector throat. This modification was made to allow for potential blockage of the ejector passage due to icing should the ejector heater fail. EVA plans called for the AMU to be donned during EVA in the adapter section of the spacecraft and transfer to the electrical and oxygen systems of the AMU for tethered flight. The EVA was to be 167 minutes in duration.

The astronaut maneuvering unit (AMU) (Figures 5.6.5 and 5.6.7) was designed and manufactured by Ling–Temco–Vought (LTV) under contract to the U.S. Air Force, and the planned experiment was designated D012. According to the plan, it was to fly with a 125 ft (38 m) tether on Gemini IX-A, then to fly untethered on Gemini XII. The AMU would allow an astronaut to operate totally independently of the Gemini spacecraft (no umbilicals). This autonomous capability was due to an oxygen supply and regulation system carried on board the AMU. The oxygen supply system (OSS) was designed and built by Hamilton Standard.

The OSS provided 5.1 lb (2.3 kg) of life support oxygen to the ELSS, which would support one hour of operation. From the OSS located in the left rear of the AMU, the gas flowed through the AMU to the ejector contained within the ELSS.

In addition to the OSS, the 168 lb (76 kg) AMU carried power for communications and the ELSS caution and warning system along with 24 lb (10.9 kg) of hydrogen peroxide fuel for its maneuvering functions. This gave a total impulse of up to 3,500 lb-s (1,591 kg-s). The AMU had 16 thrusters and featured redundant manual and automatic flight control systems.

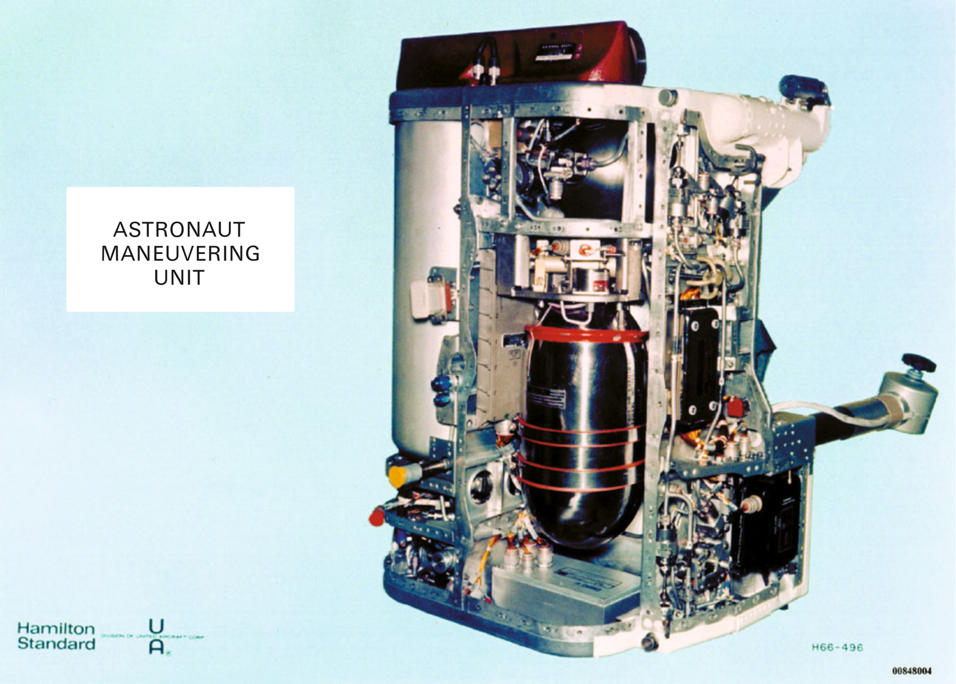


Figure 5.6.7. Internal view of the astronaut maneuvering unit (AMU) (courtesy Hamilton Sundstrand).

The ELSS display panel, in addition to the hydrogen peroxide quantity gauge, contained four AMU-related warning lights that would indicate problems with the oxygen supply, hydrogen peroxide quantity, hydrogen peroxide fuel supply pressure, or the thruster system. Attention would be drawn to any warning light by an audible tone.

In flight, the EVA crewmember wearing the ELSS and AMU would remain attached to the spacecraft by means of a 125 ft (38 m) tether made of nylon webbing. The idea was to attach this tether to the ELSS umbilical tether that would allow a total of approximately 150 ft (46 m) of separation. An intermediate hook was located at about 25 ft (7.6 m) from the end attaching to the umbilical tether, so that a separation of about 50 ft (15 m) could be used if desired.

Astronaut Gene Cernan performed the second U.S. EVA on June 6, 1966, as part of Gemini IX-A. Unlike White, who floated free on his umbilical and maintained body attitude control using the handheld maneuvering unit (HHMU), Cernan had no HHMU, but used an ELSS 25 ft (7.6 m) umbilical to translate from Gemini IX-A's aft adapter to the stowed AMU using handrails, Velcro patches, and loop-type foot restraints (Figure 5.6.8). These proved to be inadequate for controlling his body attitude, and his physical exertion exceeded the moisture removal capability of the ELSS. His helmet fogged, effectively blinding him and forcing termination of the EVA, which lasted 2 hours 7 minutes.

Figure 5.6.8. Buzz Aldrin with the astronaut maneuvering unit in donning station (courtesy NASA).

Later, back on Earth, Cernan performed an underwater simulation of his EVA in a contracted facility, validating neutral buoyancy as an EVA training tool. This was part of a July 1966 exercise carried out at Langley Research Center, and included a partial task evaluation of the proposed Gemini X EVA tasks; Cernan's reenactment of the Gemini IX-A EVA; an evaluation of the proposed Gemini XI EVA; and, finally, an evaluation of the original Gemini XII timeline which included AMU operations. All but the Gemini IX-A exercises were carried out by contractor personnel.

The Gemini XII operations were repeated with the revised mission objectives, and both Edwin "Buzz" Aldrin and Gene Cernan participated, as prime and backup EVA crewmembers, respectively. Subsequent to these underwater evaluation and training experiences, MSC converted a building that previously housed a three-person centrifuge to become the MSC Water Immersion Facility (WIF). This facility was 16 ft (4.9 m) deep by 28 ft (8.5 m) in diameter and was first located in MSC's Building 29. This facility was eventually renamed the Weightless Environment Test Facility (WETF) and was later replaced by the Neutral Buoyancy Laboratory (NBL) located at JSC's Sonny Carter Training Facility.

The disappointing results from the Gemini IX-A EVA prompted MSC suit and life support engineers to reexamine their equipment.

Cernan had commented that he had felt hot areas on his back, and examination of the suit's insulation revealed several areas where the insulation had separated, allowing a heat path through the cover layer.

Antifog solution had been applied before the Gemini IV flight, and EVA had occurred soon in the flight (less than 5 hours of elapsed flight time). For Gemini IX-A, antifog was not applied pre-flight, since the EVA was to occur later than the 12-hour life of the solution. One of the obvious corrective actions was to supply antifog patches for crew application before future EVAs.

The Gemini IX-A chestpack was human-tested in a vacuum chamber at MSC to try to duplicate the in-flight results. Fogging was obtained over about 80% of the visor at a metabolic rate of about 2,450 Btu/h (617 kcal/h). Antifog solution applied to a small section of the visor kept it fog free. Visor clearing occurred upon cessation of exercise—a phenomenon also observed during flight.

As previously stated, the ELSS design capabilities were 1,000 Btu/h (252 kcal/h) averaged over 71 minutes; 1,400 Btu/h (353 kcal/h) over 86 minutes; and 2,000 Btu/h 504 kcal/h) over 10 minutes. The Gemini IX-A mission had imposed far greater workloads than 2,000 Btu/h (504 kcal/h) for far longer than 10 minutes, and this had resulted in the heat and moisture levels being excessive. Indeed, after repressurization, the pilot was perspiring profusely and both the suit and ELSS chestpack interiors were saturated. It is also surmised that the stored expendable water in the ELSS chestpack had been exhausted due to the heat load, and this only worsened the problem.

Clearly, although the problems of maintaining body positioning and carrying out EVA tasks without excessive energy would have to be solved, it was obvious that a better means of maintaining thermal control was needed—the gas-cooling approach was simply not adequate to accommodate the promising future of EVA. Also, antifog solution was to be applied immediately before EVA on future missions.

Gemini X mission changes and objectives

In addition to attempting a dual rendezvous using an active Agena to boost them into a higher orbit to mate with the inactive Agena from Gemini VIII, Gemini X astronauts John Young and Mike Collins planned to retrieve a micrometeoroid package from that vehicle, with Collins performing the EVA and Young controlling the Gemini vehicle. Collins would also perform further evaluations of the HHMU while supported by the ELSS in umbilical EVA configuration (Figure 5.2.4G).

In most respects, the same suit configuration that had been flown on Gemini VIII was used; however, the Gemini IX-A polycarbonate visor was utilized. Also, visor antifog kits, which contained wet wipes saturated with an antifog and cleaning solution, were carried on board for application before EVA. Other minor changes were made, but were not significant.

The ELSS chestpack (Figure 5.6.9) was essentially the same version that had flown on previous missions with the exception of the design of the high-pressure

Figure 5.6.9. Gemini X to XII base suit system configuration (courtesy NASA).

check valve used in the fill section of the self-contained 7,500 psi (510 atm) oxygen system. Two instances of ignition of the valve seat had been encountered prior to Gemini IX-A; however, neither had propagated into a fire in the rest of the system. The loss of the seat resulted in external leakage that was detected and the valve was replaced prior to flight. It was decided that a better design was needed, and the soft seat was replaced by a ball-type, metal-to-metal seating configuration, which was incorporated on Gemini X and subsequent ELSSs.

For Gemini X, a special 50 ft (15 m) umbilical was developed to further the HHMU evaluation. In addition to the super-insulation, oxygen line, tether, communication, and biomedical leads, this umbilical contained a nitrogen gas line to provide HHMU propellant. Although the oxygen, electrical, and tether connections were made inside the spacecraft cabin, the nitrogen connection had to be accomplished during the early stages of the EVA, since it was located in the adapter area.

The HHMU to be used on this flight varied somewhat from the Gemini VIII version. The handle was sloped, and grooves were provided to make a friendlier interface with the pressurized glove. Actuation forces were lessened, and the distance between the "pusher" and "tractor" positions was reduced. The 5,000 psi (340 atm) nitrogen gas was stored in two tanks in the spacecraft adapter section, and a total of 677 lb-s (308 kg-s) of impulse was provided.

After launch on July 18, 1966, at just over 23 hours of elapsed flight time, Collins performed a standup EVA; however, immediately after sunrise, both crewmembers experienced eye irritation and significant tear formation, impeding vision, and the EVA was soon terminated. The eye irritation lessened gradually after hatch closure and repress. It was surmised that, somehow, the use of both suit ventilation circulating compressors was at fault, but the exact cause was not determined. It was determined, however, that no irritation occurred when only one compressor was operated.

After just over 2 days' mission elapsed time, the umbilical EVA was initiated. At this time, the spacecraft was docked with the Gemini VIII Agena target vehicle. Collins successfully grabbed a micrometeoroid experiment package that was to replace the one carried on board the Agena, and moved to connect the nitrogen supply line for the HHMU. In moving forward to the Agena, Collins had difficulty grasping its docking cone, and kept drifting away from the target vehicle. He then used the HHMU to translate back to the target vehicle. This time, he used various wire bundles and struts as handholds, and managed to retrieve the "old" experiment package. However, he elected to discard the replacement package, rather than risk losing the one he had just retrieved. Unfortunately, in addition to the loss of the 70 mm still camera used during EVA due to a lanyard retention failure, the micrometeoroid experiment package was also lost although it had been placed in a pouch. It was concluded that it had been jostled loose during the crew's struggles with the 50 ft (15 m) umbilical at the end of the EVA.

Post-flight examination of Collins' suit revealed that approximately 40% of the gold coating on the sunvisor had been removed, probably by contact with the spacecraft hatch or other items.

The ELSS chestpack performed satisfactorily during this EVA. Although workloads were not as intense as those experienced during Gemini IX-A, Collins did advance the cooling from "medium" to "high" flow on his chestpack. This occurred during his exertions in working at the Agena target vehicle. All in all, Collins commented that he was cooler than he had been during ground simulations in the vacuum chamber.

No anomalies were reported on the HHMU. Collins' comments indicated that although the "gun" wasn't extremely accurate, it took him where he needed to go, albeit with some unwanted extra-directional adjustments.

The EVA was terminated after only 39 minutes on the umbilical due to a shortage of spacecraft propellant; however, the lessons learned were significant. The workload of preparing for rendezvous with a passive target simultaneously with EVA preparation caused the crew to be rushed, and prevented the command pilot from giving the EVA crewmember as much help as planned. The need to securely tie down equipment was effectively demonstrated by the loss of items during this flight. Also, the bulk of the umbilical in the cabin caused much more difficulty than training had indicated. The conclusion was that this length (50 ft or 15 m) was undesirable.

Gemini XI mission hardware revisions and objectives

Gemini XI promised to be a very crowded mission. Astronauts Pete Conrad and Dick Gordon would be attempting rendezvous and docking with an Agena on the first orbit to simulate the plans for the Apollo Command Module to dock with the Lunar Module on the first orbit. In addition, while performing on EVA, Gordon would attach a 98 ft (30 m) Dacron tether between the Gemini vehicle and the Agena to allow a slow spin, which would generate the first artificial gravity in space. He would also attempt to conduct more evaluation of the HHMU, using a 30 ft (9 m) umbilical and the ELSS (Figure 5.2.4G). Both astronauts would then try for a space altitude record using the boost capacity of the Agena.

The suit design for Gemini XI was almost identical to that of Gemini X. The minor changes that were introduced included redundant locks of the wrist disconnects, neck ring, and pressure sealing zipper, as well as a desiccant assembly added to the wrist-mounted suit pressure gauge.

With the exception of the addition of more hook fastener material to the outside surfaces of the ELSS chestpack, it was the same version as that used on Gemini X. However, due to the problems with the 50 ft (15 m) umbilical length experienced during Gemini X, the Gemini XI umbilical length was shortened to just over 30 ft (9 m). The umbilical carried the same oxygen, electrical, and nitrogen services as those provided during Gemini X.

The HHMU for this flight differed from that of Gemini X only in that the gas coupling was changed to a quick disconnect instead of the screw-on design in order to allow for easier attachment. This change was deemed necessary because the HHMU was to be stowed in the adapter section instead of the cabin and would have to be mated to the nitrogen hose with a pressurized glove.

Gemini XI was launched on September 12, 1966, and the umbilical EVA started just after 24 hours of elapsed flight time. Unlike Gemini X, no standup EVA preceded the umbilical EVA. Almost immediately, Gordon started experiencing difficulties mounting an external camera. Next, he had considerable difficulty in establishing and maintaining body positioning while he attached the tether between the Gemini vehicle and the Agena. These problems translated into a level of exertion that soon fatigued Gordon and overtaxed the ELSS's moisture and heat removal capabilities. Gordon experienced a significant amount of sweat in his eyes, particularly the right eye. In addition, Gordon may have also experienced a higher-than-desired carbon dioxide level due to his exertions. This phenomenon had been noted during ELSS testing at metabolic rate levels above design and could have contributed to high respiration rates and decreased ability to perform work.

The spacesuits performed excellently, the only minor anomaly being a cracked extravehicular sunvisor on Gordon's helmet. He had experienced difficulty installing it prior to hatch opening, and it is believed that the damage occurred at this time. However, no detriment to performance was noticed during the EVA.

Once again, as had been the case in Gemini IX-A, the ELSS chestpack's heat and moisture removal capabilities were exceeded by the astronaut's workload. Gordon encountered a high workload early in the EVA, prior to hatch opening, due to the difficulty in attaching the extravehicular visor, and this was followed by problems with the camera installation and problems maintaining body positioning during the tether installation. The limitations of gas cooling had been demonstrated once again.

No problems were encountered during EVA or ingress with the shorter (30 ft, 9 m) umbilical. The HHMU was not evaluated, due to the early termination of the EVA. It was significant that, although Gemini X's umbilical EVA had been relatively successful with no overheating problems, the difficulties encountered by Gordon on Gemini XI in performing the planned operations and the resultant canceling of EVA tasks demonstrated that much had still to be done to restrain the EVA crewmembers adequately for work in zero-*g*. Solving this latter problem would occupy the attention of EVA planners for Gemini XII.

Gemini XII mission changes and objectives

Gemini XII was the wrap-up of the Gemini program. It needed to provide answers to lingering concerns arising from other missions and to demonstrate the ability to reliably predict what astronauts could do successfully during EVA. Flight of the Air Force AMU was one of the initial objectives of this flight; however, the EVA difficulties experienced by Cernan and Gordon generated an air of conservatism among NASA management, and the AMU was deleted from the flight in September 1966. This left the EVA evaluations to be supported by an ELSS umbilical configuration (Figure 5.2.4G). A series of simple tasks whose metabolic cost could be easily measured were to be flown.

Evaluation of various types of body restraints, handholds, and workstations both on the Gemini vehicle adapter section, and on the Agena target docking adapter were included. There was sometimes a heated debate as to what types of gear should be evaluated. During the Gemini XII Flight Readiness Review, the use of stainless steel hook-and-loop fasteners, in place of the softer nylon material then favored, was proposed. To illustrate the holding power of the steel-based design, samples were passed around the room at the Flight Readiness Review. The Gemini Program Manager, Chuck Mathews, took a piece of the steel hook and brushed it against his pants leg. The pant fabric material was shredded and Mathews summarily dismissed the use of steel hook-and-loop fasteners on the all-too-real possibility of damage to the fabric of the pressure gloves or other soft portions of the suit.

Due to the technical focus of the Gemini XII, no maneuvering equipment was flown on this mission. Although the AMU had been deleted from the flight, and with it the need for high-temperature protection in the leg areas, this change came late in the flow. The EVA suit was similar to the one used for Gemini IX-A, except that the stainless steel wire cloth used on that flight was replaced with high-temperature nylon. Four layers of aluminized H-film and fiberglass cloth super-insulation were deleted from the suit legs. The coverlayer material lay-up was quilted to the first layer of micrometeoroid protective material and quilting was used over the torso area to help to prevent the type of tears and separation experienced by Cernan during Gemini IX-A. Also, the hose nozzle interconnects used to join together the supply and return hoses from the spacecraft ECS during EVA were equipped with clip-on locking clamps to provide redundancy of the locking tabs.

The Gemini XII ELSS chestpack was similar to the one used during Gemini XI, except that by Gemini XII every usable surface of the chestpack was covered with hook fasteners.

The umbilical for Gemini XII was similar to that for Gemini IX-A, with the exceptions that the tether was shortened; its breakout point was moved nearer to the end of the umbilical; and tether hooks were changed to designs more easily operated with pressurized gloves.

Launch occurred on November 11, 1966. At a little past 19 hours into the mission, Aldrin performed a standup EVA prior to the EVA on umbilical. Collins had done this and had few problems; both Cernan and Conrad had not, and each experienced a high level of difficulty. Rest periods were programmed into the standup EVA (Figure 5.6.10), and Aldrin's heart rate and respiration were

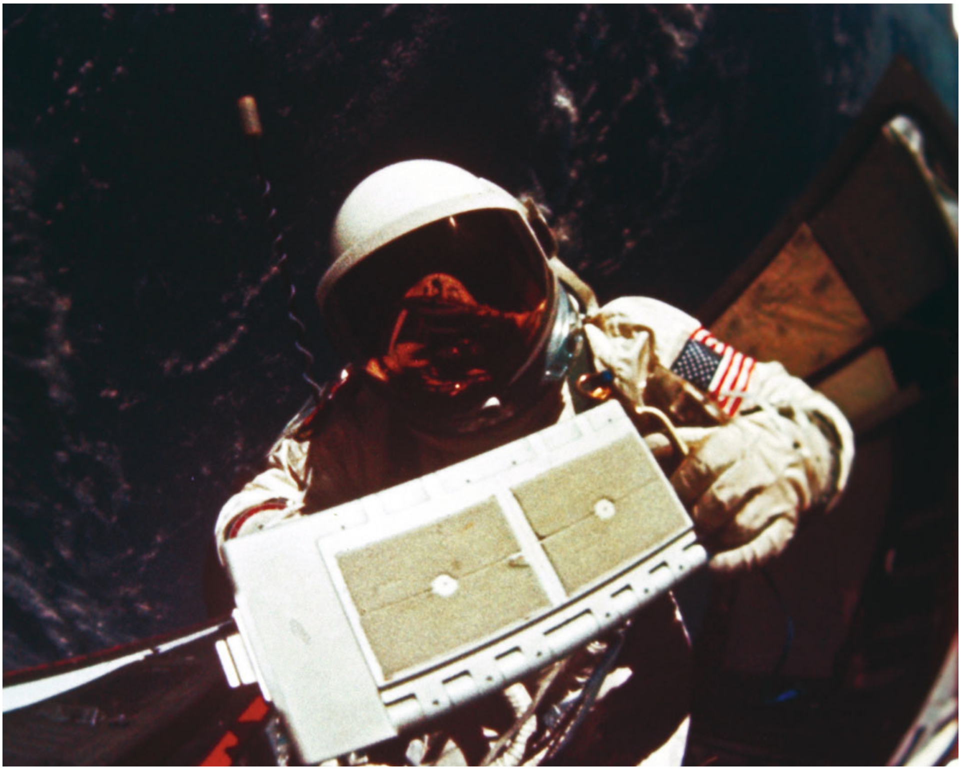


Figure 5.6.10. Astronaut Buzz Aldrin prepares camera for installation on spacecraft exterior (courtesy NASA).

Figure 5.6.11. Gemini XII EVA tests Aldrin's spacewalking techniques (courtesy NASA).

monitored in order to guard against overexertion. Everyone on the ground and in orbit was sensitized to the need to control workload. Aldrin had also been subjected to intensive underwater training prior to flight, in addition to ground training and zero-g airplane flights. All this attention paid off handsomely. The standup EVA lasted over 2 hours and went smoothly, paving the way for the crucial umbilical-based activity.

Preparations for umbilical EVA went smoothly, and the hatch was opened at a mission elapsed time near 43 hours, within 2 minutes of the planned time. Aldrin activated a micrometeoroid collection package on the Agena target vehicle. He then proceeded to the adapter section (Figure 5.6.11) where he successfully performed tasks, including making and breaking electrical and fluid connectors, torquing bolts, hooking and unhooking rings and hooks, and stripping patches of hook-and-loop fastener. He used so-called "golden slipper" foot restraints and waist tethers during these tasks. Aldrin then performed similar operations on another workstation located on the Agena target vehicle. He used a prototype of an Apollo torque wrench in addition to the other tools provided and performed some comparative operations using one, two, or no waist tethers before returning to the cabin and completing ingress. The total time of the EVA was 2 hours 6 minutes.

From the lack of in-flight comments and the results of post-flight inspections, the Gemini XII spacesuits were judged to have operated flawlessly.

As far as ELSS chestpack operation was concerned, Aldrin reported that during the EVA he was cool and his feet had been cold, but not to the point of discomfort. Pre-EVA planning had called for Aldrin to use the ''medium-plus-bypass'' flow mode for operations at the Agena, based on Gordon's Gemini XI experience. This mode would provide more dry oxygen for cooling and carbon dioxide washout than the ''high'' flow mode, albeit at the cost of extra spacecraft expendables. Aldrin, however, elected to remain in the ''high'' flow mode for the entire hatch-open period because of his sense of satisfactory cooling and the absence of visor fogging. He felt that he could have worked harder without taxing the life support system.

Aldrin also tried to detect any thrust forces caused by the 8 lb/h (3.6 kg/h) of overboard exhaust from the bottom of the chestpack. He reported that he could not detect any forces that might be caused by the ELSS. He also found no tendency to float up out of the hatch.

5.7 LESSONS LEARNED FROM GEMINI

Without question, the restrictions imposed by the limited mobility of the Gemini suit contributed to the difficulty in performing extravehicular tasks. The basic design of the suit was for intravehicular use. The so-called neutral position of the suit (i.e., the position that the suit would assume naturally when pressurized) was based on the need to operate the spacecraft controls. This meant that the suit was designed to be in a sitting position, as had the aviation ''get-me-down'' suits from which the Gemini suit had evolved. The arms of the suit were positioned to provide optimum access to the overhead controls. Any motion that moved the limbs out of these neutral positions required force on the part of the wearer, and to hold a position meant exertion over periods of time. The forces in the arms were particularly large when reaching above shoulder level. In general, the EVA crewmember could not perform sustained tasks below the waist or above the shoulder.

These compromises resulted in the need to learn to perform tasks differently from normal. For example, moving along a handrail required a side-to-side rather than a hand-over-hand motion. Sometimes, accommodations could be and were made, such as for Gemini IX-A, when the neutral position of the arms was adjusted to facilitate operation of the AMU controls.

The necessary addition of a thermal and micrometeoroid protective covering to virtually all of the suit added to mobility difficulties. Although the bulk was decreased from the initial Gemini IV configuration on later flights, it still contributed to the difficulty of movement while pressurized.

Gloves were perhaps the biggest area of difficulty. Basically, an intravehicular glove was modified by adding thermal and micrometeoroid protection. While short periods of grasping were acceptable, prolonged activity caused the EVA crewmember's hands to become very tired, and this had a noticeable effect on the ability to perform tasks. For example, on Gemini X Collins had to use both hands to hold a camera shutter release cable for the required 2-minute time exposure.

Those who worked closely with the suits during the Gemini program recommended that "priority efforts should be given to improving the mobility of space suits with emphasis on arm, shoulder, and glove mobility." There were also a host of findings related to the extravehicular life support system approach selected for Gemini. The most significant finding was that workloads encountered during EVA were much higher than anticipated, even based on high-fidelity ground training. Limitations of the gas-cooling approach were seen during Gemini IV, but by that time the system configuration for the remaining Gemini flights had been defined. It was not until Gemini IX-A that the inability to accurately predict and limit extravehicular workloads would drastically curtail EVA objectives for the remainder of the program.

The ELSS design points of 1,000 Btu/h (252 kcal/h), 1,400 Btu/h (353 kcal/h), and 2,000 Btu/h (504 kcal/h) (short-duration peak) were routinely exceeded during Gemini IX-A and Gemini XI, based on assessment of workload vs. heart rate data gathered pre flight. This condition has several negative aspects. Lack of sufficient heat rejection ultimately leads to profuse sweating, with the attendant danger of compromised vision caused by sweat in the eyes. The body's core temperature could also increase, which could ultimately lead to incapacitation. Another effect was graphically seen during Gemini XI, when Gordon's respiration rate rose sharply during sustained periods of high activity. This indicated a possible increase in helmet carbon dioxide levels. Since the ELSS relied on a fixed makeup flow of fresh oxygen, the amount of carbon dioxide that could be "washed out" of the helmet was also fixed. Assessments of Gordon's heart rate and respiration rate indicated that he was exceeding the 2,000 Btu/h (504 kcal/h) ELSS maximum design point and could therefore be inspiring higher than the desired maximum level of carbon dioxide.

Another problem encountered with the ELSS was its encumbrance, caused both by its size and location on the chest. The chest location limited the amount of effective two-handed operations by the EVA crewmember. Neither of these factors could have been reasonably avoided in the Gemini program, due to the need to don the system in the cabin while seated and to provide the EVA crewmember with a self-contained 30-minute oxygen supply. The size limitation drove the decision to keep the system fairly simple by using an ejector as the ventilation system prime mover and to make use of spacecraft oxygen and electrical services.

Umbilicals were deemed to be useful for EVA operations because they reduced the amount of gear required to be worn by the crewmember and were satisfactory for activities near the spacecraft. However, as Gemini X demonstrated, excess length presented entanglement and restowage difficulties.

Other findings included a significant number of recommendations made by those participating in the Gemini EVA program which had to do with assuring that the pre-flight training included underwater simulation and altitude chamber tests with the flight hardware, as well as providing adequate body restraints and workload control. Underwater, or neutral buoyancy, training has progressed and remains a major tool in determining the feasibility of proposed EVA tasks and equipment, as well as helping to develop relatively reliable timelines. However, the viscosity effects of the fluid medium and the unavoidable limitations posed by the effects of gravity on tools and other equipment which cannot be neutrally buoyed detract from a perfect zero-g simulation.

The HHMU, though its evaluations were limited, seemed to perform adequately and be worthy of further study.

The euphoric aura of Gemini IV had been quickly dispelled by the disappointing EVAs of Gemini IX-A and Gemini XI. The feasibility and utility of EVAs were not really proven until the conservative, methodical conduct of Gemini XII. However, the Gemini EVA lessons were not lost on the upcoming Apollo EVA program.

6

Apollo: Mankind starts the exploration of the Moon

The Apollo astronauts made it look so easy. The “lunar lope” and the riding around on their rovers seemed so effortless. It is difficult for those not involved in the actual day-to-day activities making up the planning and execution of such a complex undertaking to imagine the grueling effort by thousands that preceded the accomplishments of those lunar explorers. The film footage of the lunar astronauts shows only a few mishaps and falls as the Apollo extravehicular activity (EVA) crewmembers learned how to walk and maneuver on the Moon. The story of how the Apollo EVA system came into being had many more difficulties and stumbling blocks.

On May 25, 1961 when the U.S. President John Fitzgerald Kennedy announced the goal to go the Moon by the end of the decade, the U.S./Soviet space race gained a specific destination and timetable. There were no mission plans, no vehicles designed, or even an agreement on the technical approach for getting men to the Moon and back. The surface of the Moon could have been covered with dust fields of unknown depth. Effective spacesuit insulation that would protect the explorer from the Moon’s possible temperature range of $+250^{\circ}$F to -250°F ($+121^{\circ}$C to -156°C) was yet to be experimentally tested. The magnitude of the challenges associated with heat removal, mobility, reliability, and durability were yet to be realized.

In addition to the technical challenges, the very manner in which Apollo spacesuits were developed has proven to be a confusing subject. At the beginning, Apollo had two parallel suit efforts. One was the Apollo spacesuit program that was originally aimed at the early lunar missions. The other was NASA-funded development of advanced suits for more extensive lunar exploration missions that were to follow (Section 7.1). Two years into the Apollo suit system contract, NASA reorganized this into three separate suit system programs that aligned with Blocks I, II, and III of the Apollo spacecraft program. Block I suits were for the initial flights that had no Lunar Module and no extravehicular activity (EVA). As Gemini pressure suit development was already adequate to support Block I missions, the

K.S. Thomas and H.J. McMann, *U. S. Spacesuits*, Springer Praxis Books,
DOI 10.1007/978-1-4419-9566-7_6,

David Clark Company was awarded a Block I suit contract. Block II included EVA. A 1965 competition determined which manufacturer would provide Block II pressure suits. Block III was focused on later, longer duration missions. For this, more advanced EVA suit systems were planned (see Section 7.2).

Apollo spacesuits also have been confusing in that it is not one story but rather the stories of the many hundreds who were involved. Some participants have differing memories of the same events. This is understandable in that no one person was aware of all the events as they were unfolding. Additionally, salesmanship plays a role in industry and government. The art of salesmanship is to present the most positive case for the cause under promotion. However, this leaves biased trails.

The loss of Astronauts Chaffee, White, and Grissom in January 1967 resulted in yet another change in Apollo spacesuit direction. A NASA-wide safety review was conducted. The resulting safety improvements were incorporated into only one suit system to support both Apollo Blocks I and II. In yet another twist, the Block III missions were canceled. While there was evolution, one base suit system ultimately supported all the Apollo missions. The path through these overlapping and intertwined Apollo spacesuit stories is as follows.

6.1 BEFORE THE APOLLO SUIT PROGRAM (1960–1962)

The start of U.S. lunar and extravehicular space exploration efforts began two years before it was declared a national goal and a decade before man first set foot on the Moon. In the summer of 1959, the newly created NASA tasked its High Speed Flight Station (now Dryden Research Center near Edwards AFB, California) with creating initial requirements for spacesuits for lunar exploration in the not too distant future. By 1960, contractor organizations were engaged in lunar-specific efforts either by internal funding or under study contracts to NASA. In this period, before the creation of mission profiles and system requirements, any vision of a lunar suit system was potentially viable.

To understand the state of potential EVA suit technology before 1962, it may be helpful to reflect on some systems evaluated for potential manned lunar technologies. The Litton Mark I pressure suit (Figure 6.1.1A) pre-dated NASA and the Apollo program. Created in the 1950s by Dr. Sigfried Hansen, the Mark I was developed to facilitate real-time vacuum tube development inside a vacuum chamber. While it had far more mobility in most areas than the aviation-type pressure suits of the time, its mobility was still inadequate for lunar surface exploration and the suit system did not meet the dual purposes of launch/entry plus EVA requirements that came into being for the Apollo program.

Republic Aviation (Figure 6.1.1B) and Space General Corporation both offered suit/capsule concepts that could potentially replace the pressurized enclosure of the Lunar module and would provide the astronaut with friendlier support during all day EVAs.

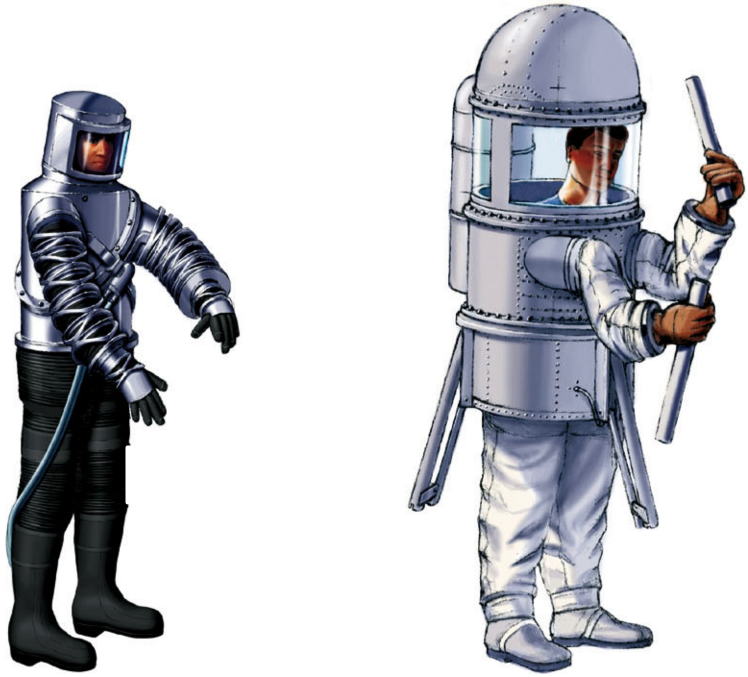
International Latex Corporation used the picture of their SPD-117 Mercury competition suit dressed in a mockup cover garment (Figure 6.1.1C) in advertising during the 1960–1961 timeframe. In 1961, International Latex worked with Garrett (now Honeywell) Corporation, as the portable life support provider, to offer a complete suit system that was presented as ready for lunar exploration. While such optimism seems at odds with the realities and challenges that waited in 1963–1964, without requirements and in the context of later experience these claims were potentially credible.

In September 1961, NASA's Crew Systems Division (CSD) at the Manned Spacecraft Center in Houston (now the Johnson Space Center) issued contracts for pressure suit studies that included preliminary prototypes. While these 1961 studies and the Gemini and Apollo programs that started in 1962 were not neatly linked, NASA's Mathew I. Radnofsky recounted in a 1966 interview that studies issued to Arrowhead Rubber, David Clark Company, International Latex (Figures 6.1.1D to 6.1.1F, respectively) and Protection Incorporated (configuration details unknown) produced the first "Apollo suits". Radnofsky was the Assistant Head of the Crew Equipment Branch and was directly responsible for both pressure suit and portable life support development on Apollo. Though the subsequent uses of all these suits are unknown, the David Clark preliminary study prototype saw use in conjunction with the Hamilton Standard Apollo competition proposal.

The David Clark prototype was a derivation of David Clark's X-15 suits. Like the X-15 model of the time, the David Clark prototype had a rear entry that was well liked in defense high-altitude pressure suits but had a zipper bulge that ran across the back when pressurized that could be uncomfortable in an on-the-back position. In comparison with the International Latex study prototype, the David Clark prototype had more conformal fit in the shoulders that provided inches more volume that would later prove to be of great benefit in the tight confines of the Apollo capsule. However, at this point in the process, the capsule volumes had not yet been established. The David Clark pressure suit could provide mobility in almost any direction with moderate effort by the standards of the time.

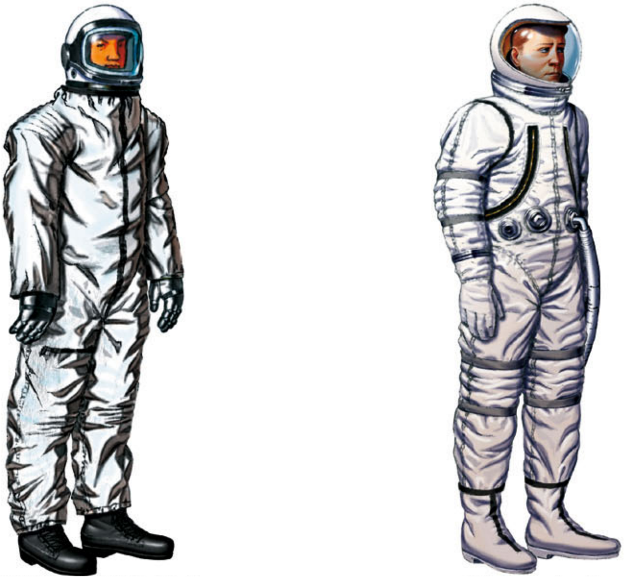
The mobility joints of the International Latex study prototype offered much lower effort mobility in specific directions as the joints pivoted around their two side restraints. What was potentially less apparent was that movement in other directions required great effort to achieve even limited mobility. The performance of the International Latex study suit sufficiently impressed NASA's Radnofsky that he later depicted this 1961 study round as where NASA selected International Latex as the Apollo pressure suit provider.

The formal competition for the Apollo spacesuit assembly (SSA) contract started on March 30, 1962. The only known competitor making a prototype specifically for the Apollo SSA competition was International Latex. NASA designated its prototype as the AX1L design (Figure 6.1.1G). The original Apollo SSA plan was to accomplish pressure suit development in three design iterations in 10 months. No one envisioned that it would require 26 design iterations, involve 4 space pressure suit design organizations, and take over 3 years before reaching the prototype base concept that would serve the first lunar missions.



(A) Litton Mark 1 vacuum tube development suit (1957)

(B) ''Capsule suit'' concepts, Republic Aviation's shown (1960)



(C) ILC SPD-117 with mockup EVA accessories (1960)

(D) Arrowhead study suit (12/61)

Figure 6.1.1. Pre–Apollo competition spacesuit development.

(E) David Clark study suit (12/61)

(a) With thermal cover (b) Without thermal cover (c) Without covers

(F) ILC study suit (12/61)

(a) Front view (b) Rear view

(G) ILC AX1L compeition suit (3/62)

6.2 THE ORIGINAL APOLLO SPACESUIT ASSEMBLY PROGRAM (1962–1964)

The Apollo spacesuit assembly (SSA) program started with NASA formulating and issuing a request for proposal. In the request, NASA provided its best estimates of the suit system requirements. One significant requirement was that the pressure suit had to support launch, re-entry, rescue, and extravehicular activity. The contractors or contractor teams then provided responses to those requirements in the form of their proposal submittals, which were due on March 30, 1962. NASA's selection of a proposal and subsequent contract negotiations established the initial program requirements. The field of competitors or competitor teams included

- Bendix Corporation's Eclipse-Pioneer Division of Litton Systems
- General Electric/B.F. Goodrich
- Grumman Aircraft/AiResearch Division of Garrett Corporation
- Hamilton Standard/David Clark Company
- International Latex/Republic Aviation/Westinghouse Corporation
- Ling–Temco–Vought
- North American Aviation
- Northrop Corporation's Space Laboratory.

In April, NASA decided it desired Hamilton Standard to be the portable life support system and overall suit system provider with International Latex Corporation being the pressure suit subsystem designer and fabricator. While both organizations pledged that they could and would work together, NASA's decision to split two contractor teams was described by many who participated as a "shotgun wedding". By aerospace paradigms, the Hamilton/International Latex negotiations should have taken days to reach a working agreement. It took 4 months. In the meantime, NASA was under pressure to provide Apollo suits to support vehicle preliminary development. To fill that need, NASA issued a direct contract to ILC for a very limited quantity of production versions of the ILC AX1L competition suit (Figure 6.1.1G). While this may have given mixed signals to International Latex and eroded the Hamilton position, the difficulties and delays in reaching a contract were probably more a clash of cultures.

By aircraft industry convention, the negotiations should have been simple. International Latex had submitted an Apollo proposal to NASA defining its schedule and cost in terms of man-hour estimates and rates to accomplish the designated tasks. Typically, in technically challenging or large programs, the contractor places an on-site representative engineer to act as an engineering and management liaison. Hamilton's chief negotiator was the Apollo SSA Manager Alfred E. Rhinehardt whose career was in aircraft industry management. Rhinehardt was a bright, frank, hard-driving engineer who had proven, within the conventions of the aircraft industry, to be a highly effective manager of challenging programs.

The chief negotiator for International Latex was its Vice President and Treasurer, D. Irving Obrow. Coming to the negotiations with a different experience base, to Obrow there were no conventions and everything was subject to negotiation. International Latex desired higher hourly rates than those proposed to NASA in the Apollo competition to compensate for lost advertising value from International Latex not being the prime contractor. Hamilton placing an engineer on site at the Specialty Products Division in Dover was not acceptable.

Until August, neither side relented. Hamilton's Rhinehardt and International Latex's Program Manager Leonard F. "Len" Shepard had grown to be incompatible. Finally, the impasse was broken by the escalation of negotiations to include Wallace O. "Wally" Heinze and William E. "Bill" Diefenderfer, the presidents of International Latex and Hamilton Standard, respectively. In the end, International Latex was granted its negotiation positions and mutually agreed to Roger D. Weatherbee replacing Rhinehardt as Hamilton SSA Manager. Weatherbee was an equally bright engineer-manager but brought a more reserved, polished, and gentlemanly style. These agreements included Republic Aviation continuing to be International Latex's subcontractor to provide anatomical data developed from Republic's pressure suit programs, technical support, and suit test facilities. In September, Hamilton was allowed to direct International Latex to proceed in advance of the first formal contract award that followed in October 1962.

Weatherbee was a quiet, gentlemanly engineer-manager who would principally concentrate his activities on NASA suit system support and Hamilton portable life support development. For over a year, cordial Bill and Wally correspondence would provide the principal means of resolving organizational differences on the Apollo SSA contract.

Even before the contract was formally awarded, the requirements for the Apollo program were becoming better understood and modified. An example of this was the Apollo extravehicular mission metabolic profile that drove subsequent requirements such as oxygen consumption, carbon dioxide removal, heat removal, battery size, and, ultimately, systems weight and volume. In its request for proposal, NASA originally set the Apollo metabolic requirements at 11,300 Btu/day (2,848 kcal/day). Using this as a basis, the winning Apollo spacesuit proposal was based on an average rate during EVA of 500 Btu/h (126 kcal/h) with no peak metabolic requirement. By the time the Apollo contract was issued, NASA had already gained greater insight into the metabolic requirements unique to EVA. The requirement was increased to 930 Btu/h (234 kcal/h) average, with a 1,600 Btu/h (403 kcal/h) peak metabolic load. A year into the program, manned testing would cause Apollo suit system metabolic requirements to be increased again to the final specifications of 1,204 Btu/h average and a 2,000 Btu/h (504 kcal/h) peak metabolic load. Each increase caused redesign. The final increase required invention and development, as it was beyond life support technologies available in 1962.

In addition to the problems encountered by the life support system, Apollo pressure suit development also had technical challenges. Apollo was the first U.S. space program to take a promising suit prototype and develop it into a suit system that would reliably and effectively meet a space application. Lacking past experience, no one in the process knew the magnitude of the challenges that were ahead. Adding to the difficulties was that there were no clear and quantifiable suit mobility requirements other than being able to rise from an on-the-back position after a fall. The pressure suit mobility requirements in the first year of Apollo were principally being defined as adequate to meet the mission requirements by the NASA evaluators. The detailed mission activities, which were the real drivers for requirements definition, had yet to be developed. Another development barrier was the subjective judgment of "adequate" or "inadequate" that could vary significantly from one individual to the next.

There were actually two suit activities at the outset. In parallel to flight suit system development for Apollo, there was also the need for an initial training suit fleet. The first training suit fleet was based on the International Latex competition prototype suit, NASA designation AX1L (Figure 6.1.1G). These first Apollo suits were contractually identified model SPD-143 training suits (Figure 6.2.1A). Twenty SPD-143 suits were made. Like the International Latex prototypes that had preceded it, the SPD-143 was a contrast of medium olive fabric sections and black molded rubber convolute mobility joints. The SPD-143 suits differed from the AX1L suit in that the SPD-143 helmet lacked an eye protection sunvisor and the SPD-143 torso featured circumferential torso restraints. The torso restraints may have reflected lessons learned from NASA testing of directly purchased AX1L suits before the formal issuing of the Apollo contract. To add confusion to this period, International Latex also preferred to call the SPD-143 model "AX1L" suits.

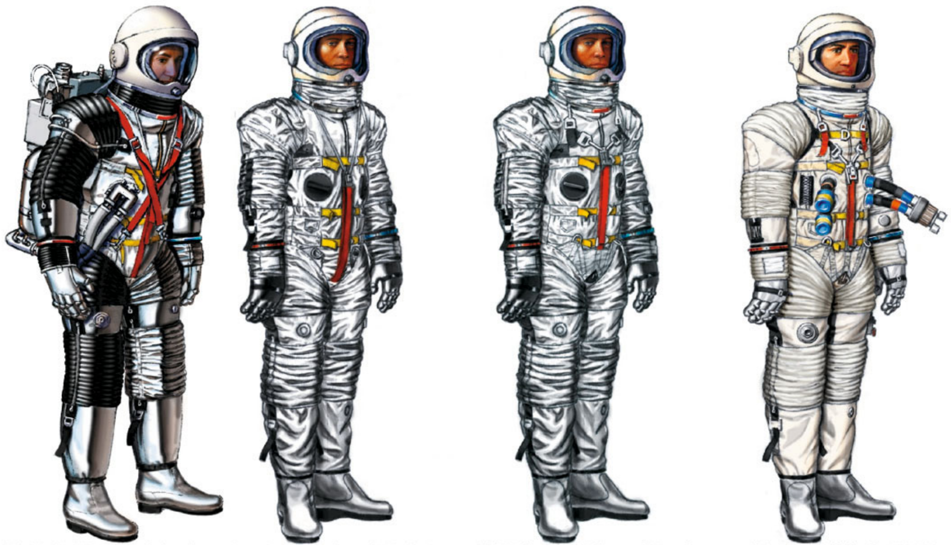
The delivery of the first four SPD-143 suits in November 1962 brought to the forefront the cultural differences between Hamilton and International Latex and the quality complexities of space products. NASA did and still does invoke a quality requirement called "trace" on spacesuit items that requires a paper trail on all materials going into the suit from raw stock to finished detail parts validating the materials and processes used meet all requirements. This allows readily available information if a part fails or appears to be prematurely degrading. This is important because commercial industry generally consumes dozens of test articles in a certification process. Due to the expense of space program unique items, space programs usually consume only one unit in the flight certification. To assure safety, more stringent quality controls are used.

In the receiving inspection of SPD-143 serial number (S/N) 001 to S/N 004, thread used in sewing of the garments lacked trace documentation. The precise spools of thread used could not be identified. To allow the delivery of the S/N 002 to S/N 004 suits, S/N 001 was tested to ultimate pressure requirements. Since S/N 001 did not fail, the test data allowed the acceptance of S/N 002 to S/N 004. However, this left the question, was S/N 001 still acceptable for human pressurized use after ultimate load testing? The requirements for ultimate loads are simple. An item either catastrophically fails or it does not. In going to an ultimate load, structural degradation and permanent dimensional changes are acceptable. International Latex viewed S/N 001 as acceptable based on it not failing a worst case requirement. This reflected a commercial industry engineering judgment that S/N 001 probably would function properly without endangering anyone. Hamilton viewed S/N 001 as unacceptable because it was reasonable to expect it may have experienced degradation in physical properties. Hamilton was keenly aware of the stringent statistical

(A) ILC SPD-143 training suits (10/62-9/63

(a) With EVA mockups

(b) and (c) Rear and front views



(B) ILC AX1H suit and first HS PLSS backpack (8/63)

(a) EVA system

(b) IVA system

(C) ILC AX2H second-design suits (9/63 and 10/63)

(D) ILC original AX3H configuration (2/64)

Figure 6.2.1. Original development period suits.

reliability requirements for delivered items imposed by the NASA contract. After much debate and delay, S/N 001 was modified to become a vent pressure engineering aid in late 1963. The above is but one example of the significant differences in engineering culture between International Latex and Hamilton Standard, illustrative of the differences between how "softgoods" and "hardgoods" were addressed technically.

S/N 004 went to manned testing at Republic Aviation. While potential mitigating factors such as forthcoming suit mobility and ventilation development improvements were still unknown, this early manned testing provided a strong indication that Apollo metabolic requirements would significantly increase.

The first new Apollo pressure suit development was pressure gloves. This was intermixed with SPD-143 production. SPD-143 suit production started with AX1L-type gloves. AX1L gloves were leather with sewn-on restraint webbing to bring about a more conformal shape and share the pressure load. The glove fit tightly at the wrist for limited wrist mobility and required unzipping a zipper to don or remove the glove.

Soon after the start of training suit production, International Latex introduced iterative glove designs for evaluation with SPD-143 deliveries. By December 1962, the prototype of the 1963–1964 Apollo glove had been fabricated. This was incorporated into SPD-143 production in the spring of 1963. For the design, a new durable glove bladder was created by use of a woven nylon tricot glove-shaped sock being dip-impregnated and coated with a neoprene/natural rubber mixture (Figure 6.2.2, left). In the fingers, the bladders were also the restraint mechanism. In addition, the fingers had easement (extra material) formed into the backs of the fingers to allow the fingers to bend with minimum compression of the interior volume, which reduced grasping effort (Figure 6.2.2, right). A stainless steel conduit started at the side of the thumb, went between the thumb and pointer finger, and ran across the palm. This was integrated into the glove bladder and

Figure 6.2.2. 1963–1964 Apollo pressure glove views (courtesy ILC Dover LP).

was part of a multiaxis restraint system and doubled as the rigid, palm-side part of the palm bar system to prevent ballooning of the palm area. A metallic cable attached to the wrist disconnect, ran up the wrist, through the stainless steel conduit in the palm, down the wrist on the other side, and attached to the other side of the wrist disconnect. The wrist portion of the glove featured a convoluted, semi-constant volume joint (Figure 6.2.2, left). The palm area of the glove had an outer restraint assembly that looked like a fingerless glove. This attached to an abrasion and thermal protective wrist cover (Figure 6.2.2, center and right). For this glove system, International Latex developed techniques for dip-molding fabric-and-cord-reinforced gloves over forms that ultimately created repetitively accurate moldings from hand casts of the individual Apollo astronauts. Except for palm bar and wrist improvements introduced in 1965, this was the glove design used in the early Apollo missions with a derivation supporting the later Apollo missions and Skylab.

The next new area of Apollo spacesuit development also came during production of the SPD-143. This was the beginning of thermal overgarment prototyping and evaluations. In the first 5 years of the Apollo program, the approach to thermal and micrometeoroid protection was the use of separate overgarments that were put on like ski pants and coat over the pressure suit assembly before leaving the spacecraft. Thermal garment development started with the creation of donning evaluation mockups and then progressed to prototype units that could be evaluated for actual thermal protection capabilities. In this initial attempt, International Latex exclusively performed the development. The garments were first tested at Hamilton, and then forwarded to NASA for further evaluation. The garments were found to be inadequate for both thermal and particle impingement protection. As a result, Hamilton assumed the engineering lead in overgarments. The next generation of development overgarments that would eventually be tested in 1964 was many times thicker.

SPD-143 suits were used for early evaluations of the Lunar Excursion Module (later changed to Lunar Module) and the Command Module. This included interface studies with the portable life support system facsimiles (Figure 6.2.3). These evaluations were carried out in late 1962 and early 1963. Because of these evaluations, the portable life support shape and size was changed three times in the first 6 months. The changes were driven by vehicle hatch sizes and internal clearances. Command Module testing identified SPD-143 shoulder width as an issue with operating controls when the three suited crewmembers were in their couches for liftoff and entry. However, it was recognized that the SPD-143 shoulders were of the preceding AX1L design and did not meet Apollo suit width requirements. In addition, the Command Module volume requirements were based on the preliminary spacecraft design. There were expectations by some that the shoulder width allowance might increase in the Command Module's final design.

In October 1962, International Latex had committed to a five pressure suit development schedule. Two prototypes were to complete mobility development by April 1963. One prototype with thermal/micrometeoroid cover garments was delivered by June to support initial thermal and suit system testing. By July 1963,

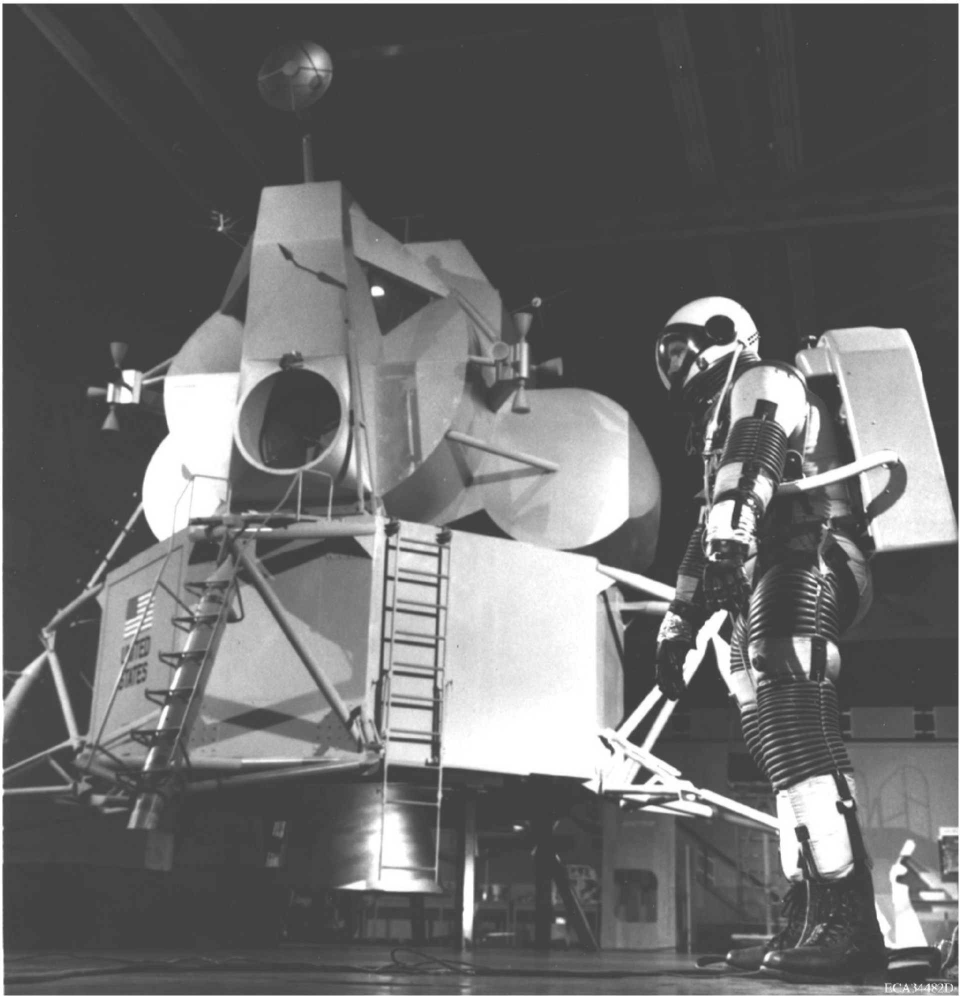


Figure 6.2.3. 1963 lunar excursion module evaluation (courtesy Hamilton Sundstrand).

two more refined prototypes with cover garments were provided. These last two prototypes, mated to portable life support systems, would support complete suit system evaluations by August 1963. In retrospect, the five prototypes in 10 months reflected the fledgling space community's underestimation of the challenge of achieving adequate EVA mobility.

The first pressure suit issues were not performance related, but were concerned with cost and schedule. The first prototype defining a new Apollo mobility design was originally expected in April 1963. In May, International Latex informed Hamilton of an expected overrun equal to 44% of their contract. Without suits to test, cost and schedule probably received greater management attention than they otherwise might have, providing distractions that may have further served to slow suit development.

In July 1963, the first two AX1H-type prototype suits arrived at Hamilton. With these deliveries, the definition of a delivery became a topic of discussion. One of the two prototypes was created from an already delivered SPD-143 training suit that was incrementally modified for mobility improvement. While this produced a twin to the AX1H-021 (Figure 6.2.1B), which was an entirely new build that soon followed, Hamilton and NASA were not inclined to count the SPD-143 retrofit prototype as a program suit delivery. Even if it were counted, three more prototypes were to have been delivered by August 1963. That milestone was reached in February 1964 with another suit development cost overrun being announced in the preceding November. However, there were reasons for these difficulties.

While International Latex was a major corporation with significant manufacturing resources and had been a competitor in the X-15 and Mercury suit competitions, its Specialties Product Division had produced only infrequent pressure suit prototypes prior to the Apollo contract. Simultaneously undertaking production of 20 SPD-143 training suits in 8 months while developing a new Apollo glove, helmet, and torso assembly in 10 months coupled with becoming acclimated with government contracting requirements probably should have made such delays and development overruns something to be expected.

The AX1H configuration differed from the SPD-143 training suits in that it incorporated a two-cable shoulder joint, had fabric abrasion covers over all the mobility joints, featured a torso assembly with aluminized outer surfaces to permit thermal evaluation, and used a new design helmet. The helmet featured a pressure visor that retracted into the helmet shell in the up position for protection when not in use. One's ability to bend the inflated suit into a seated position was provided by a torso drawstrap with cables that attached to the suit neckring and brief. The drawstrap wrapped around pullies at both ends to act like a block and tackle to reduce the effort for reaching a seated position. Non-lacing, slip-in leather boots were added for improved don/doff capability. Hamilton provided the communications and bio-medical data relay system and a Hamilton-designed, Air-Lock-manufactured, "dual-port" life support connector system for the suit. The dual-port connector permitted attachment of the oxygen inlet and exhaust in one movement.

AX1H torso mobility development started with the modification of an SPD-143 suit. International Latex replaced one mobility element at a time (Figure 6.2.4) allowing it to be comparatively tested against the unmodified side that represented AX1L mobility technology. This made International Latex confident that significant mobility improvements had been accomplished.

The first new-design build of the Apollo SSA program was then started. The first new-design suit prototype was designated the AX1H-021 by NASA. In the Gemini and Apollo programs, the assigning of NASA designations to suit configurations was not a formal configuration management system directed by NASA headquarters. Rather, it was an informal function left to a quiet, thoughtful, well-respected NASA engineer named Charles C. Lutz to provide a trail and

Figure 6.2.4. AX1H incremental development (courtesy ILC Dover in Fredrica, DE).

commonly accepted identifiers to what otherwise would have been chaos. The "A" in AX1H-021 stood for Apollo program. The "X" was for experimental prototype. A "-" (dash) in that location meant the suit was a production unit. The "1H" reflected the first design of the Hamilton-to-NASA contract. The "021" identified it as the 21st suit under the Hamilton/Apollo program.

The AX1H-021 suit was first tested at Hamilton. At that point in the program, there were no quantitative ways of measuring mobility element resistance to movement or quantitative requirements for mobility. "Reasonable effort" to move or hold a position was the principal criterion. The judgment of what was a reasonable and acceptable level for bruising was subjective to the individual evaluator. To have a basis of quantifying Apollo mobility improvement, Hamilton comparatively tested the AX1H against an SPD-143 suit (Figure 6.2.5). Mobility progress was

Figure 6.2.5. Comparative evaluation of AX1H and SPD-143 (courtesy Hamilton Sundstrand, Windsor Locks, CT).

questioned and the shoulder width was found to be greater than the specification (Figure 6.2.6) (i.e., too wide), but the suit was otherwise found acceptable. Given the method used in development, International Latex had difficulty understanding Hamilton's mobility findings. With shoulder width, International Latex felt there was additional Command Module volume available and anticipated the shoulder width allowance to change. The AX1H-021 suit was then sent for its NASA debut where the suit experienced an entry zipper failure. The suit was sent to International Latex, repaired, and returned to NASA for evaluation where NASA objected to the stance of the suit when pressurized but not the mobility or shoulder width. While this left the need for further development in question, Hamilton directed mobility development to continue into the AX2H configuration.

Concurrent with the delivery of the AX1H suit, Hamilton was ready for manned testing of the first Apollo portable life support system and backup emergency oxygen supply. Manned testing was conducted with the pre-AX1H prototype that started as an SPD-143. The portable life support system was found to meet the then current contract performance requirements of 930 Btu/h (234 kcal/h) average, 1,200 Btu/h (302 kcal/h) maximum. The system utilized gas cooling for heat removal and was capable of sustaining an astronaut for up to 4 hours while working at the average metabolic rate. The system contained an oxygen tank, an oxygen regulator, a fan, a lithium hydroxide (LiOH) canister for carbon dioxide removal, an elbow-shaped water separator, a wick-type water boiler with a temperature control valve, and a battery. The water boiler removed the heat load imposed on the life support system due to metabolic rate, external heat leak, and equipment heat loads. In this system,

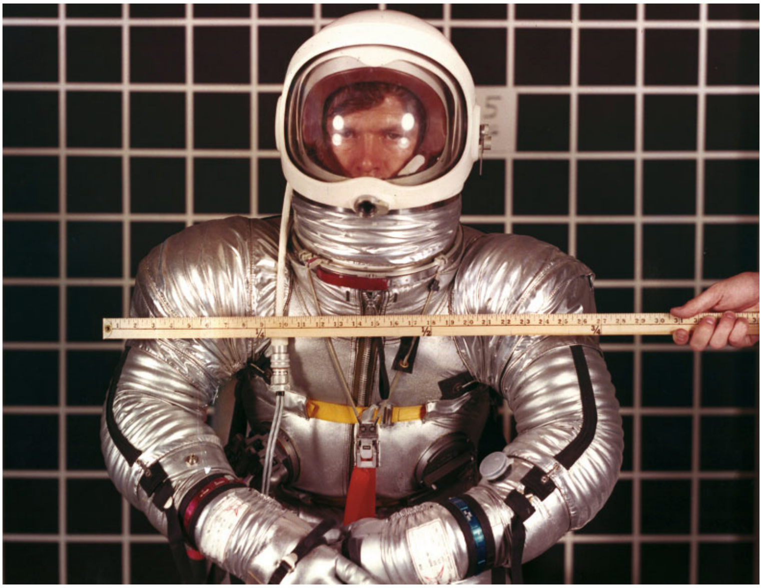


Figure 6.2.6. AX1H-021 shoulder width measurement (courtesy Hamilton Sundstrand, Windsor Locks, CT).

ventilation gas carried the heat from the points of generation to the heat rejection device, which was the water boiler (see Figure 3.2.1 and discussion in Section 6.2).

However, this manned testing (Figure 6.2.7) confirmed that the 930 Btu/h requirement was not sufficient for projected needs on the lunar surface mission. More importantly, the astronauts would experience unacceptable levels of dehydration because heavy sweating was required for removal of body heat. These findings made the first model of the portable life support system immediately obsolete. Additionally, the new requirements were beyond the capabilities of a system based on heat removal by circulating cool ventilating gas. Development and demonstration of a satisfactory system in manned testing would take another two years.

Backup life support for the Apollo suit system was provided by the emergency oxygen system. This device contained an oxygen bottle that provided five minutes of purge flow. The first design of the emergency oxygen system also met the program requirements but soon became obsolete in the drive to find more volume and weight savings to offset the next generation of Apollo portable life support systems.

In early September 1964, the first of two AX2H suits, S/N 023, was delivered (Figure 6.2.1C). The AX2H-022 suit was delivered in October and was a prototype training configuration featuring white nylon outer fabrics to facilitate cleaning and reduce manufacturing cost. For the AX2H series, the neckring restraint cable attachments and the torso compression strap were revised into separate assemblies. The stance of the AX1H design had been corrected. The AX2H design had the same base mobility architecture as the AX1H, but the shoulder width had been reduced, although still not within specifications. The reduction of shoulder width had

Figure 6.2.7. First AX1H suit and life support testing (courtesy Hamilton Sundstrand).

resulted in a slight reduction of shoulder mobility; however, some lower arm mobility had been gained.

While the management of International Latex had not yet accepted mobility as an issue, it was responding to cost. This was probably in anticipation of a forthcoming contract for 38 new-configuration training suits. International Latex internally funded a prototype where the life support system's (LSS) connection/disconnection was in the umbilical that attached to the suit by a short hose. The LSS connectors were inexpensive, off-the-shelf, commercial units. As the Apollo program LSS connectors were custom-designed for the Apollo program and highly expensive, this had significant potential to reduce program costs while make the donning and doffing process for EVA much easier as the connections would easily be in sight. From a distance, this suit looked like the AX3H that followed. However, up close, the use of hardware store bolts and nuts made a noticeable aesthetic difference. The demonstration of this prototype to NASA probably resulted in the direction to Hamilton for the AX3H configuration features.

Pressure suit mobility became a significant program issue in November 1963 with the test of an AX2H suit in reduced lunar gravity simulation. Equipped with a volumetric representation of the then current portable life support system shape, subjects were unable to rise from an on-the-back position. This was one of the few definitive initial Apollo mobility requirements. While initial life support system shapes were designed to make it easier to meet this requirement, later iterations of the shape reduced the front-to-back dimension to facilitate movement through vehicle hatches. This helped reduce vehicle weight but worked against the ability of astronauts to roll over and right themselves from an on-the-back position. NASA judged this configuration to be a failure to meet contract requirements, which is serious in the aerospace industry.

Based on the mobility evaluations of the AX2H configuration, mobility development was extended to a third design iteration, the AX3H, being delivered in February 1964. The total number of prototypes was reduced from five to four. Additionally, downward visibility of both the AX1H and AX2H helmets was found to be unacceptable. NASA directed helmet redesign to correct this condition.

On February 20, 1964, the AX3H-024 prototype suit (Figures 6.2.1D and 6.2.8) was delivered from International Latex to Hamilton for testing. The AX3H-024 suit featured "training white" outer fabrics. As originally built, the AX3H-024 featured an International Latex concept for life support connection, improvements to the torso compression strap system, additional torso-sizing looptape (nine sets—two on the front, seven on the back), an International Latex-redesigned helmet with improved downward visibility, and an improved pressure visor activation mechanism. Per unit suit cost was an issue in this period as more than a hundred suits were expected to be produced to support development, training, and finally the lunar missions. International Latex saw life support connectors as an area of potential cost savings. The AX1H and AX2H suits used a system specifically designed for Apollo that simultaneously connected the life support inlet and exhaust. These were expensive as they were custom-made to exacting tolerances and had very limited order quantities. International Latex developed a concept where short life support umbilicals allowed life support connection to occur in the umbilical within the wearer's sight. This allowed evaluation and potential implementation of off-the-shelf commercial connectors into the program. The AX3H shoulder and arm design were refinements of the AX1H and AX2H designs that still did not meet the Apollo shoulder width requirement. Mobility did not improve significantly.

The AX3H-024 suit was sent to Grumman for a Lunar Module progress review and astronaut evaluation in March. The suit soon experienced a suit-to-umbilical-interface failure. The repaired umbilical attachment failed a second time causing the suit to decompress while under test with a Grumman suit subject. NASA astronauts were also part of the evaluation. The astronaut ratings were unanimously unfavorable. To show his dissatisfaction with the AX3H suit, Astronaut Gordon Cooper

Figure 6.2.8. Original configuration AX3H suit (courtesy Hamilton Sundstrand).

elected to announce to an assembly of hundreds that "I would not go to the Moon in that suit," adding that he much preferred his Gemini suit. This sent shock waves through the Apollo SSA program and caused a flurry of activity (see Section 6.5).

6.3 THE POSSIBILITY OF FLYING THE "LUNAR LEAPER" (1963–1965)

NASA's first EVA system efforts were not limited to the space pressure suit and portable life support but included transportation systems. Before the mid 1960s, the lunar surface was an unknown. The surface could have been rocks, hills, and steep mountains. Such a terrain would have been unsuitable for wheeled vehicles such as the Lunar Rover concept. As a backup approach to the rover, NASA funded development of a "rocket pack" system to permit lunar astronauts to fly over otherwise impassable terrain. In addition to a lunar flying propulsion system, NASA also desired an orbital man-maneuvering capability. NASA issued a request for proposal based on a system to serve both orbital zero-g applications and lunar surface missions. The system requirements for the study contract encompassed the total system including an inertial guidance system and bipropellant (two-constituent) system where the oxygen and fuel are stored in separate vessels.

In 1963, Hamilton Standard won the feasibility study contract based in part on its having both inertial guidance and space reaction engine design and manufacturing capability. The study was officially named the propulsion and locomotion pack or PAL-Pack. However, the effort soon gained the nickname "Lunar Leaper". The resulting study was delivered in 1964 and recommended that separate Lunar and zero-g systems be developed due to weight and volume restrictions. The study additionally recommended the use of a monopropellant propulsion system using hydrazine as the fuel. Hydrazine acts as a monopropellant since it spontaneously decomposes when placed in contact with certain platinum-based catalysts. Thus, the use of hydrazine requires only one storage tank and one set of plumbing. Bipropellant propulsion systems require two storage systems, two metering systems, a mixing system, and usually an ignition system. The study identified that if a bipropellant were used, the recommended fuel would be a hypergolic (auto-igniting upon contact) mixture of monomethyl hydrazine and dinitrogen tetroxide (MMH/N_2O_4) and the propulsion system would have two types of thrusters, a 35 lb (16 kg) and a 20.5 lb (9.23 kg) combination unit being used in four clusters. The study submittal included a full-scale mockup of the PAL-Pack system (Figure 6.3.1, left).

NASA's response to the report was favorable, but the agency selected the more proven bipropellant technology. Hamilton won the subsequent development and production contract for a lunar-specific system in the summer of 1964. While the official program name was the one-man locomotion system, the most commonly used name remained the Lunar Leaper. The manual flight controls (Figure 6.3.1, right) were to provide electronic input to the avionics package that utilized a "strap-down" gyroscopic control system specially designed for the $\frac{1}{6}g$ lunar application. The "strap-down" system was one of the pioneer inventions of the time. The system obtained its movement reading from the amount of force the gyroscopes reacted to on their fixed mounting systems, thus eliminating weight and technical complications associated with mounting the gyroscopes in bearing-equipped gimbals. This technique would quickly become a standard approach in space guidance systems that continues to the present.

In early 1965, the final one-man locomotion system/Lunar Leaper was in the component and subsystem testing phase (first of four phases) of certification when the program was canceled due to the findings from lunar probes that lunar surfaces were acceptable for the rover concept, making the one-man locomotion system unnecessary. While limited information has survived about this classified program, the right-side of Figure 6.3.1 shows the fold-up, compact storing and operational features of the final one-man locomotion system design.

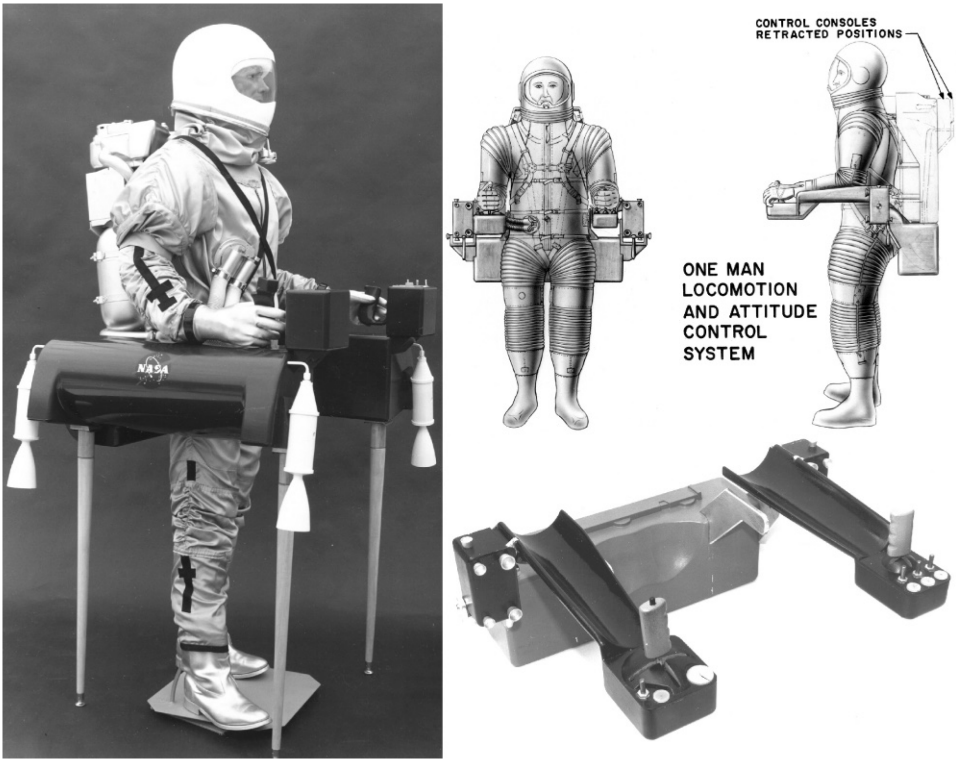


Figure 6.3.1. 1964 Lunar Leaper mockup and 1965 incomplete prototype (courtesy Hamilton Sundstrand).

6.4 THE LUNAR ROVING VEHICLE (1963–1972)

In the first two years, Lunar Roving Vehicle (LRV) development paralleled the "Lunar Leaper" and could have been canceled if the lunar terrain had proven unsuitable for such a vehicle. Unlike the Apollo suit system and manned maneuvering unit contracts, the LRV program progressed through a more normal flow of feasibility, development, and "production". Feasibility contracts were awarded to Bendix Corporation and Boeing Aerospace. Boeing subsequently won the development contract for the LRV or "rover".

In early 1965, the LRV program was ready for initial interface studies. An Apollo "late" A-4H training suit was initially provided for evaluation with Boeing's initial evaluation mockup (Figure 6.4.1). This was replaced by a pair of Hamilton "mobility suits" with mockup EVA accessories. While the preliminary design was far from the final product that was used on the Moon (Figure 6.7.14), this reflects the development and progress that had been made.

Three rovers were driven on the Moon. Each rover was used on three exploration sorties; one per day over the 3-day course of each mission. The Lunar

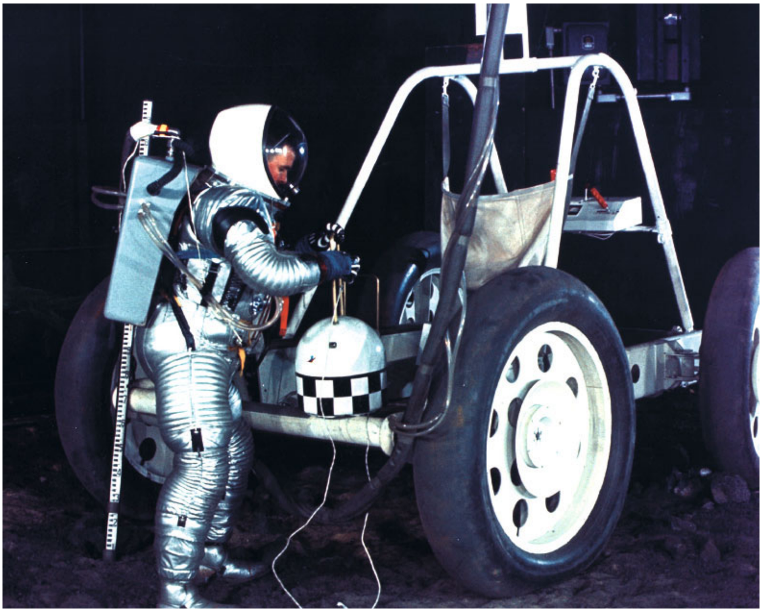


Figure 6.4.1. Late A-4H suit in rover development (courtesy Hamilton Sundstrand).

Roving Vehicle had a mass of 463 lb (210 kg) and was designed to hold a payload of an additional 1,080 lb (490 kg) on the lunar surface. The frame was made of welded aluminum alloy tubing. The chassis was hinged in the center so it could be compactly folded up for the journey to the Moon. The rover had two side-by-side foldable seats made of tubular aluminum with nylon webbing and aluminum floor panels. The wheelbase was 7.6 feet (2.3 m). The vehicle length was 10.2 feet (3.1 m). The maximum height when unfolded and seats deployed was 3.7 feet (1.14 m).

Each wheel featured a spun aluminum hub that contained its own 0.25 hp (186 watt) DC electric drive motor and a mechanical brake. The motors were capable of up to 10,000 rpm and attached to an 80 : 1 drive reduction. This provided four-wheel drive without the complications of axles and drive shafts. The wheels were 32 inches (81.8 cm) in diameter and featured 9 inch wide (23 cm) tires made of zinc-coated woven 0.033-inch diameter (0.083 cm) steel strands attached to the rim and disks of formed aluminum. Titanium chevrons covered 50% of the contact area to provide traction. Inside the tire was a 25.5-inch diameter (64.8 cm) bump stop frame to protect the hub. Dust guards were mounted above the wheels.

The rover had front and rear steering motors that allowed both sets of wheels to turn in opposite directions. Controlled by a T-shaped steering bar in place of a steering wheel, front and rear steering gave the rover a turning radius of only 10.2 feet (3.1 m) to maneuver around obstacles.

Two non-rechargeable, 121 amp-hour, 36-volt silver–zinc potassium hydroxide batteries provided power. This battery system powered not only the drive and steering motors but also supported the communications relay unit and the TV camera. Passive thermal controls kept the batteries within an optimal temperature range.

The control and display modules were situated in front of the T-bar control handle and gave information on the speed, heading, pitch, and power and temperature levels. Navigation was based on continuously recording direction and distance through use of a directional gyro and odometer and inputting these data to a computer, which would keep track of the overall direction and distance traveled. For further information on the rover, see the Apollo 15–17 discussions in Section 6.7.

6.5 SUIT SYSTEM RECOVERY THROUGH REPLAN AND INVENTION (1963–1965)

The Apollo program was a national priority. Failing was not an option. The results of the original Apollo suit system contract proved to have been principally a learning experience. The first 17 months of the program resulted in neither an acceptable pressure suit nor an adequate portable life support system. Life support development was the area first recognized as being deficient to support Apollo's needs and was the first to receive attention. This was soon followed by recognition of pressure suit limitations. This proved to be the greater challenge causing multiple parallel pressure suit efforts. Ultimately, the base pressure suit technologies and provider for the first lunar surface missions were determined by competition.

Developing the lunar "backpack" (1963–1965)

While the aluminized Mylar and spacer cloth insulation developed for the NASA programs could protect astronauts from the extreme temperatures of space, this left another thermal problem: the removal of metabolic heat retained within the suit. To avoid dehydration, heat had to be removed from the body with minimal perspiration. In addition, the heat had to be effectively and reliably rejected from the life support system to space.

Unlike Earth where there is an atmosphere to accept the transfer of heat, space is a vacuum. An effective way to dissipate heat to space is by using the heat transfer dynamics from the evaporation of water. One way to do this is to use low pressure (e.g., the vacuum of space) for evaporation. The water is "boiled" by exposing it to controlled low pressure. However, the 1962 development of the water boiler for the gas-cooled portable life support system pointed out the many complexities associated with wick-type water boilers. One problem with water boilers arises if the pressure is allowed to degrade to vacuum conditions. Water will reach a state that is called the triple point where liquid, ice, and vapor co-exist. If ice buildup occurs, the boiler does not operate effectively. Thus, Hamilton continued company-sponsored research programs to investigate other methods that included the feasibility of controlled evaporative cooling by water sublimation to vacuum through a porous metallic plate having microscopic holes.

When preliminary manned testing at the beginning of 1963 indicated that the heat load requirements for the Apollo life support backpack might increase, Hamilton started internal funding of space heat rejection research and development. In the fall of 1963 when the requirement was formally increased, a technically credible alternative to the water boiler was proven in theory. This was a "space sublimator" (U.S. patent No. 3,170,303, inventors George C. Rannenberg and John S. Lovell). The beauty of the sublimator lay in its simplicity and self-regulating characteristics. The water boiler required a back pressure control valve that responded perfectly to conditions, otherwise loss of function or damage might occur. The Apollo Command Module environmental control system contained perhaps the most sophisticated and complex approach to a water boiler and associated mechanical and electronic control system that could be imagined. The sublimator, by comparison, has a simple metallic plate constructed to provide specially sized microscopic pores allowing water to freeze in the plate without damaging the plate. As the water in the sublimator picks up body and system heat, the ice in the plate thaws allowing water to pass through the plate and evaporate to space, removing heat from the suit system in the process. When no more heat is available for removal, the water in the plate cools and refreezes, sealing the plate. This provides a self-regulating system with no moving parts. The sublimator is not without its drawbacks, however. The microscopic nature of the pores in the welded-in-place plates makes the sublimator susceptible to clogging and eventual failure; therefore, the plate had to be sized to accommodate the gradual accumulation of contamination during its pre-lunar use to assure adequate capability for the required duration on the Moon. Making the porous plates replaceable was a lesson learned and utilized for the Shuttle.

The development to obtain the efficiencies needed to meet the Apollo weight and volume requirements would take two years. However, sublimator-equipped portable life support systems would support the Earth orbital mission of Apollo 9 and the successful Apollo 11, 12, 14, 15, 16, and 17 lunar explorations without a failure or out-of-specification incident. Additionally, sublimation was incorporated into the Lunar Module environmental control system and Saturn rocket electronics heat rejection systems. Later, porous plate sublimators were used in the Space Shuttle and its extravehicular mobility unit. In the Soviet Union's space program, Plant 53 (now Zvezda) had a sublimator-type evaporating heat exchanger designed and tested in 1963. Sublimators were first used in a Soviet EVA in 1969 as part of the Yastreb EVA suit system. The sublimator has been used in all subsequent Soviet/Russian EVA suit systems.

As a parallel backup to Hamilton's life support activities, NASA funded the AiResearch Division of Garrett Corporation (now Honeywell) for continued development of the personal environmental control system (PECS), which was a holdover from the Gemini program. The PECS had some rather exotic features, such as utilizing sodium chlorate "candles" as the oxygen supply. The development success of Hamilton's second backpack effort resulted in NASA not funding the PECS to completion of development under the Apollo program. A later attempt to resurrect PECS for Skylab also proved unsuccessful.

Another key element of Hamilton's second backpack effort originated with Royal Air Force (RAF) pilots sitting in their Spitfire and Hurricane fighter aircraft on airfields waiting do battle in the skies over Great Britain in World War II (WWII). With this, RAF flight surgeons learned the challenges of keeping pilots comfortable and physically ready to perform effectively in combat. The flight surgeons recognized that the logistics associated with early jet aircraft and the locales of potential conflict posed significant new challenges to pilot function. In the early 1950s, the RAF conducted experiments into liquid-cooling vests as a solution. From this, two intertwining Apollo trails resulted.

The first trail was that RAF research into liquid transport (i.e., removal) of body heat had continued. In November 1962, the RAF clothing laboratory at its Human Engineering Division in Farnborough, England started manufacture of an RAF full torso liquid-cooling garment (LCG) prototype. About that time, NASA recruited a distinguished RAF flight surgeon named Dr. John Billingham to head NASA's Environmental Physiology Branch in Houston. Billingham was aware of the RAF LCG experimentation and contacted the RAF to borrow their LCG prototype for an Apollo evaluation. Because the RAF knew the shortcomings of their first prototype, they elected to fabricate a second, improved version for NASA/MSC testing called RAE 2. The testing probably occurred in September or October 1963. The RAF LCG was completely dependent on liquid transport for heat removal as the LCG's outer garment was made of a heavy, tightly knit material that precluded evaporation of perspiration from cooling the wearer. RAE 2 appears to have returned to England without NASA sharing these activities with Hamilton Standard. This may be due to government contracting requirements to assure fair competition for possible future contract competitions or because NASA wished to understand the state of Hamilton developments without the benefit of RAF influence. The RAF issued the final report covering its two prototypes in April 1964.

The second trail starts in January 1963 with Apollo program manned testing at Republic Aviation. The evaluation results were disseminated through progressively higher levels of the community in February and March. This caused mixed reactions within the community. At least some NASA personnel were confident that the forthcoming new pressure suit design, the AX1H, would alleviate helmet fogging and thermal issues by requiring lower effort on the part of the astronauts and better ventilation. Perhaps others within NASA had concerns that resulted in the aforementioned evaluation of the RAF LCG prototype. Hamilton internally interpreted this as a warning that Apollo metabolic requirements were insufficient. Multidirectional internally funded research resulted. One of the people drawn into finding a solution was an engineer named David Jennings. Jennings was aware of the 1950s' RAF liquid-cooling vest study. In October 1963, NASA requested a presentation of Hamilton liquid-cooling developments within two weeks. Two weeks later, Jennings presented proof-of-concept test results. In this test, Jennings wrapped and taped 300 feet (91 m) of $\frac{3}{16}$-inch (48 mm) vinyl tubing around a test subject. Then he sealed the test subject in plastic, precluding evaporation of perspiration. The test then added various levels of clothing including multiple layers of the warmest winter outerwear available. Under a physician's supervision, the subject then exercised strenuously on a treadmill for periods up to two hours.

Before the end of 1963, Hamilton had created a ''spacesuit (liquid-cooling) undergarment'' prototype named CG1. CG-1 had 232 feet (70.7 m) of $\frac{1}{16}$-inch (1.6 mm) inside diameter tubing contacting the body. The 232 feet divided into 40 parallel cooling circuits. The method of holding tubing to the body was an open, cotton mesh two-piece garment comprised of upper-torso and lower-torso assemblies. The open mesh allowed the ventilation gas flowing through the suit to additionally cool and remove humidity supplementing the benefits from liquid cooling and increasing comfort. Through the spring of 1964, Hamilton and NASA rigorously tested CG1 in Windsor Locks, Connecticut and Houston, Texas. In parallel, Hamilton was developing dedicated LCG production facilities in Windsor Locks.

In May 1964, the next LCG prototype, CG2 (Figure 6.5.1), was completed and sent to Houston for testing. NASA's Gil Freedman was able to perform on a treadmill for an hour without noticeably perspiring. CG2 started the one-piece full torso LCGs that have continued to be the norm in extravehicular spacesuits worldwide to the present. For CG2, body-contacting internal tubing increased to 267 feet (81 m).

June 1964 was a confusing month in LCG history. By the beginning of that month, Dr. John Billingham, Head of the Environmental Physiology Branch at NASA's Manned Spacecraft Center (MSC) Houston had created his own LCG using department store ''long johns'' and vinyl tubing. Billingham's LCG would later be depicted as the first Apollo LCG prototype.

That same month, NASA took an RAF LCG, serial number RAE 3, to Hamilton for feedback on the simple RAF technique of weaving the tubes through holes in the garment to hold the tubes in place. This is the first known time that NASA provided Hamilton access to an RAF LCG. Hamilton pointed out the potential disadvantages. The RAF tube attachment method was not adapted into the Apollo LCG.

Also in June, Apollo CG3 made its debut. With CG3, the number of parallel cooling circuits in the LCG increased to 48, the body contacting tubing increased to 296 feet (90.5 m), and the total tubing with manifolds grew to 300 feet (91.4 m). These parameters would remain as a constant for the Apollo program through the fall of 1965. Minor changes to CG3 and the addition of another CG3-like garment called CG3B caused CG3 to be redesignated the CG3A.

The first spinoff of Apollo LCG technology to the commercial sector came in July 1964 with the debut of Hamilton's NASCAR (National Association of Stock Car Auto Racing) driver cooling system. The ''system'' resembled the current Apollo LCG, a variable speed water recirculating pump powered by vehicle electricity and a high-quality ice chest. In a race where track-level temperatures reached 130 degrees, driver Paul Goldsmith reportedly was able to remain comfortable and focused.

The fall of 1964 brought many changes in Apollo LCG development and production. On September 4, 1964 Hamilton filed a patent request on Jennings LCG concept. Before the year's end, Hamilton created and evaluated prototypes

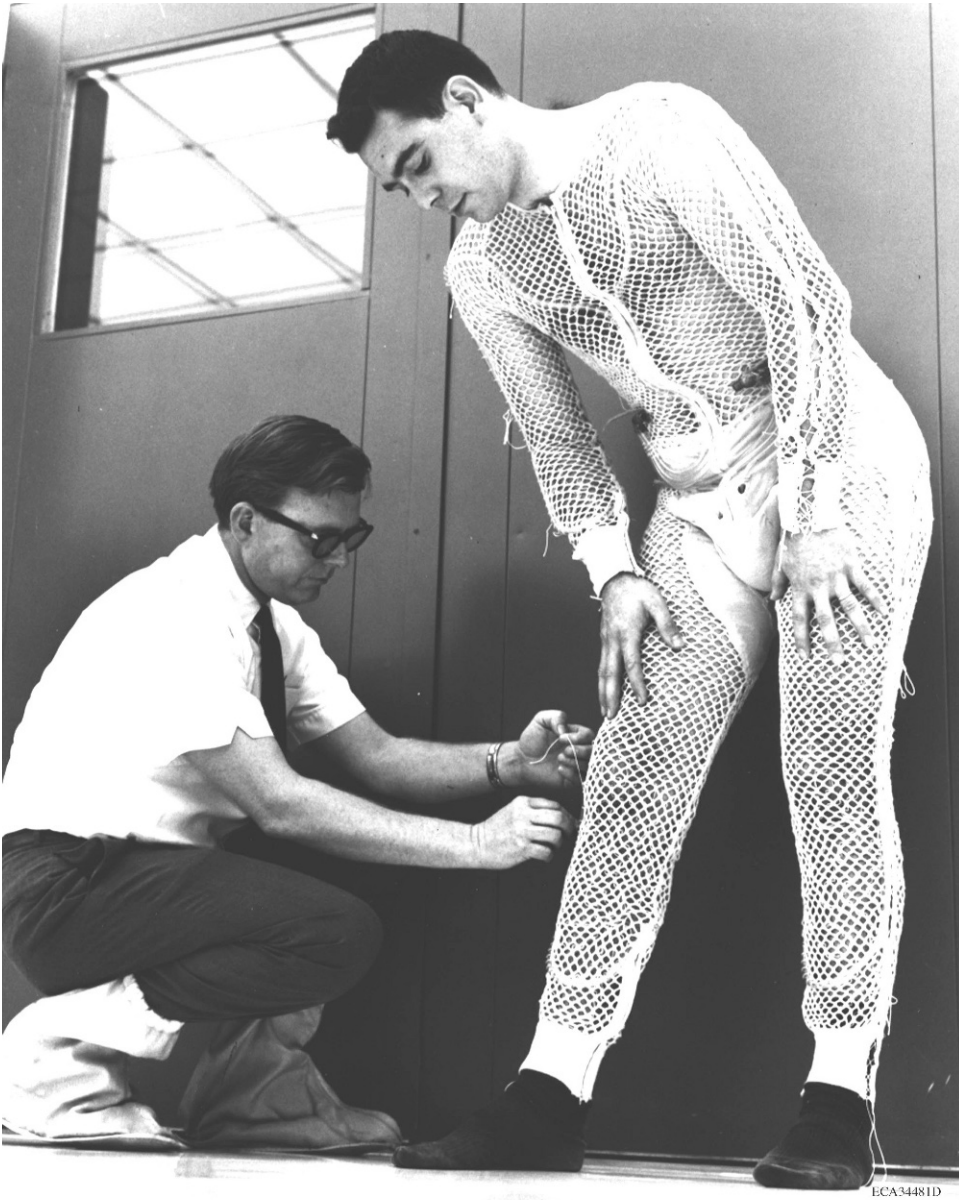


Figure 6.5.1. Development of the liquid-cooling garment (courtesy Hamilton Sundstrand).

CG4 and CG5 for subtle improvements in cooling tube routing. Hamilton also retained B. Welson & Company of Hartford, Connecticut for Apollo LCG manufacture. This brought new talent and softgoods-manufacturing experience. The first B. Welson LCG is CG6. This was the first Apollo LCG to feature machine-sewn tube attachments to the garment (a B. Welson innovation). CG6 was also the first "elastomeric" mesh garment, which held its conformal fit better under multihour treadmill evaluations. Previous Apollo LCGs were all or mostly cotton mesh. CG6 was the first of two prototypes that used a dark-blue mesh material. With B. Welson supporting Apollo, Hamilton reallocated its internal LCG development and production resources to U.S. Air Force cooling and heating projects.

In February 1965, Jennings demonstrated CG7 at NASA's MSC. To alleviate concerns regarding comfort from prolonged exposure, Jennings had continuously worn the garment for the preceding 14 days. Jennings entered the presentation wearing a suit and tie over the LCG. When the ability of the LCG to provide comfort in prolonged use was challenged, Jennings removed his outer clothes in Clark-Kent-changing-into-Superman fashion.

Probably also in February, the Apollo program gained a design concept from Eleanor Jennings, David Jennings' wife. The concept was a chiffon abrasion protection and comfort liner incorporated into CG8. Testing indicated negligible heat transfer impairment. The liner became standard in subsequent Apollo LCGs. CG8 also marked the short-lived change to light-blue mesh material. The other light- blue units were the CG9 that was the first to have reduced bulk under the arms without mobility impairment and the CG10 which initiated biomedical instrumentation pockets in Apollo LCGs.

The CG11 and subsequent LCGs were part of the AX5H, AX6H, and A5H suit deliveries, which began in March 1965. At NASA request, these LCGs used natural (white) mesh material producing the appearance that has continued to the present.

Thus, the British idea of liquid transport coupled with an American torso concept and development became the Apollo liquid-cooling garment (U.S. patent No. 3,289,748, inventor David C. Jennings). To add yet another facet to spacesuit LCGs, the Soviet Union's first experiments with LCGs for space applications started at Plant 53 in 1962. This resulted in a functional system built into a Russian lunar suit prototype in 1965. From these origins, open-weave LCGs continued to become standard in all U.S. and Russian spacesuits.

To create the volume and weight reduction needed for the addition of liquid transport/removal of body heat, Hamilton also had to develop a second emergency/backup life support system. Like the first system, it was also named the emergency oxygen system and supplied 5 minutes of life support. However, it was a much lighter and more compact, donut-shaped device. To maximize the use of space, this was to be attached to the back of flight helmets with an interface that would allow easy post-EVA replacement if required.

Development of the liquid-cooled portable life support system (PLSS) or "backpack" continued into 1965 to reach the system efficiencies needed to provide the increased life support capacities within the already established volume constraints. The PLSS was successfully man-chamber-tested in the fall of 1965 (Figure 6.5.2). This was the -2 (dash two) PLSS that reflected improvements that had occurred during development. The -2 and the subsequent Apollo program "dash number" model designations stemmed from the use of the same base design and part number from 1965 through 1972 with minor changes advancing the dash number.

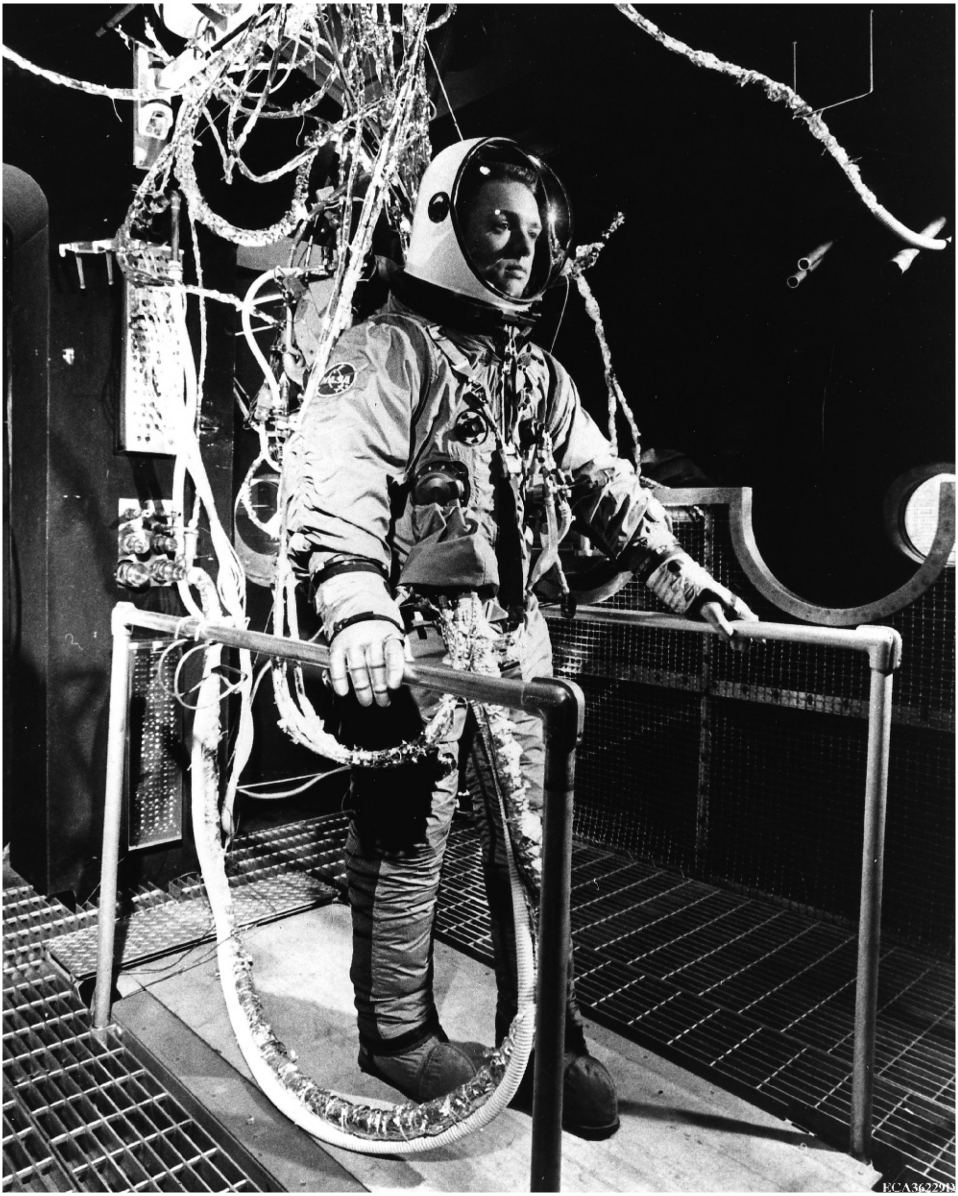


Figure 6.5.2. 1965 manned chamber–testing of the liquid-cooled backpack (courtesy Hamilton Sundstrand).

The -2 life support system still lacked a chest-mounted display and control device that typified the surface mission Apollo spacesuits. Of the Apollo EMU subsystems that were used on the Moon, only the PLSS completed development and reached certified manned chamber testing in the first 3 years of the Apollo program.

Parallel efforts to develop the "Moon suit" (1964–1965)

Awareness that pressure suit mobility could be a potential Apollo program challenge started after delivery of the first new-design prototype—the AX1H-021—in July 1963. Mixed reviews delayed a clear program response. In the cramped confines of the Apollo Command Module, shoulder width had also become a significant mobility issue as shoulder/arm interference precluded adequate operation of controls. International Latex had expected that the shoulder width allowance would be expanded. Due to Command Module design challenges, NASA and the maker of the Command Module, North American Aerospace, judged that increasing the shoulder width allowance was not possible.

Disagreements on the adequacy of the suit's mobility ended in November 1963 when subjects using subsequent design AX2H suits were not able to right themselves from the on-the-back position in lunar gravity testing. A formal finding for failure to meet a contractual requirement was issued against Hamilton Standard. Hamilton offered corrective actions, which NASA accepted in December 1963. The actions included International Latex continuing mobility development in the AX3H effort, Hamilton supplementing the International Latex suit design effort with Hamilton internal resources, Hamilton assuming the helmet redesign so International Latex could concentrate on torso redesign activities, and the Hamilton development of quantifiable/measurable mobility requirements. While this pacified NASA, this placed additional strains on the fragile Hamilton/International Latex working relationship. International Latex's Specialty Products Division had a strong sense of identification with helmets as it had gained its entrance into high-altitude aviation through the development and production of partial and full pressure suit helmets. With these events, the patterns of the Bill Diefenderfer and Wally Heinze presidential correspondence changed. "Bill and Wally" dialog would no longer be a venue for resolution of International Latex/Hamilton disagreements. These organizational leaders were resolute in differing positions. This would have technical and programmatic consequences.

From the beginning of the Apollo SSA program, NASA had intended to replace the SPD-143 training suit fleet with a fleet of current Apollo suits once mobility development was complete. On November 20, 1963 NASA issued a request for proposal (RFP) to Hamilton for 38 (then AX2H, later AX3H-based) training suits. Hamilton solicited a quote from International Latex, added expected Hamilton content, made adjustments where it deemed necessary, and submitted a proposal. To understand the events that followed, one needs to know the levels of NASA management involved in Apollo suit development decisions at the time. This ranged from Richard S. "Dick" Johnston (Chief of Crew Systems Division, CSD), through Edward L. "Ted" Hays (Deputy of CSD), James V. Correale (Head of the Crew Equipment Branch), Matthew I. Radnofsky (Assistant Head of the Crew Equipment Branch), and Charles C. Lutz (Head of the MSC Space Suit Section) to Jerry Goodman (Apollo Suit Group Manager).

In January, Hamilton discovered that International Latex had submitted a competing proposal for a direct-to-NASA contract. Radnofsky and Lutz were in support of a direct contract with International Latex based on expected cost savings. Hamilton subsequently met with Dick Johnston to present why Hamilton should remain the Apollo suit sole source. Johnston concurred and on January 29, 1964 issued a program memorandum to Maxime A. "Max" Faget, the Assistant Director for Engineering & Development at the Manned Spacecraft Center (MSC) in Houston providing sole source justification. Radnofsky, being a bold and tenacious individual, responded the next day with a rebuttal memo. In a parallel move, NASA reduced the quantity of the new training fleet from 38 to 14 suits due to mobility development issues, thus reducing the potential cost savings. Both Johnston and Radnofsky remained firm. On February 10, 1964 a second program memorandum initialed by Ted Hayes and signed by Johnston reaffirmed the single source decision, probably with the expectation that this would bring the issue to closure. While further details of the conflict have been lost, a partial compromise appears to have been the result. By February 10th, the first suits in the disputed contract were probably already under construction. Perhaps as a result NASA issued a direct-to-International Latex contract in time to support the March delivery of (probably three) A-2L Apollo suits. NASA subsequently issued a contract to Hamilton for 27 A-3H suits.

The Apollo A-2L (Figure 6.5.3A) suits were derivations of the AX3H-024 suit but featured Gemini-style individual inlet and exhaust connectors and used AX2H-style helmets. As the intended use of the first A-2L suits was to support NASA's Human Engineering Criteria Mobility Analysis Review (HECMAR) being conducted at North American Aerospace (NAA), the A-2L were frequently called HECMAR suits.

Concurrent with A-2L production, there were two Apollo prototypes. These were the Hamilton playsuit and an International Latex state-of-the-art (SOA) Command Module pilot (CMP) prototype. In the aerospace industry and Hamilton paradigm, a development prototype is usually concepted, designed, engineering drawings produced, and then manufactured according to those drawings. International Latex approached prototyping from a "cut-and-try" method where concepting and manufacturing the prototype were essentially one activity, and engineering drawings, if any, came afterwards. This was another example of the difference in engineering approach between essentially softgoods providers and those of hardgoods. To follow the International Latex way in an aerospace engineering environment, Hamilton created the classification "playsuit" to take exception from the normal processes. The Hamilton playsuit started as an obsolete International Latex pressure suit acquired by Hamilton. Hamilton's Advanced Engineering Group concepted and fabricated multidirectional elbow and shoulder designs, which were integrated into the garment (Figure 6.5.3B). Hamilton additionally searched the pressure suit community for a pressure suit expert to augment existing Apollo resources. By mid March, Hamilton successfully recruited Dr. Edwin G. Vail from a U.S. Air Force pressure suit consultant position to head Hamilton's Windsor Locks, Connecticut Apollo efforts.

With the state-of-the-art (SOA) Command Module pilot (CMP), International Latex not only created a new prototype, it introduced a new way of thinking about suit architectures within the Apollo program. In the Apollo program in 1962–1963, the mindset had been that the Lunar Module crew extravehicular (EV) suits and the Command Module pilot (CMP) suits would all have the same features and volumetric requirements. ILC's recognition of the potential advantages of having more specialized EV and CMP suits caused ILC to fund the SOA/CMP prototype. The premise for the SOA/CMP was that a suit with narrower shoulders was less of an impediment to the functions of the CMP, but a more compact CMP suit would improve pressurized suit operations within the Command Module. The SOA/CMP was AX3H-based and probably benefited from the AX3H having been delivered first as the SOA/CMP featured a body-hugging umbilical that still allowed exploration of commercial connectors but was less likely to catch on objects (Figure 6.5.3C). To test the potential benefits of such an approach, ILC delivered the SOA/CMP suit with the first Apollo A-2L suits that were evaluated in HECMAR.

Command and Lunar Module evaluations in March 1964 brought more attention to Apollo pressure suit development and delayed the start of the then planned A-3H training suit production. The Command Module evaluation included three David Clark Company Gemini G2C (rear-entry) suits (Figures 5.2.1 and 5.2.3), two AX2H suits (Figure 6.2.1C), the Hamilton playsuit, two or three A-2L, suits and the International Latex SOA/CMP. The evaluation conclusion was that only the Gemini G2C suits were adequate for Command Module operations. From Command Module evaluations, Apollo suit durability also came into question.

Lunar Module evaluations conducted at Grumman marked the NASA debut of the AX3H-024 prototype. The evaluation results reaffirmed the need for pressure suit durability and mobility improvements. In the first week of April 1964, NASA placed a verbal stop-work on an order for 27 (then) A-3H training suits and compiled a list of AX3H deficiencies that required correction. The response was three parallel activities. First, the very week the AX3H suit was returned to International Latex, Hamilton placed a task force on site at International Latex for corrective action identification. Second, Hamilton initiated a dialog with B.F. Goodrich for parallel suit mobility development. Third, Hamilton created an internal tiger team of its best talent for further mobility development.

Astronaut preference for the David Clark rear-entry Gemini suits (Figure 6.5.3D) caused International Latex to take interest in exploring rear entry by the end of 1963. Hamilton was unwilling to support such development, as it was not among the areas where NASA expected improvement. In 1964, International Latex began conducting internal research and development into Gemini-style rear-entry zipper systems. This started with the retrofitting of now obsolete AX1L and SPD-143 suits to rear entry for evaluation (Figure 6.5.3E). This was the beginning of the rear-entry system that supported the first human exploration of the Moon.

Around May 1964, NASA evaluated a modified A-2L suit (Figure 6.5.3F). This featured Gemini-style boots and a configuration of shoulder abrasion patches that pre-dated the remanufactured AX3H. This modified A-2L suit was most likely an International Latex internally funded effort that was in response to evaluation

(A) ILC A-2L suit
(as built, 3/64)

(B) HS playsuit, modified
ILC suit (3/64)

(C) ILC SOA Command
Module pilot prototype (3/64)

(D) DCC Gemini suit influences (1963–1965)
(a) and (b) External front and rear
(c) Without cover garments

(E) ILC R&D, obsolete suits modified
for rear-entry development (1964)

Figure 6.5.3. Program recovery effort suits.

(F) ILC A-2L suit with Gemini boots (1964)

(G) ILC remanufactured AX3H (5/64)
(a) Evaluation suit system
(b) Pressure suit

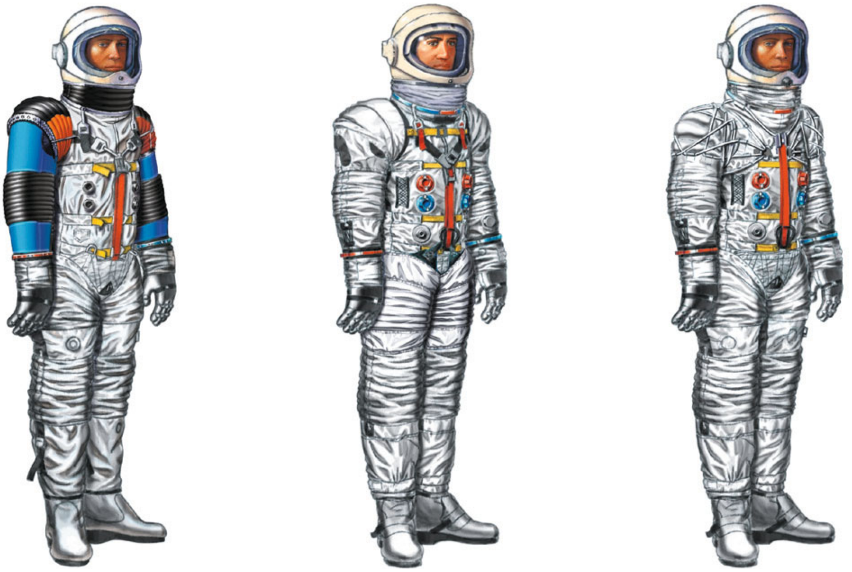
(H) ILC early A-4H training suit (6/64–1/65)

(I) BFG mobility suit (9/64)

(J) HS/BFG mobility suit prototype (10/64)

(K) BFG XN-20 suit (11/64)
(a) External view (b) Without covers

Figure 6.5.3. Program recovery effort suits (*cont.*).



(L) ILC playsuit with
ILC shoulders (11/64)

(M) ILC SOA suit (front entry),
ILC brief design (11/64)

(N) ILC suit with BFG
shoulders (11/64)

(O) HS XT1 tiger suit
prototype (11/64)

(P) HS XT2 prototypes
from ILC suits (12/64)

(Q) ILC late A-4H training suits (3/65–6/65)
(a) EVA system (b) IVA system

Figure 6.5.3. Program recovery effort suits (*cont.*)

(R) HS "mobility suits"—
modified ILC suits (1/65)
(a) External view (b) Without covers

(S) ILC rear-entry SOA
"retroactive AX4L" (2/65)

(T) DCC A1C Block I suit
(a) External view (b) Without covers

(U) HS AX5H suits (3/65–6/65)
(a) EVA external view (b) IVA external view
(c) Without covers

Figure 6.5.3. Program recovery effort suits (*cont.*)

(V) HS/BFG AX6H competition suit (5/65)
(a) EVA system (b) IVA system (c) Without covers

(W) DCC AX1C competition suit (5/65)
(a) External view (b) Without covers

(X) ILC AX5L competition suit (6/65)
(a) External view (b) Without covers

(Y) HS PLSS and
HS/DCC TMG
development (6/65–9/65)

(Z) HS XT5 (7/65)

Figure 6.5.3. Program recovery effort suits (*cont.*)

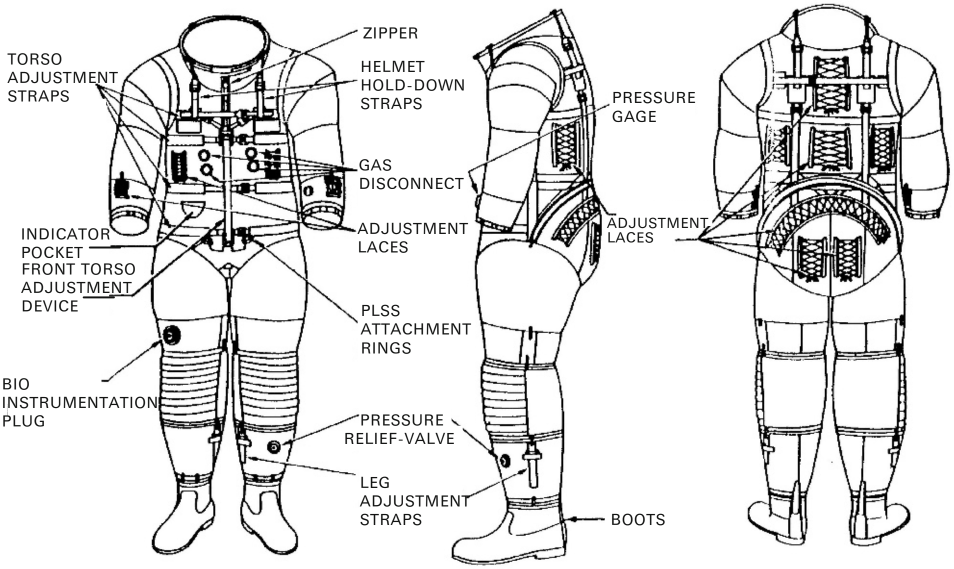


Figure 6.5.4. Features of the A-4H training suits (courtesy Hamilton Sundstrand).

comments favoring the Gemini foot traction over the Apollo AX1H/AX2H cowboy-style boot.

By late May, the AX3H-024 was remanufactured with Gemini-style life support connectors and a Hamilton (designed and manufactured) "universal" helmet (Figure 6.5.3G). Except for a glove failure, all testing in the next month was favorable. By the end of June 1964, NASA had directed the resumption of training suit manufacturing based on the remanufactured AX3H features (Figure 6.5.4) and design improvements. To differentiate this training suit production from the original AX3H configuration performance, NASA later directed the training suits to be designated AX4H until the first delivery was accepted and then A-4H to indicate "production" suits.

With the remanufactured AX3H-024, International Latex delivered a separately donned thermal/micrometeoroid overgarment and test samples that represented the overgarment layers and construction to support parallel testing. The samples met thermal requirements, but not impingement requirements. The premise driving impingement requirements was that an astronaut should be able to survive ejecting into space as a result of a meteor strike and then be drawn back to the surface of the Moon by lunar gravity. The remanufactured AX3H went on to be used with the overgarments in a system-level field evaluation conducted in Bend, Oregon (Figure 6.5.5). This location was selected for its similarity to a lunar landscape. The evaluation included Walter Cunningham, who was part of the Apollo 7 first manned mission. Movement over uneven terrain in the pressurized suit was difficult. The thermal overgarments provided significant encumbrance. This only reaffirmed NASA's view that suit mobility was not yet adequate for lunar exploration.

Figure 6.5.5. Apollo 7's Walter Cunningham AX3H test in Oregon (courtesy NASA).

From December 1964 to May 1965, the correspondence between the presidents of International Latex and Hamilton Standard brought no resolution to Apollo program issues. By the end of May, Wally Heinze had managed to make the acquaintance of William P. Gwinn, the Chief Executive Officer of United Aircraft.

Heinze took the opportunity to register complaints about Hamilton's performance on the Apollo SSA program and Hamilton's assumption of the new helmet design and manufacture. This triggered events, but not in ways that ILC's Heinze desired. Gwinn in turn contacted Hamilton Standard's Diefenderfer. Diefenderfer provided status and Gwinn appears to have been satisfied and supportive of Hamilton's actions and position. Probably at Diefenderfer direction, Hamilton's internal efforts for suit mobility received an infusion of significant resources, B.F. Goodrich quickly came under contract for mobility development, and Hamilton internally funded Goodrich for a prototype embodying their state-of-the-art mobility technology.

In June 1964, NASA changed the name of the upcoming fleet of Apollo training suits from A-3H to A-4H. The first two suits started as AX3H-025 and AX3H-026 to denote these were pre-production prototypes and were renamed AX4H-025 and AX4H-026 prior to delivery to Hamilton. NASA quality concerns delayed the delivery of S/N 025 and S/N 026 until November. S/N 027 through S/N 036 had an A-4H designation to reflect their being "production" hardware. A-4H suits featured either dual-port or separate Gemini-style inlet/exhaust life support connectors. Suits S/N 025 through S/N 029 were an early A-4H configuration (Figure 6.5.3H) that were sister suits to the remanufactured AX3H-024 and differed only in that they were produced with aluminized outer fabrics.

The next two Apollo suit prototypes came in September. The first was a B.F. Goodrich (BFG) prototype called the mobility suit (not to be confused with the Hamilton modified International Latex suits of the same name a few months later). The BFG mobility suit (Figure 6.5.3I) was a simple pressure garment with olive outer fabrics based on BFG's high-altitude/Mercury suit technology. While this prototype did not provide the mobility solutions needed for Apollo, it led to a Goodrich/Hamilton collaboration that quickly produced yet another prototype.

This second BFG prototype started with an obsolete pressure suit to reduce cost and eliminate many long-lead hard details. The upper torso was retrofitted with Hamilton-designed Teflon cord and ferrule shoulders and Goodrich-designed arms that featured pressure-sealing bearings at the biceps. This combination (Figures 6.5.6 and 6.5.3J) produced a configuration that met the shoulder width and upper-torso mobility requirements of Apollo. Unfortunately, there was initial reluctance by NASA's CSD to the use of bearings in the arms. The reluctance was based on concerns about hard contact causing discomfort or injury and crewmember safety if a pressure seal was damaged. Consequently, Hamilton and BFG focused their development efforts on multidirectional, bearingless concepts. However, an element within the Hamilton suit group liked the potential provided by bearings attached to axial restraint mobility elements. This Hamilton/Goodrich prototype saw sporadic continued development of the lower torso that became the XT5 prototype (Figure 6.5.3Z) in July–August 1965.

The beginning of October 1964 marked the second anniversary of the start of the Apollo spacesuit program, and suit mobility development had yet to meet the challenge. NASA announced that the Apollo pressure suits would be segmented in a manner similar to that of the vehicle systems (i.e., Blocks I, II, and III). NASA

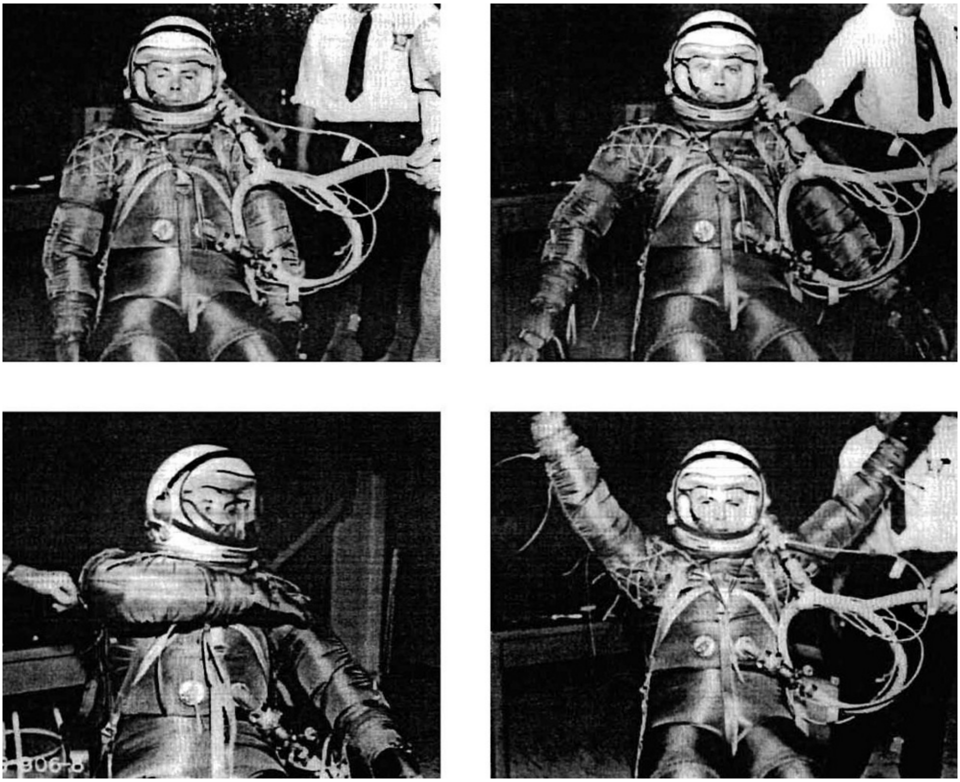


Figure 6.5.6. September 1964 second BFG prototype (Hamilton Sundstrand).

informally announced the intent to use David Clark Company Gemini-based suits for the early Apollo orbital Block I missions and initiated internal efforts for the development of helmets and other suit features for Block II. The pressure suits for Block II were for flights using the Lunar Module. The contract for these suits was competed in 1965. The Block II suit system was renamed the extravehicular mobility unit (EMU). Block III suits were to be an advanced EVA configuration developed in yet another program (addressed in Chapter 7).

November saw a flurry of suits for evaluation from B.F. Goodrich, International Latex, Hamilton Standard, and David Clark. Goodrich delivered two prototypes. The first named the "take-apart" suit may have been an already existing early Gemini prototype or a derivation of the Gemini take-apart suits. Records indicate the suit demonstrated good shoulder range and low torque but the shoulder diameter and arms-down position required improvement.

The second suit was the XN-20 (Figure 6.5.3K), which was the last Goodrich design of the Apollo program. For this suit, Goodrich elected to utilize Hamilton-developed Teflon cord and Teflon ferrule technology for which Hamilton provided engineering support and materials. The outer layers of the cover garment featured aluminized nylon. Underneath, the restraint layer of the pressure garment was an olive-colored synthetic fabric. Hamilton tested the XN-20 in late November or early December 1964. A potential winner at the time, data comparison with contemporary and later designs indicated the XN-20 was similar in performance to the latest Apollo suits but the Hamilton design had better range of motion.

There were three prototypes from International Latex Corporation (ILC). The first to arrive was called the "playsuit". This was an entirely different unit from the Hamilton prototypes of the same name. This ILC playsuit was an A-4H similar test suit that provided a testbed for upper-torso mobility systems by replacing the shoulders and arms. As received at Hamilton on November 12, 1964 the ILC playsuit featured Goodrich-designed tapered convolute shoulders. While this met the Apollo shoulder width requirement and arms had good fit in the down position, these elements did not provide the needed mobility or reach. The suit was immediately returned to ILC for retrofit to ILC soft-cone bellows shoulders (Figure 6.5.3L). By November 25, 1964 the playsuit had returned to Hamilton, but the evaluations showed promise.

The second ILC prototype was the SOA (state of the art) suit. This was an Apollo program–style front-entry garment but featured the latest ILC design thigh and brief section (Figure 6.5.3M). While the design was not yet fully refined and had significant user comfort issues that resulted it being nicknamed the "crotch cutter", this was a forerunner of the brief system of the competition-winning AX5L, which with some minor improvements, would see service on the Moon and Skylab.

The third prototype was the ILC suit, which featured Goodrich XN-20–style shoulders. The intent of this prototype was to demonstrate that, if NASA selected the XN-20 shoulders for the A5H training suit design, then ILC was still capable of pressure suit manufacture. This garment (Figure 6.5.3N) arrived at Hamilton on or soon after November 25, 1964. By similarity of performance in comparative testing against the XN-20 suit of the time, the ILC suit successfully verified that ILC could produce the A5H series if NASA selected the Goodrich shoulder. This was the last complete prototype pressure suit from ILC under the Hamilton/Apollo contract.

November also saw the debut of Hamilton's first complete design and prototype manufacture. This was Experimental Tiger Suit No. 1 (XT1). Called the "tiger suit" (Figure 6.5.3O), it was an interesting conformal fitting olive-and-white two-tone pressure garment. While it met the Apollo shoulder width requirement, it did not provide any advancement in mobility. During its NASA debut, the XT1 suffered unexpected arm growth due to a shoulder restraint cable failure.

In parallel to the efforts that had produced the tiger suit, Hamilton had a second group working on pressure suit design. Principally comprised of young engineers, this group had produced shoulders for a Hamilton/Goodrich prototype in September. They continued this technology development with the focus on bearingless multidirectional joints. By December, this group was using the former Hamilton playsuit and another obsolete suit as testbeds for development. These suits gained the names "upper-torso suit" (Figure 6.5.3P) and "thigh suit". These suits would comprise the development that Hamilton would later identify as XT2. Based on the comparative testing of the preceding designs, Hamilton recommended the XT2 technology be used for production of the next training suit design, the A5H, and in the Hamilton/International Latex competition suit.

Also in November, NASA provided a David Clark Gemini G2C training suit to Hamilton for comparative mobility testing (Figure 6.5.3D). A David Clark Company representative supported the evaluation. The comparative test results demonstrated that the Apollo suit technologies were finally competitive with the Gemini benchmark and had advantages in some areas.

In parallel to mobility development, there were events that drove helmet changes. At the beginning of 1964, all U.S. space helmets had pressure visors made of acrylic, and the helmet fit tightly on the astronaut's head. Most helmets incorporated a pressure-sealing neck bearing to allow the head to rotate with head movement and a neck mobility system to allow looking down and up when pressurized. In 1964, a Gemini training accident had caused an acrylic helmet pressure visor to fracture resulting in NASA mandating polycarbonate pressure visors. Polycarbonate had far superior impact properties but no one had developed the ability to form polycarbonate with the required optical quality. Another desire was to remove headborne loads. In normal 1*g* and multi-*g* situations, the *g*-forces applied forces on the user's neck. If not adjusted correctly, the suit pressure load tried to pull the tight-fitting helmet off the wearer's head. Movement could result in changes in suit volume/pressure applying forces to the neck and head causing discomfort. Yet another desire was to eliminate the weight of the pressure visor retraction mechanism and the potential for visor malfunction. Integration of the pressure visor into the helmet shell alleviated those issues. Apollo was the first space program to certify and implement a helmet with a polycarbonate pressure visor that exhibited satisfactory optical properties. This was the C3 helmet.

The C3 responded to NASA desires of the time. The C3 was a roomy "fixed-type" helmet that had no neck joint or bearing. The system impacts of the C3 helmet necessitated the introduction of the Hamilton "bump cap" or communications carrier assembly (CCA). Unlike preceding helmets that had the communication microphones and earphones integrated in the helmet shell, the late A-4H configuration placed communications equipment—the CCA—onto the head of the wearer. This Hamilton-produced CCA would see Apollo program use for less than one year. Subsequent CCAs by other organizations would retain the architecture but see refinements and improvements. As the CCA was similar in appearance to the headgear of a popular cartoon character, this soon became more commonly known as the "Snoopy cap": a nickname that has endured through the decades.

NASA directed C3 helmet incorporation into A-4H training suits at the earliest opportunity. Serial numbers (S/N) 030 and subsequent were selected. At this point NASA was also attempting to phase out the Xs and dashes in program suit models so the A-4H was becoming A4H. As there was already direction in place for an A5H training suit configuration, the A4H suits with C3 helmets were most often called "late A-4H" suits (Figure 6.5.3Q). These were S/N 030 through S/N 036. Deliveries of these ranged between March and June 1965. The late A4H had a larger neckring to support the dimensional differences of the C3 helmet and four sets of torso-sizing adjustment looptape on the back of the suit, reduced from seven, by eliminating the lowest three sets. S/N 030 to S/N 032 had aluminized outer fabrics and S/N 033 to S/N 036 had outer surfaces of white nylon to provide a more easily cleanable training configuration.

In December, NASA reviewed the comparative data from the November testing. Apollo mobility developments had finally progressed past the Gemini benchmark. The Goodrich XN-20 and Hamilton XT2 upper-torso designs both met all Apollo requirements. Hamilton presented the case that the XT2 was (marginally) better than the XN-20 and provided the recommendation that A5H training suits use XT2 technology in the upper-torso area. However, the Apollo designs still needed greater mobility in the waist and brief sections of the lower torso. As brief mobility was continuing, further upper-torso mobility improvements continued in parallel.

In January 1965, ILC delivered its composite mockup suit. This was expected to be the latest ILC attempt at A5H design for a Block II competition suit. The delivered prototype consisted of only an A4H-like torso with legs. This probably adequately reflected the Hamilton/International Latex relationship. The reaction from both NASA and Hamilton appears to have been negative. Hamilton issued a stop-work order to International Latex on all Apollo development activities. Prior to this event, Hamilton's President Bill Diefenderfer resisted those who advocated that Goodrich become the Apollo pressure suit provider. After this delivery, Diefenderfer directed that the Goodrich option be expored with all haste. By the beginning of February, International Latex was agreeing to manufacture Hamilton designs and the stop-work had been lifted. Both organizations were proclaiming a commitment to working together. However, Hamilton's exploration of the Goodrich option did not desist and International Latex demonstrated no further developments to Hamilton.

In January, Hamilton took an A-4H similar suit, possibly the ILC composite mockup, and retrofitted it with XT2-style shoulders and arms. Hamilton named this the "mobility suit" (Figure 6.5.3R). The Hamilton mobility suit immediately saw service in NASA vehicle development activities.

Under the Hamilton/Apollo contract, International Latex had proprietary internal development rights that it was not required to share with Hamilton or NASA. By early February, International Latex had completed an internally funded state-of-the-art (SOA) rear-entry prototype (Figures 6.5.7, 6.5.8, and 6.5.3S). This suit did not have cover garments over the shoulder and elbow sections. To protect competitive details, almost all the photographic negatives of the time were modified to obscure details of the mobility systems to allow photograph dissemination. However, a photograph that was previously thought to be the July 1965 AX5L shows an elbow with a molded black rubber convolute. The elbow rubber on the AX5L was dyed a light blue to match the torso fabric (Figures 6.5.3X and 6.5.8). In February, NASA engineers James "Jim" O'Kane and Dr. Robert "Bob" Jones started making trips to the ILC Dover plant developing a polycarbonate full bubble helmet prototype around the rear-entry SOA prototype.

O'Kane and Jones were advocating the development of a full bubble helmet that would take exception to the Apollo program's 95th percentile head-size requirement.

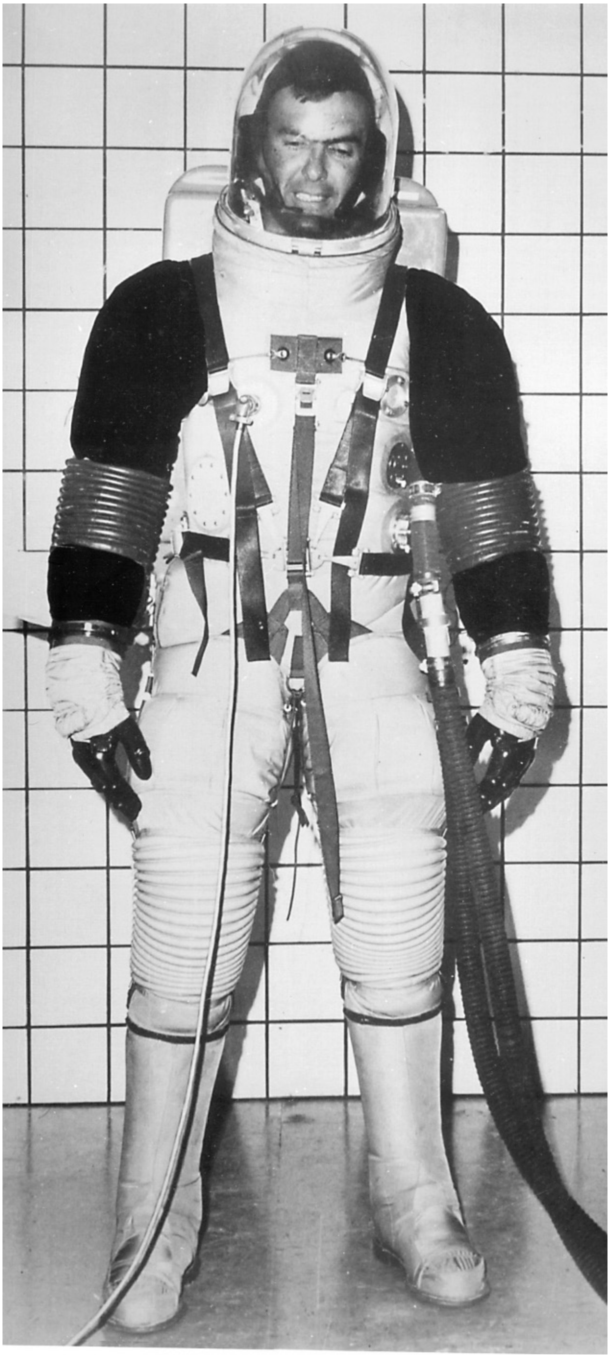


Figure 6.5.7. ILC rear-entry SOA suit with "blacked out" shoulders (courtesy ILC Dover LP).

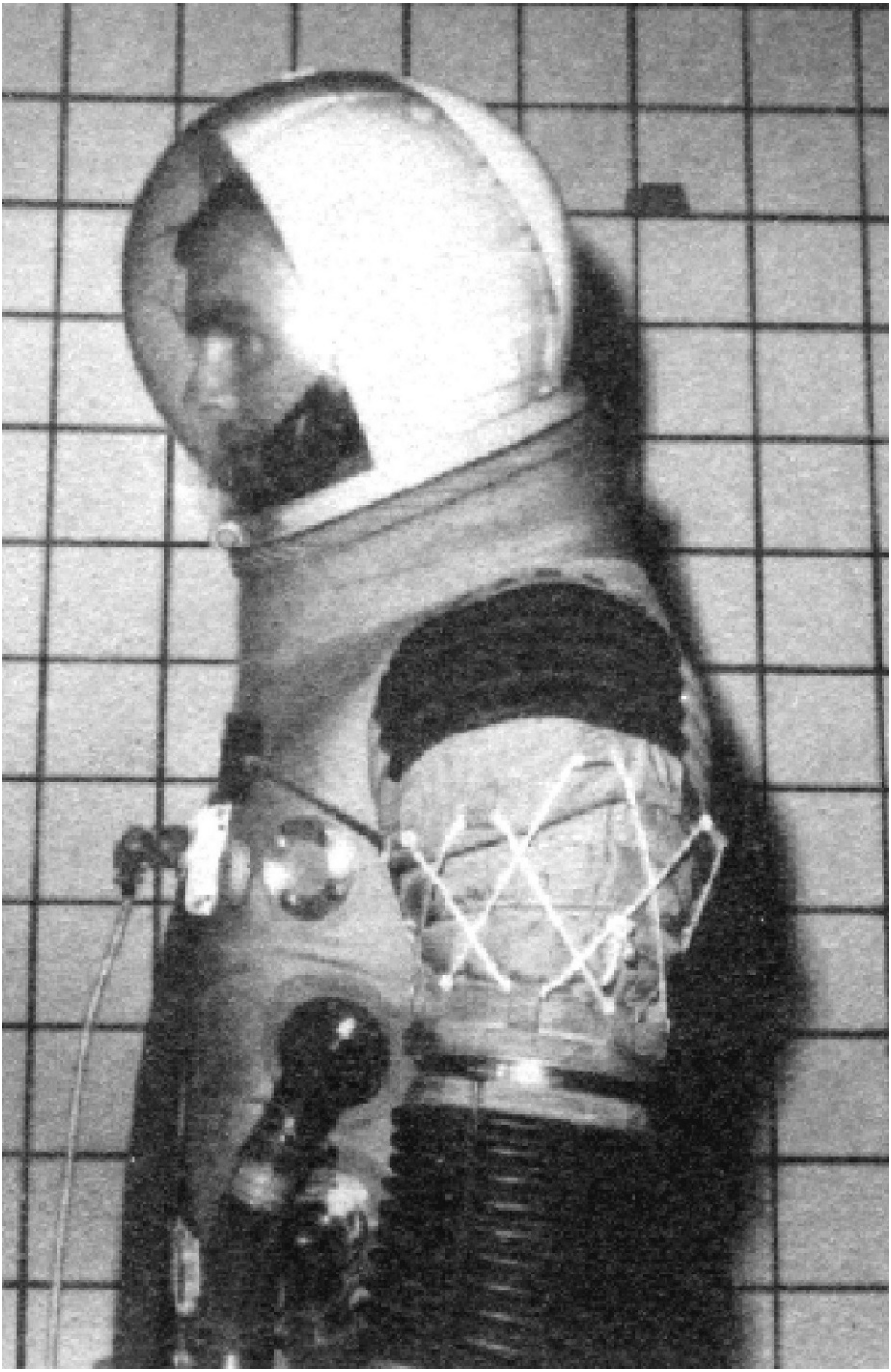


Figure 6.5.8. ILC rear-entry SOA suit shoulder and arm (courtesy ILC Dover LP).

Instead, they measured the Apollo astronauts and allowing only one half of an inch extra in any direction concepted a more compact geometry. This came at a time when Apollo had become the first space program to have a polycarbonate pressure visor. Manufacturing an optical quality full bubble in polycarbonate was a much greater challenge. O'Kane and Jones did not find a vendor willing and able to support their quest until 1967. However, their design supported all the Apollo and Skylab missions plus all the subsequent U.S. spacewalks to the present.

In February 1965, Hamilton presented the latest round of comparative test results on all known designs. This did not include the International Latex rear-Entry SOA suit. The results indicated the Hamilton XT2 upper-torso suit and thigh suit designs were providing the best comfort, the greatest range of motion, and the lowest effort. Based on the findings, NASA directed the use of the XT2 mobility systems for production of the A5H training suits.

Because the Hamilton mobility suit was committed for demonstrations, Hamilton modified another A-4H–like test suit to Hamilton arms and shoulders. The performance of the resulting "A-4H retrofit suit" sufficiently impressed NASA that it issued direction for retrofit of A-4H training suit S/N 032 and S/N 033 to Hamilton arms and shoulders.

Fourteen weeks before the Apollo Block II pressure suit competition, International Latex had delivered no new prototypes to Hamilton since November. On March 3, 1965 NASA allowed Hamilton to switch to Goodrich for exclusive Apollo pressure suit design support and subsequent model production. International Latex remained under contract to Hamilton for completing A-4H training suit deliveries.

In March 1965, NASA formally awarded the Apollo Block I suit contract to David Clark Company for Gemini-based suits (Figure 6.5.3T and Section 6.6) to support the first Apollo manned missions. These would have the NASA designation A1C.

To support delivery schedules, Hamilton delivered the first two A5H training suits in March with the intent of returning them in two to three months for upgrades to subsequent mobility improvements. Until March 1965, the A5H training suits and A6H flight configuration were to have the same helmets and neckrings as the late A-4H suits. A5H development suits were to be pre-production prototypes for both configurations. These prototypes would feature new "soft" slip-in pressure boots that were an extension of the torso bladder and restraint assembly. The boots had ankle joints to facilitate lunar walking (U.S. patent No. 3,605,293, Hamilton inventors Getchell, Korobowski, and Marroni). Astronaut Mike Collins was to be the suit evaluator in the Block II suit competition that was starting on June 15, 1965. The first prototype A5H (Figure 6.5.3U), later called AX5H, was to be sized to Collins as it was to additionally serve as the Hamilton/Goodrich competition prototype. The second A5H prototype in parallel flow was being sized for Dan Galvin, a Hamilton suit evaluator. The Collins and Galvin prototypes were completed and delivered in parallel to continuing mobility system development/refinement to support program needs. The Collins suit was sent for use in a Command Module critical design review. Goodrich had developed a pressure-sealing zipper that showed promise of dramatically reducing suit leakage. The Galvin suit was sent to Goodrich for the addition of this feature.

In April 1965, NASA desired a smaller neckring and more compact helmet with greater range of visibility than the late A-4H suits. This became a requirement for the A6H flight model. The A5H training suit configuration, at this point, was not going to be changed to permit retaining the delivery schedule on the prototypes and subsequent production. This necessitated the creation of an all new Hamilton/Goodrich competition prototype. Due to schedule constraints, the competition suit, called the AX6H, was built at Hamilton. In parallel, the Galvin A5H prototype was completed by Goodrich. The suit showed no measurable leakage in a test of its new entry system, which was a remarkable feat for any zipper entry suit regardless of historical period.

By mid-May, both the AX5H prototypes were in remanufacture to the latest mobility developments. Also in May, a third A5H-type suit was under construction at Hamilton. This was being custom-sized for a suit evaluator named Goodman. The Galvin suit was delivered to Hamilton on June 11, 1965. This was considered too late to include the suit in the evaluation delivery to the Apollo Block II suit competition. With NASA's redelivery acceptance, this officially became the first AX5H suit. By the beginning of July, the Collins AX5H suit was delivered.

A4H training suit deliveries finished in June 1965. The fleet supported many key activities in 1965 including Grumman system development of the Lunar Rover Vehicle (Figure 6.4.1). With the conclusion of late A4H suit deliveries, International Latex also delivered an A4H thermal/micrometeoroid garment prototype system and test samples. The garment was even heavier and more restrictive than the AX3H system. Sample testing still did not meet Apollo impingement requirements. The credibility of the requirements came under serious question. These would prove to be the last thermal garments produced by International Latex for Hamilton Standard.

While the generally anticipated Block II competitors were Hamilton Standard and David Clark Company, International Latex was attempting to make the competition. Going into the competition, International Latex management desired additional development acknowledgment. Expecting that the Hamilton entrant would be an AX5H, International Latex made a presentation to NASA's Charles Lutz advocating that two preceding ILC configurations had been significant to the Apollo program and should have NASA designations retroactively. The presentation was successful. While the presentation and its details have been lost, the retroactively assigned AX3L and AX4L designations were probably for the November 1964 ILC SOA suit (Figure 6.5.3M) and the subsequent rear-entry SOA prototype (Figures 6.5.3S, 6.5.7, and 6.5.8).

The Block II suit competition officially began on June 15, 1965 at the Manned Spacecraft Center in Houston. The Hamilton team completed the AX6H-037 suit (Figures 6.5.3V and 6.5.9) on the morning of the competition. To avoid disqualification, it flew in a rented private jet with engineers completing assembly during the flight to make the competition deadline. With the delivery of the AX6H, Hamilton resumed development of this prototype calling it XT5 (discussed on pp. 144 and

Figure 6.5.9. DCC (left) AX1C and HS/BFG AX6H 1965 (right) competition suits (courtesy NASA).

145). Delivered in a timelier manner, the David Clark AX1C (Figures 6.5.3W and 6.5.9) was in Houston waiting for the competition. This prototype was a front-entry suit with shoulder bearings and many advanced features. For details, see "The 1965 EVA Pressure Suit Competition" discussion that follows in the next subsection. Two weeks into the competition, International Latex was permitted to enter its internally funded prototype, the AX5L (Figures 6.5.3X and 6.5.10). "The 1965 EVA Pressure Suit Competition" discusses AX5L features.

In July 1965, NASA directed that the subsequent A5H training suits should also have the smaller neckring and AX6H-type helmets, so the AX5H configuration probably consisted of just the aforementioned three suits. An AX5H, probably the Goodman suit, had in its final configuration an improved derivation of the A-4H leather boots. The Air Force used this suit in Manned Orbiting Laboratory–related evaluations.

The next thermal overgarments delivered on the Apollo program were from David Clark. Hamilton tested these using AX5H and AX2H suits. These overgarments embodied improvements beyond the AX6H configuration overgarments: these included a separate visor cover and jacket rather than the parka-style overgarment (Figure 6.5.3U). Immediately following this delivery, NASA decided to relax the thermal and impingement requirements. This allowed for the creation of thinner, more conformal David Clark overgarments for Hamilton evaluation (Figure 6.5.3Y). This included the covering for a Hamilton-designed EVA visor assembly that bore a resemblance to the visor system used on Apollo 11–13 (Figures 6.7.9–6.7.11).

Figure 6.5.10. The ILC AX5L 1965 competition suit (courtesy NASA).

The introduction of the AX5L to the Block II suit competition caused a flurry of Hamilton activities. Prior to this, AX5H and AX6H configurations drew resources that slowed and intermittently stopped other Hamilton suit development. However, such activities did continue. Hamilton began a Manned Orbiting Laboratory (MOL) suit effort that had produced the XT3 and XT4 designs and continued the Hamilton/Goodrich collaboration Apollo prototype. This prototype differed from the A5XH and AX6H designs in that it utilized arm and thigh bearings for increased arm/leg mobility and range of motion. Arm and leg restraints were revised to steel cable to significantly reduce torso stretch when pressurized. A new, more compact multi-directional shoulder provided an even greater range of motion. This prototype was hurriedly updated to the latest mobility developments and given the name XT5 (Figure 6.5.3Z). However, this prototype came too late for Apollo program consideration.

NASA unofficially informed Hamilton at the end of July that International Latex would be the Apollo pressure suit assembly provider. The three new-build

A5H training suits in flow (S/N 038, S/N 039, and S/N 040) were production clones of the AX6H suit (Figure 6.5.3V) less thermal cover garments. These were completed and delivered in 1965. Hamilton management of Apollo pressure suit development activities effectively concluded in September 1965. Due to intellectual property and contractual issues, Hamilton's contract covering Apollo pressure suit and integration formally terminated in March 1966.

The 1965 EVA Pressure Suit Competition

The competition for what was envisioned at the time to be just Apollo Block II pressure suits started on June 15, 1965. The prototypes evaluated in this competition were the Hamilton Standard AX6H and the David Clark Company AX1C. NASA allowed International Latex Corporation to enter the competition two weeks later with their AX5L prototype.

Hamilton AX6H-037 (Figures 6.5.3V and 6.5.9, right) improvements over the AX5H configuration included elimination of neckring retention cables for improved unassisted don/doff, a helmet with a greater range of visibility, a quick disconnect extravehicular visor system, and a complete thermal overgarment system. Another interesting facet of the AX6H suit was its gloves. The gloves featured David Clark–supplied fingertip lights on a Hamilton derivation of an International Latex design fabricated by Goodrich. Like the AX5H, the AX6H featured a liquid-cooling garment and "walking" pressure boots.

The David Clark AX1C (Figures 6.5.3W and 6.5.9, left) suit was a significant departure from their rear-entry Gemini (Figure 6.5.3D) and Apollo Block I A1C suits (Figure 6.5.3T). While all these designs utilized Link-net restraint technology, the AX1C had scye (shoulder) bearings to enhance shoulder mobility and front/top entry like the 1962–1964 Apollo suits. However, the AX1C featured improvements. Like the Hamilton AX6H front-entry system, the David Clark design did away with cable attachments to the neckring. This allowed unassisted donning and doffing. The AX1C additionally featured a full bubble helmet that was larger and had better optical quality than the helmet used on the AX5L. The AX1C also used Apollo dual-port life support connectors and had accommodations for a liquid-cooling garment. Unlike its competitors, the thermal/micrometeoroid garments of the AX1C were integrated onto the torso and gloves (rather than separate units). Going EVA required only the separate donning of a visor assembly, over boots and backpack.

The International Latex AX5L (Figures 6.5.3X and 6.5.10) probably featured a further evolution of their rear-entry SOA suit (Figure 6.5.3S). Specifically, the AX5L featured International Latex soft-cone bellows shoulders that included a Teflon cord, ferrule multidirectional mobility element, and pressure-sealed bearings in the upper arms adjacent to their molded convolute bi-axial elbow joints. The Gemini-style rear-entry system included a Goodrich pressure-sealing zipper. This gave the AX5L the lowest leakage rate of the competing suits. Like the David Clark and Hamilton entrants, a block and tackle–style front drawstrap permitted pulling and holding the suit in a bent-over position. A strategic feature of the AX5L was its walking brief and thigh restraint system (patent No. 3,699,589, inventor George P. Durney). This permitted a significantly lower effort walking stride than preceding designs. The AX5L pressure gloves featured improved, steel cable, multidirectional wrist joints.

In the Apollo Block II suit competition, the AX5L proved to have the best mobility and lowest leakage rates of the competition suits with the shape retention under pressure and durability/reliability being at least equal to the AX1C. NASA informally announced the AX5L suit the winner at the end of July. In August, NASA began assuming the role of EMU integrator with International Latex and Hamilton Standard being NASA's prime contractors for the pressure suit assembly and portable life support system, respectively. Beyond the features of the AX5L, the subsequent International Latex designs would gain the liquid-cooling garment, multiple water connector, and "walking" (ankle joint) pressure boots of the AX6H before setting foot on the Moon.

6.6 APOLLO BLOCK I SUITS, ALMOST (1965–1967)

In March 1964 testing, only David Clark Gemini suits had proven acceptable without further development for Apollo Command Module operations. This caused NASA to explore the use of Gemini-based David Clark suits for the

Figure 6.6.1. The Apollo Block I David Clark A1C suit system (courtesy NASA)

Figure 6.6.2. Final A1C configuration (Grissom, Chaffee, and White, left to right, courtesy NASA).

earliest Apollo missions that did not involve the Lunar Module or EVA to permit additional development time for the Apollo dual-purpose launch/entry/EVA suits. This two-suit system approach was adopted in September/October 1964 with the Apollo Block I contract being formally signed in March 1965.

NASA gave the David Clark Apollo Block I suit the designation A1C. The A1C utilized the David Clark Gemini entry and restraint system (Figures 5.2.1 and 5.2.2). Unlike the Gemini system, the A1C helmet featured a fiberglass outer shell over the pressure-sealing and sun visors (Figures 6.5.3Q and 6.6.1) for impact protection, and a flotation device was provided in place of the parachute harness system. During the production of the A1C, the flotation device was initially mounted on the upper part of the chest (Figure 6.6.1). By late 1966, the flotation device was revised into a harness system with flotation devices under each arm (Figure 6.6.2).

The A1C suits were to have started flight service with the first planned manned mission of Astronauts Chaffee, White, and Grissom (Figure 6.6.2). However, a capsule test fire in January 1967 claimed the lives of the first Apollo crew and stopped all program activities for a safety review of all systems. This included the review of all materials for flammability and off-gassing of potentially toxic chemicals, and the results caused the creation of more stringent material requirements. This impacted the lightweight fabric materials and chemical compounds used in Apollo pressure suit fabrication and resulted in revisions and recertifications.

The delay from the safety review, coupled with the progress in Apollo Block II suit development in 1965–1966, caused NASA to reconsider the approach of separate suit systems for Blocks I and II. The outcome was a return to using one suit system, the International Latex suit, for both the Block I non-EVA flights and Block II EVA missions.

6.7 COMPLETING THE APOLLO JOURNEY (1965–1972)

In September 1965, with NASA assuming the Apollo EMU systems integration responsibility, the pressure suit and life support system issues were separated into two contractual efforts. However, Apollo EMU evolution activities continued, which are described in the discussions that follow:

- Pushing to orbit (1965–1967)
- Apollo 7–10: Extravehicular mobility unit and use (1968)
- Apollo 11–13: EMU experience (1969–1970)
- Apollo 14: EMU configuration (1970)
- Apollo 15–17: EMU—improving existing systems and use (1968–1972).

Pushing to orbit (1965–1967)

Before the first extravehicular activity (EVA) on Apollo 9, there would be certification, additional refinements, implementation of flight systems, training, and dress rehearsals. In the drive to an Apollo launch, NASA's first challenge as the systems' integrator was to obtain a fleet of the latest configuration training suits. In September 1965, NASA ordered A5L training suits (Figure 6.7.1A) from International Latex on the basis of the Apollo Block II competition results. This suit model began to appear prior to the end of 1965. The A5L required limited development to accommodate a liquid-cooling garment, and refinements in patterning from the AX5L evaluations. At least 14 A5L suits were made.

1966 was expected to be the year of last changes. Three unmanned missions in that year had set the beginning of Apollo manned missions to start in early 1967. The manned portion was to start with orbital missions to prove out the Command Module and then to verify the Lunar Module systems before venturing to the Moon. The Lunar Module–related orbital missions would introduce the Block II systems, including the Apollo extravehicular mobility unit (EMU). Given the leadtimes associated with ordering, manufacturing, delivering, training processing crews on configuration subtleties, and training flight crews on system usage prior to flight, the Block II Apollo EMU (Figure 6.7.1B) was expected to be made up of the International Latex A6L pressure suit assembly (PSA) and the Hamilton Standard -2 (dash 2) portable life support system (PLSS). The A6L PSA was essentially the flight version of the A5L training suits. By adding an EVA visor assembly, thermal overgarments, a portable life support system, an emergency oxygen supply, thermal overgloves, and thermal insulating overboots, the PSA was transformed into the EVA configuration. In the development of Apollo cover garments, David Clark

(A) ILC A5L training suits (1965)
(a) External view (b) Without covers

(B) ILC A6L (starting configuration, 1966)
(a) EVA system (b) IVA system

Figure 6.7.1. The Apollo Block II preparing-for-the-Moon configurations.

Company was tasked with sharing its Gemini production experience with International Latex. Still absent in 1965–1966 was the chest-mounted display and control module of later flight configurations.

In 1966, it was decided that the backpack PLSS would be left on the surface of the Moon to maximize the geological payload returned in the Lunar Module ascent stage. The possibility of the Lunar Module being unable to dock with the Service and Command Modules raised a new safety concern. The Apollo EMU at the time had only a 5-minute emergency oxygen supply, and an extravehicular transfer from the assent stage of the Lunar Module to the Command Module was estimated to take up to 30 minutes. The first solution was the development of a much smaller and lighter additional system named the ‘‘transfer life support system’’. This was to be stowed in the Lunar Module and used only if needed, thus adding no additional weight or bulk to the EVA suit system. Hamilton designed the transfer life support system to utilize existing Lunar Module environmental control system and Apollo portable life support system components wherever possible to minimize design and certification costs. Only one prototype of this system was fabricated due to additional changes in Apollo requirements.

Before the end of 1966, lunar payload and volume penalties had driven the decision to develop a single, 30-minute, suit-borne backup life support system to support both lunar exploration and the contingency of orbital transfer. The resulting new subelement, the oxygen purge system (OPS), was capable of providing an astronaut with substantially greater than 30 minutes of pressurization, ventilation, and cooling via a purge rate of 8 lb/h (3.6 kg/h) of O_2. This rate was needed to provide both convective and evaporative cooling from the extremely dry expanding gas. If cooling was not required, an optional low-flow setting could provide almost an hour and a half of gaseous life support. The OPS would be stored separately in the Lunar Module and attached via slide-in brackets for EVA assembly and use.

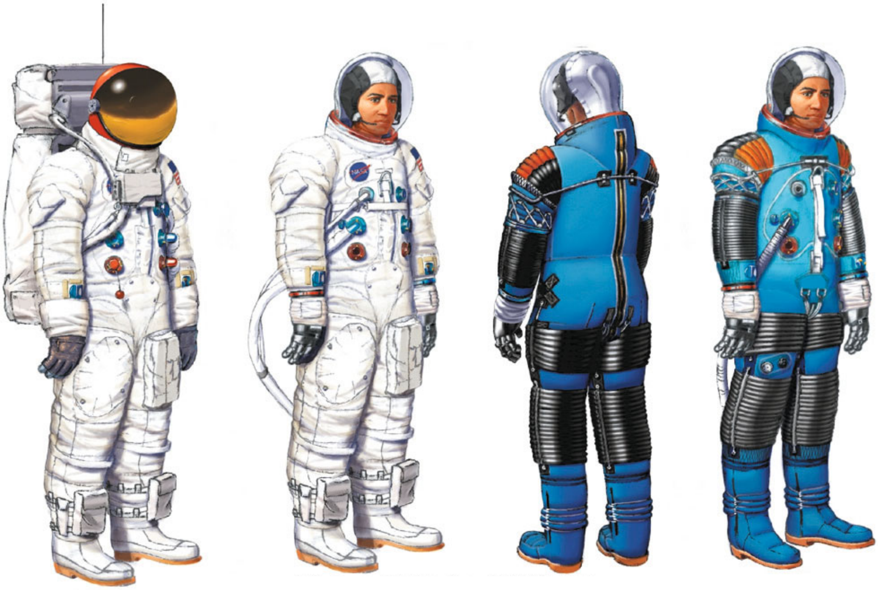
The January 1967 Apollo 1 capsule test fire caused a halt to all program activities until materials and safety reviews were conducted. Material changes resulted in the -3 (dash 3) PLSS. On the pressure suit side, the A6L evolved into prototypes for the A7L PSA that would be used on Apollo 9. These evolutionary improvements included the use of fire-resistant materials, a thermal garment added to the lunar extravehicular visor assembly to cover the neckring, an attached integrated thermal/micrometeoroid garment (TMG), and pressure boots with ankle joints for walking. Many factors combined to cause the thermal garment to be integrated to the pressure garment. With the relaxation of thermal and impingement requirements in 1965, the outer garments had become much thinner and lighter. The NASA experience with the simplicity of integrated EVA cover garments on the David Clark Gemini G4C suits, and the difficulties being experienced with the Apollo suit layered approach, all coincided with a program delay, which gave the opportunity to incorporate an integrated cover garment. At least 25 A6L pressure suits were delivered as part of the Apollo program.

The program delay also permitted the parallel exploration of a chest-mounted display and control system named the "remote control unit" (RCU). While the -3 PLSS was only certifying material improvements, the -4 was additionally developing the RCU. The development was successful, resulting in the -4 PLSS being adopted into the Apollo EMU design in 1967.

Another suit subelement to become part of the pressure suit before the discontinuation of the A6L was the NASA/Air-Lock full bubble helmet. This effort started in late 1964 with NASA's internally initiated development of a full polycarbonate bubble that would attach directly to the neckring, eliminating a connecting (usually fiberglass or aluminum) shell. NASA engineer James O'Kane and Dr. Robert Jones led this development. In 1965–1966, NASA explored a variety of vendors to form optically acceptable helmet bubbles without success. In 1966, Air-Lock Incorporated of Milford, Connecticut, started an internally funded polycarbonate full bubble helmet development. This resulted in the production of optical quality helmet bubbles in 1967. With minor revisions, this helmet has supported Apollo, Skylab, and Shuttle EMU configurations.

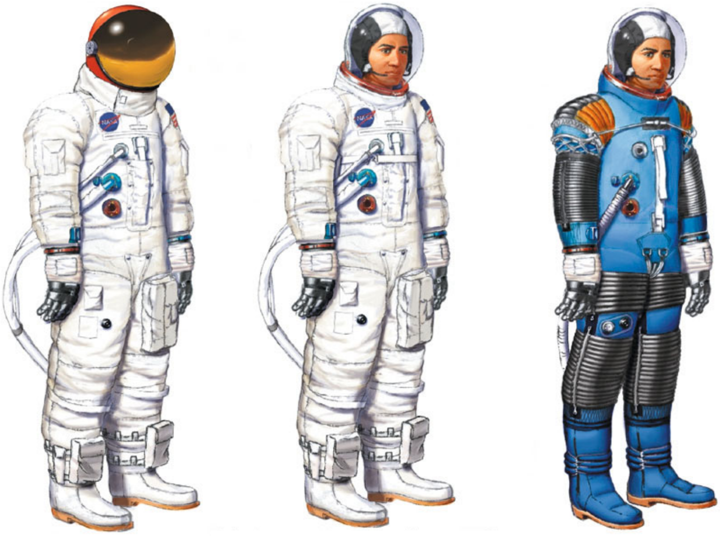
Apollo 7–10: Extravehicular mobility unit and use (1968)

In 1968, the Apollo program was again moving at full speed towards the first manned missions. The unmanned Apollo 4–6 missions had verified the safety and reliability of the revised Apollo vehicle systems. International Latex, which was in full production of A7L pressure suits (Figures 6.7.2 and 6.7.3), produced two types of A7L suits. The configuration for the Lunar Module crewmembers could transform into the lunar surface exploration system. The Command Module pilot (CMP) version lacked bearings in the upper arms, did not use a liquid-cooling



(A) Lunar Module crew EMU system

(a) EVA system (b) IVA level (c) and (d) Without covers (rear and front)



(B) Command Module pilot EMU system

(a) EVA system (b) IVA level (c) Without covers

Figure 6.7.2. Apollo 7–10 extravehicular mobility unit (EMU) configurations.

Figure 6.7.3. A7L suit production floor at International Latex (courtesy ILC Dover LP).

garment, and contained less insulation in its outer garments. These differences not only reduced cost but provided slightly greater crewmember volume within the Command Module. By the end of production, at least 105 A7L suits had been produced. Some Lunar Module–style A7Ls would be retrofitted into A7LB CMP suits for use in the Apollo 15–17 missions.

In October and December, Apollo 7 and 8, respectively, used A7L pressure suit assemblies (PSAs) as launch and entry emergency suits. Apollo 7 astronauts Walter Schirra, Don Eisele, and Walter Cunningham circled the Earth 163 times, performing Command and Service Module prove-out exercises before returning. On the second manned flight, Apollo 8, Astronauts Frank Borman, Jim Lovell, and Bill Anders circled the Moon.

By Apollo 9, the EMU was a highly evolved modular system with over 15 components (see Figure 6.7.4). In order of normal donning, these were as follows: (A) the biomed belt provided astronaut medical data to ground control during EVA; (B) the urine collection and transfer assembly (UCTA) was a male-only device that provided for the hygienic collection, storage, and eventual transfer of liquid waste; (C) the fecal containment system (FCS) provided for emergency containment of solid waste matter when the spacecraft facilities were not an option; (D) the constant wear

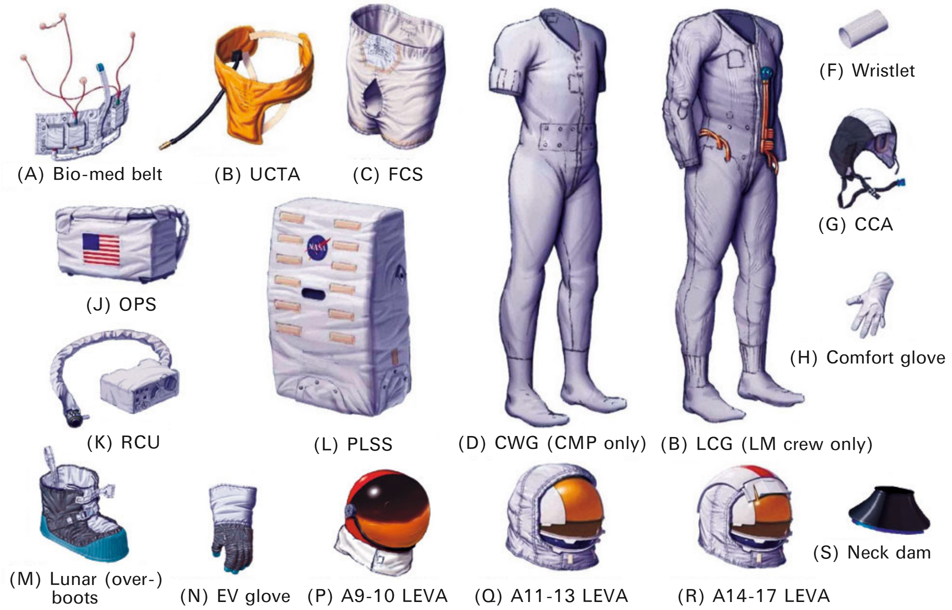


Figure 6.7.4. Components of the Apollo EMU system.

garment provided abrasion protection and better humidity control for the Command Module pilot; (E) the liquid-cooling garment (LCG) provided the crew with cooling in Lunar Module EMUs; (F) astronaut wristlets were frequently worn to provide the wrists with abrasion protection and greater comfort; and (G) the communications carrier assembly (CCA) or "Snoopy cap" supplied communications and bump protection to the astronaut's head. To complete the intravehicular configuration, the astronaut donned the pressure suit's torso assembly, gloves, and helmet. (H) The option of donning comfort gloves provided abrasion protection plus better thermal and moisture control to the hands. The helmet had a feed port for providing food and drink while pressurized.

To convert the PSA from launch/entry configuration to the EVA configuration (see Figure 6.7.4), the astronaut mounted the oxygen purge system (OPS—J) and remote control unit (RCU—K) onto the portable life support system (PLSS—L). For orbital transfers for emergency life support, the OPS could also be strapped behind the head without the PLSS. The RCU would later be attached at the chest to provide easy access to controls and displays. The lunar boots (M) would then be placed over the PSA's pressure boots for surface EVAs. The PLSS/RCU/OPS would then be donned followed by the extravehicular (EV) gloves (N). The EV gloves featured a Velcro attachment of the thermal overglove. This thermal overglove could easily be removed to provide a spare pair of pressure gloves for in-flight emergencies or entry. Finally, the lunar extravehicular visor assembly (LEVA) would be put on over the pressure suit's bubble helmet to allow the astronaut to perform EVAs. The LEVA provided eye protection from potentially permanently

Table 6.7.1. Lunar Module crew extravehicular suit materials.

Material	*Function*
Teflon-coated yarn Beta fiberglass fabric	Fire protection (completely nonflammable in oxygen atmosphere)
Aluminized Kapton/Beta marquisette (super-insulation)	Aluminized Kapton for reflective insulation. Beta fiberglass serves as spacer separating reflective surfaces.
Aluminized Mylar film	Reflective insulation
Non-woven Dacron	Spacer material
Neoprene-coated nylon	Inner liner of the thermal outer garment
Nylon fabric	Restraint (outer) layer of the pressure suit
Neoprene-coated nylon	Bladder material serves as an impermeable layer containing suit pressurization oxygen
Lightweight Nomex fabric	Comfort liner

blinding light and reflection control. Of the three styles of LEVA that would be used in the Apollo missions, the configuration used for Apollo 9 and 10 (P) was the most simple. The Apollo 11 to 13–style LEVA (Q) that followed provided greater thermal protection and a modest level of reflection control. The Apollo 14–17 LEVA (R) provided greater tolerance of dusty conditions and better reflection control. The final Apollo EMU component was not an EVA accessory but rather a post-landing item. With the helmet removed, the neck dam (S) sealed the suit to provide extra flotation and greater in-water comfort/thermal protection in a rescue emergency.

The Apollo A7L pressure suit was made from a variety of materials that were essentially constructed in layers (listed in sequence from the exterior surface of the suit to the interior in Tables 6.7.1–6.7.4). The A7L suit was actually two different configurations. The suit used by the Lunar Module crew had material and feature differences specific for surface exploration (Table 6.7.1), including a liquid-cooling garment (Table 6.7.2). The Command Module pilot used a suit using somewhat different materials (Table 6.7.3), and a constant wear garment was worn in place of an LCG (Table 6.7.4).

The Apollo PSA had many layers. Each layer was specifically selected or designed to perform specific functions. The Apollo outer layer consisted of woven glassfiber called Beta fabric. Because Beta fabric was made of glass, it would not burn and would melt only at temperatures substantially above the burning temperature of most of the materials in the capsule (1,200°F, 649°C). The fact that this material was made of glassfiber seriously limited its abrasion resistance, thus this outer layer of Beta fabric was coated with Teflon to improve its service life. Super Beta supplanted Teflon-coated Beta on all Apollo suits, starting with Apollo 10, to

Table 6.7.2. Liquid-cooled garment materials.

Material	*Function*
Nylon Spandex mesh	Retains tubing close to skin
Polyvinyl chloride (PVC) tubing[a]	Water distribution for cooling
Porous lightweight nylon	Comfort layer

[a] The PVC tubing in the Apollo liquid-cooling garments was a PVC that contained a plasticizer to make the tubing soft enough to bend. While this worked well for the Apollo program, the plasticizer caused filter clogging in the Shuttle EMU program and posed problems for long-term preservation of Apollo spacesuits and components as historical artifacts.

Table 6.7.3. Command Module pilot's suit materials.

Material	*Function*
Teflon-coated yarn Beta fiberglass fabric	Fire protection (completely nonflammable in oxygen atmosphere)
Nomex (high-temperature nylon)	Snag and fire protection
Aluminized Kapton/Beta marquisette (super-insulation)	Aluminized Kapton for reflective insulation. Beta fiberglass serves as spacer separating reflective surfaces
Aluminized Mylar film	Reflective insulation
Non-woven Dacron	Spacer material
Neoprene-coated nylon	Inner liner of the thermal outer garment
Nylon fabric	Restraint (outer) layer of the pressure suit
Neoprene-coated nylon	Bladder material serves as an impermeable layer containing suit pressurization oxygen
Lightweight Nomex fabric	Comfort liner

Table 6.7.4. Constant wear garment.

Material	*Function*
Cotton	Comfort layer

Table 6.7.5. Specifications for the -5 and -6 portable life support systems.

Duration (maximum)	4 hours
Metabolic rate: Average (3 hours) Average (4 hours) Average (6 hours) Peak	 1,600 Btu/h (403 kcal/h) 1,200 Btu/h (302 kcal/h) 930 Btu/h (234 kcal/h) 2,000+ Btu/h (504+ kcal/h)
Total useful heat removal capability	5,550 Btu (1,399 kcal)
Gas flow rate	6 CFM 170 litres/min)
Liquid flow rate	4 lb (1.8 kg) per minute
Weight	50 lb (22.7 kg)
Overall dimensions	8.4 × 16.6 × 27.2 in. (213 × 422 × 691 mm)
Power source: Battery	33 watts, rechargeable silver–zinc
Expendables: O_2 storage pressure O_2 storage quantity (recharge) Water storage quantity (recharge) LiOH quantity Contaminant control cartridge weight	 850 psi (57.8 atm) 1.0 lb (0.5 kg) 7.5 lb (3.4 kg) 2.7 lb (1.2 kg) 4.5 lb (2.0 kg)

improve its useful life. However, the lifespan of the thermal/micrometeoroid garment (TMG) was still limited by this material. The nested TMG layers of insulation also proved to be extremely labor intensive, thus expensive to produce. To enhance the flame protection of the suit's cover garment, the outer two layers of Mylar were replaced by two layers of Kapton sandwiched with layers of Beta fabric marquisette. The Beta marquisette was bonded to the Kapton to retard breakage of the Beta insulation.

Extensive testing resulted in minor changes and the -5 (dash 5) PLSS (Tables 6.7.5 and Figures 6.7.5 and 6.7.6). This was part of the Apollo 9 configuration EMU that entered extensive manned vacuum chamber testing (Figure 6.7.7) before use in Apollo 9.

In NASA's patent of the A7L Apollo pressure suit that would come later (patent No. 3,751,727), NASA acknowledged ILC Industries' (formerly International Latex) employees Lenard F. Shepard, George P. Durney, Melvin C. Case, A. J. Kenneway, Robert C. Wise, Dixie Rinehart, Ronald J. Bessette, and Richard C. Pulling as well as the ILC organization for their technical contributions to Apollo.

Apollo 9 launched into space on March 3, 1969. On the fourth day of the Apollo 9 mission, Lunar Module Pilot Russell Schweickart and Commander James

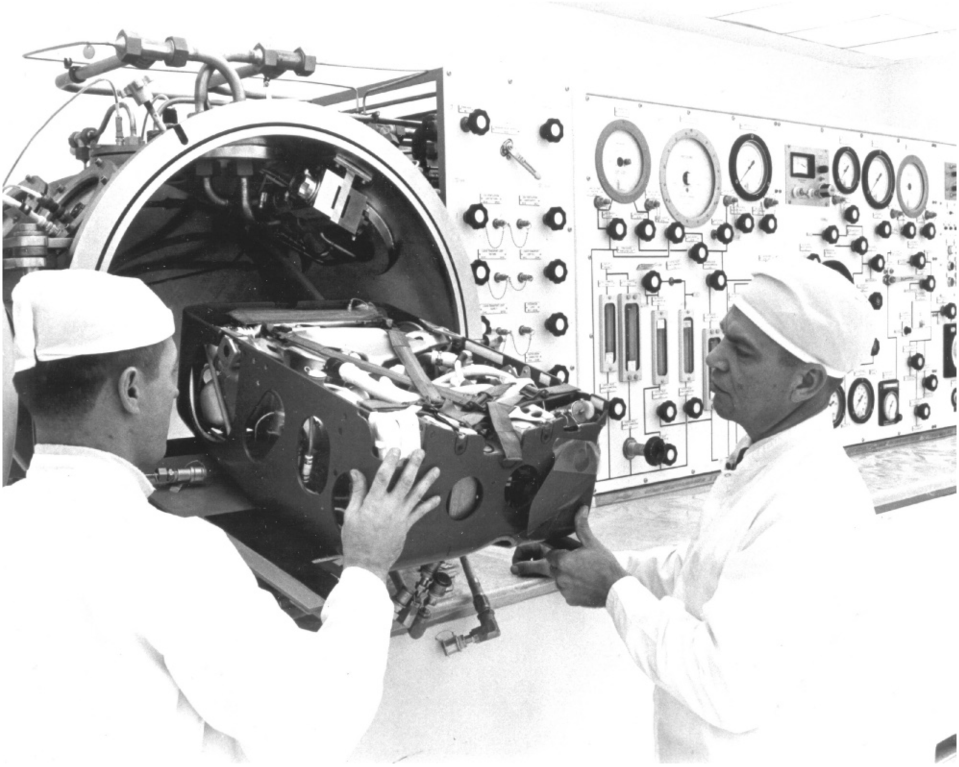


Figure 6.7.5. Hamilton pre-delivery testing of ''PLSSs'' (courtesy Hamilton Sundstrand).

McDivitt went into the Lunar Module. The astronauts then depressurized both the Command and Lunar Modules. Schweickart emerged from the Lunar Module to test a foot restraint system called the ''golden slipper'', and his EVA was supported by a PLSS (Figure 6.7.8). David Scott partially emerged from the Command Module's hatch, supported by an umbilical system connected to the Command Module's life support system. The EVA lasted only 46 minutes but allowed verification of both EVA configurations of Apollo's EMU. This would be the only Apollo EVA prior to the Apollo 11 lunar landing mission.

Apollo 11–13: EMU experience (1969–1970)

While Apollo 10 was preparing for and making its historic flight to the Moon, the lessons learned from the Apollo 9 mission were incorporated into the EMU that would support the early Apollo missions (Figures 6.7.9 and 6.7.10). These changes were to the remote control unit and the lunar extravehicular visor assembly (Figure 6.7.4Q). The chest-mounted remote control unit was slightly enlarged and gained a front bracket to hold a camera assembly to facilitate lunar photography. Additionally, the controls were revised for easier use with pressure gloves. The

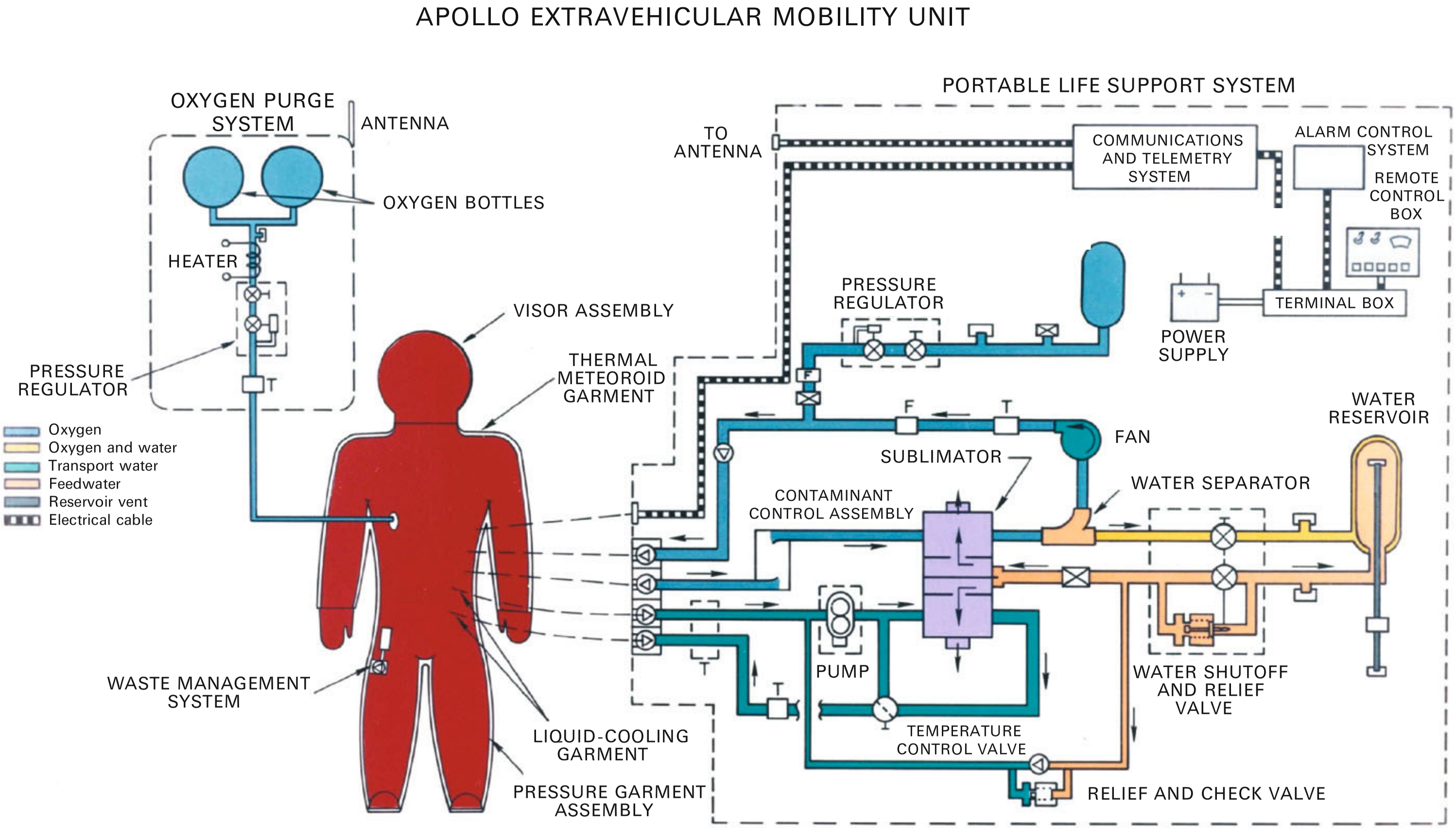


Figure 6.7.6. Apollo PLSS schematic (courtesy Hamilton Sundstrand).

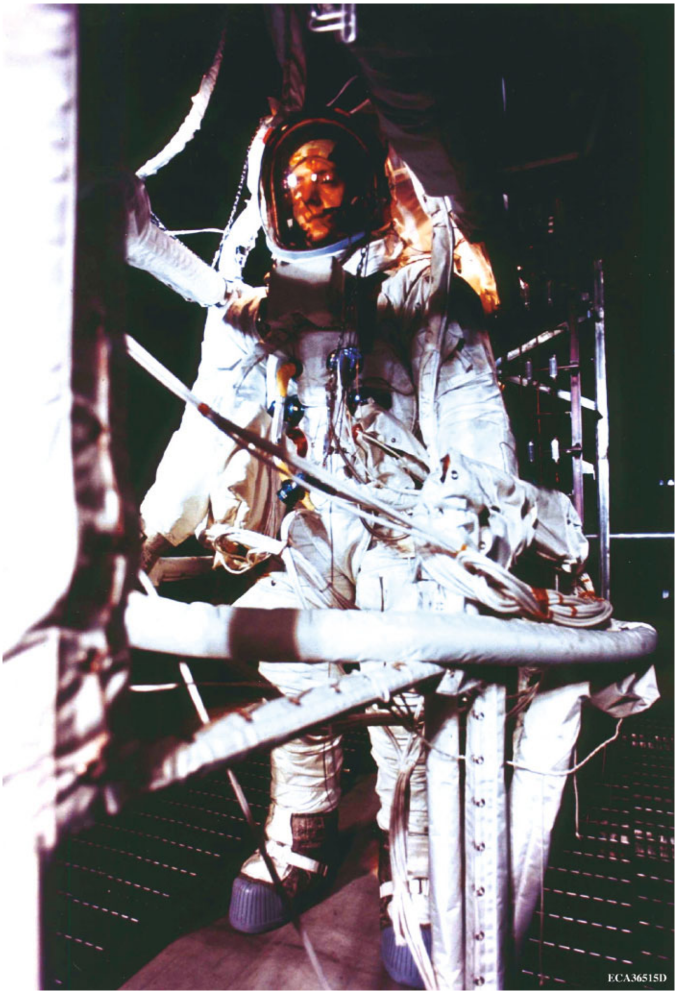


Figure 6.7.7. Pre–Apollo 9 EMU chamber prove-out (courtesy Hamilton Sundstrand).

lunar extravehicular visor assembly gained an outer shell and a thermal outer cover to preclude condensation in the helmet and to provide better light reflection control. The resulting Apollo 11, 12, and 13 spacesuit system (Figure 6.7.11) successfully supported 20 man-hours of extravehicular exploration.

Apollo 11 launched into space on July 16, 1969, heading to a landing site in the Moon's Sea of Tranquility. While satellites had characterized the site as relatively flat and smooth, the automated landing on July 20 had to be interrupted to avoid crashing into a field of boulders. The then manual near surface flight continued almost to the point of having to abort due to fuel consumption before reaching an adequate landing site. However, the landing was successful and two hours after touchdown, four and a half hours early, Astronauts Armstrong and Aldrin were given permission to initiate preparation for the first lunar EVA.

Figure 6.7.8. Apollo 9's Russell Schweickart in first EVA without an umbilical (courtesy NASA).

Preparation took more than two hours. Armstrong had difficulties exiting through the hatch of the Lunar Module due to the dynamics of not knowing what one does not know. The size of the hatch had been reduced to save weight and thus allow more return payload. The suit and backpack had not been redesigned because dimensional studies indicated hatch reduction would be acceptable. Subsequent ground training did not identify difficulties with ingress and egress through the hatch. However, the lesser gravity of the Moon introduced unforeseen challenges. Some of the highest heart rates recorded by Apollo astronauts were encountered while entering or leaving through the Lunar Module's front hatch.

While climbing down the nine-rung ladder, Armstrong pulled a lanyard, which deployed the modular equipment stowage assembly and activated an attached TV camera. This allowed blurry black-and-white images of the first lunar EVA to be broadcast immediately to over 600 million people on Earth. Armstrong stepped off *Eagle*'s ladder and into history with the words: "That's one small step for (a) man, one giant leap for mankind." With that act, he fulfilled the first half of President John F. Kennedy's goal to land a man on the Moon and return him safely to Earth before the end of the 1960s.

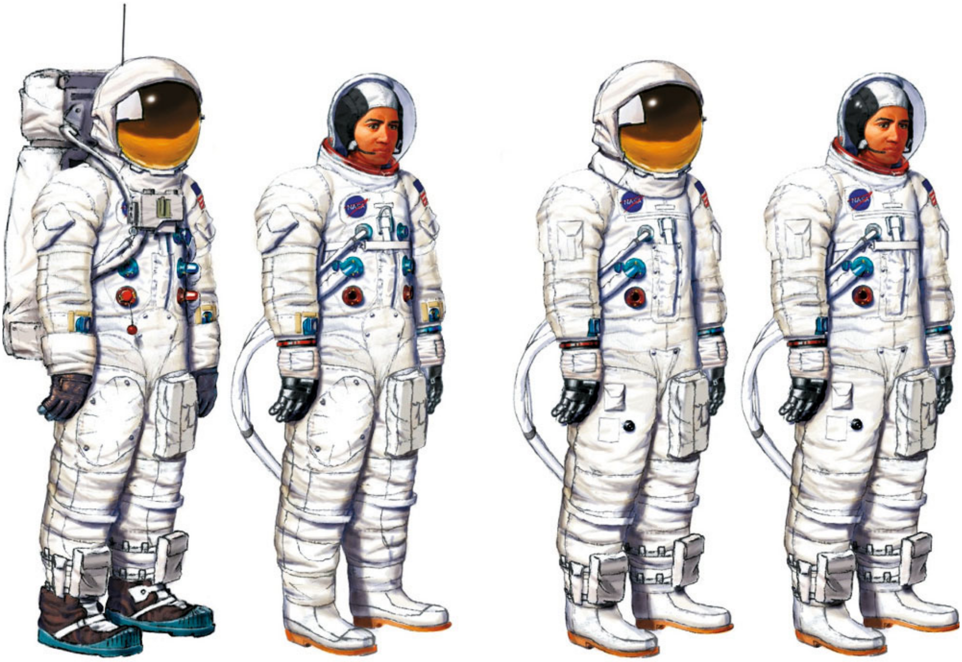

(A) Lunar Module crew EMU system
(a) EVA system (b) IVA level
(B) Command Module pilot EMU system
(a) EVA system (b) IVA system

Figure 6.7.9. Apollo 11–13 EMU configurations.

To provide documentation of the post-landing condition of the Lunar Module, Armstrong took photographs of the vehicle. He then collected soil samples using a sample bag on a stick before he removed the television camera from the modular equipment stowage assembly to provide the Earth with a panoramic sweep. Next, he mounted the camera on a tripod 40 ft (12 m) from the Lunar Module. Aldrin joined Armstrong in testing methods for moving around, which included two-footed kangaroo hops or what was characterized as the "lunar lope". The weight of the life support backpack created a tendency to fall backwards, but this did not pose a serious problem for maintaining balance. Loping quickly became the preferred method of movement. The fine surface soil was quite slippery but under the surface the ground was very hard. The two astronauts inserted the pole of the American flag into the ground and the EVA was temporarily halted for a call from U.S. President Richard Nixon.

The suit's insulation effectively protected the lunar explorers from the intense heat of direct sunlight and the cold of the lunar shadows. "Aldrin remarked that moving from sunlight into *Eagle*'s shadow produced no temperature change inside the suit" (from *Walking to Olympus*—see Portree and Trevino in the Bibliography).

The astronauts later deployed the Early Apollo Scientific Experiment Package, which included a passive seismograph and a laser ranging retroreflector. Armstrong

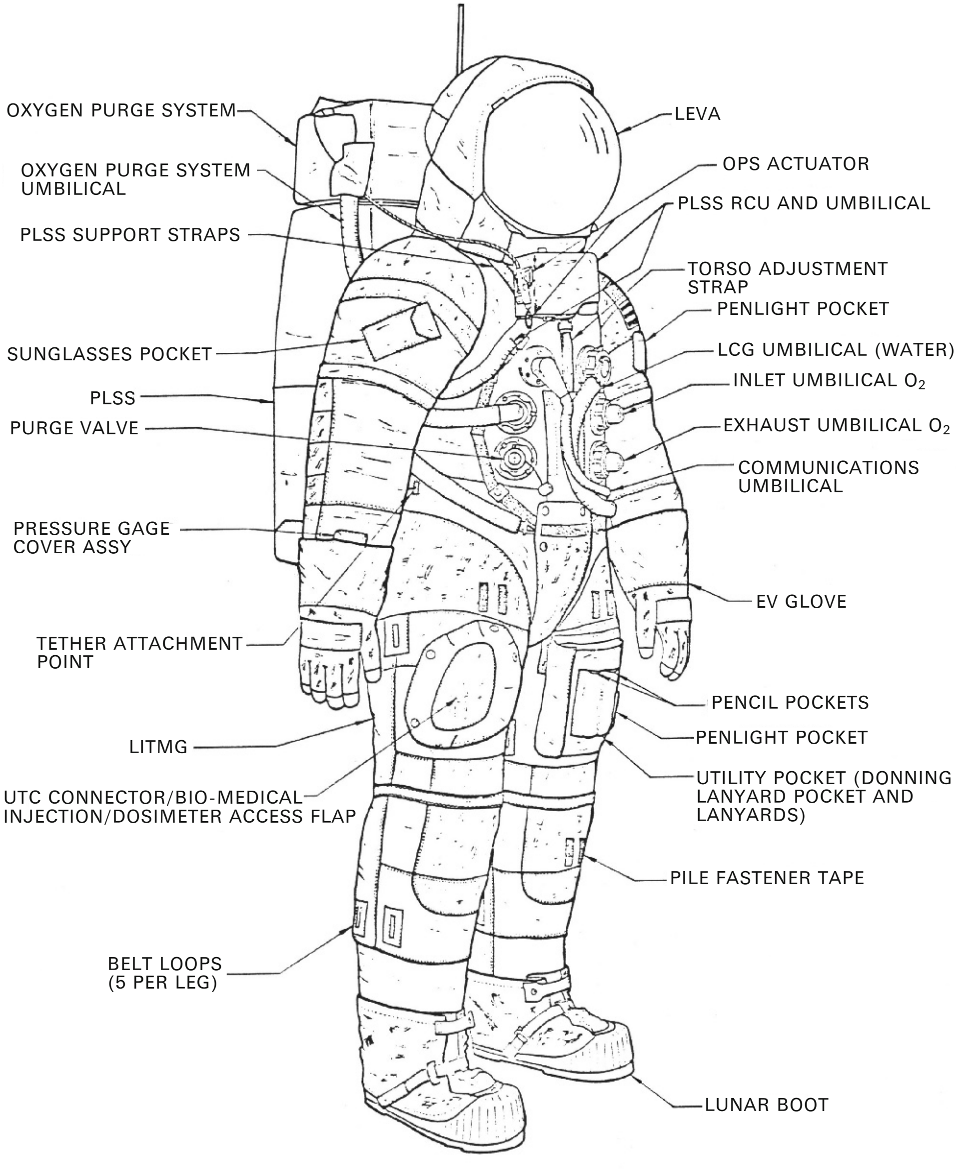


Figure 6.7.10. Apollo 11–14 EMU features (courtesy NASA).

then loped about 400 ft (120 m) from the Lunar Module to take photographs from the rim of East Crater. Aldrin collected two core samples, using a geological hammer to pound the collection tubes into the ground.

Aldrin reentered *Eagle* first. The astronauts had difficulty lifting a film container and two boxes containing more than 48 lb (22 kg) of lunar surface material samples

Figure 6.7.11. Apollo 11 EMU supporting man's first lunar exploration (courtesy NASA).

into the Lunar Module even though they were provided with a cable pulley device. Once all was on board the Lunar Module, the astronauts discarded their life support backpacks, lunar overshoes, and other unneeded equipment onto the lunar surface before closing the hatch to conclude the 2-hour 32-minute EVA. The *Eagle*'s rockets were fired to send the ascent stage back into lunar orbit while leaving the descent stage on the lunar surface. The Lunar and Command Modules then reunited in orbit for the return to Earth, the pressure suits serving as part of the crew's survival and escape system.

On November 14, 1969, Apollo 12 rocketed away from the Earth for a rendezvous with the Moon's Surveyor Crater. The location was so named because it was the landing site of the *Surveyor 3* unmanned spacecraft. One of the mission goals was to see if Apollo vehicle technology could allow landing close to a specific target on the Moon. While coming in for the landing, visual sighting of the lunar surface was lost at an altitude of 40 ft (12 m) by dust being kicked up by the descent engine. In spite of this, the Lunar Module landed within 600 ft (180 m) of Surveyor 3.

Apollo 12 had two EVAs during Earth day, November 19. The first EVA started with setting up Apollo 12's color television camera, but the camera failed to operate.

Later it emerged that, during setup, the camera had inadvertently been pointed at the Sun. As the direct sunlight had damaged the camera's vidicon tube, video coverage was lost. After exhausting attempts to obtain video, Astronauts Charles Conrad and Alan Bean proceeded to plant the flag, collect nearby rocks, and deploy the advanced lunar science experiment package approximately 600 ft (180 m) north of the Lunar Module. Conrad at one point lost his balance for a low-speed and harmless fall due to uneven footing. With some difficulty, the astronauts successfully unloaded a plutonium fuel cartridge from the Lunar Module to power the experiment package. This process required care, as the cartridge was hot enough to melt a hole in a spacesuit. During the EVA, the astronauts observed the Command Module pass overhead at an altitude that gave it the appearance of a bright star. As the suits had picked up amounts of lunar dust, the astronauts dusted each other off before climbing back into the Lunar Module to complete the 3-hour 39-minute EVA and for a sleep period.

Still on Earth day November 19, Conrad and Beam emerged to perform a 3-hour 48-minute EVA that would include exploring the lunar site, collecting geological samples, and inspecting *Surveyor 3*. Conrad and Bean first stowed the dam—collecting geological samples and observations—that finally reached *Surveyor 3*. The astronauts were initially puzzled by the apparent change in *Surveyor*'s color. Ultimately, it was determined that the nearby landing had created a fine coating of tan-colored lunar dust. Conrad and Bean gained the distinction of being the first extraterrestrial archeologists, as they had collected pieces of *Surveyor 3* for study by scientists interested in the long-term effects of the lunar environment on equipment. The astronauts then returned to the Lunar Module and stowed the lunar sample boxes and mission tools. Once inside, they jettisoned the portable life support systems and unneeded EVA items before blasting off for their rendezvous with the Command Module.

On their return, the EVA astronauts reported hand fatigue from fighting the internal pressure of the A7L gloves. The integrated thermal/micrometeoroid garments were severely worn by abrasion from lunar dust. It was also reported that lunar dust that was brought into the Lunar Module from the EVAs became weightless during ascent to lunar orbit and the astronauts found breathing difficult without their helmets. Also, the lunar dust forced the astronauts to clean the air filter screens in the Command Module every two to three hours during the flight home.

Apollo 13 introduced a minor change from the Apollo 11 and 12 EMU configuration in that the mission commander's suit featured red stripes on the knees, shoulders, and helmet for ease of identification during and after the mission. This tradition of using stripes to differentiate between EVA crewmembers continues to this day.

Apollo 13 launched on April 11, 1970, for a mission to the Moon's Fra Mauro Hills. On April 13 during cryogenic oxygen and hydrogen tank "stirs", a sharp bang was followed by a significant vibration. Astronaut Jack Swigert radioed: "Houston, we've got a problem." Apollo 13 was 205,000 miles (329,845 km) from Earth. The Command Module's electrical power generation systems were soon lost, and the Lunar Module was immediately activated to provide a "life boat". During the emergency lunar orbit and return, the crew of Apollo 13 wore their suits to stay as warm as possible in the powered-down Command Module and the emergency low-level power-down of the Lunar Module. The carbon dioxide removal cartridges for the EMU life support "backpacks" were designed to be additionally usable in the Lunar Module life support system, as Hamilton Standard had made both. The backpack cartridges were used to provide the time needed to adapt the Command Module carbon dioxide removal cartridges to the Lunar Module's life support. The successful entry and splashdown of Apollo 13 on April 17, 1970 illustrated the expertise of the U.S. space community.

Apollo 14: EMU configuration (1970)

This single-mission version of the Apollo EMU logged 19.2 EVA man-hours and differed from the Apollo 11–13 configuration in that it introduced the "baseball cap" lunar extravehicular visor assembly, which was mounted externally to the visor assembly's outer shell and featured a hinged center shade (Figure 6.7.4R). This visor system would also be used on Apollo 15–17. The visor changes were to further reduce internal reflections inside the helmet.

Apollo 14 also carried, as an emergency device, the buddy life support system. This was an 8 ft (2.5 m) liquid-cooling umbilical, which allowed an astronaut with a malfunctioning backpack life support system to activate his oxygen purge system (OPS) and draw cooling water from his companion's healthy backpack until they could return to the Lunar Module. This would allow the OPS to run on low flow, thus doubling the duration of emergency life support. Otherwise, the Apollo 14 EMU configuration was the same as that of Apollo 11–13.

Apollo 14 launched on January 31, 1971 for an arrival at Fra Mauro, which was originally the landing site of the aborted Apollo 13 mission. Apollo 14 astronauts Alan Shepard and Edgar Mitchell would perform two EVAs. The first, on February 5, started with the collection of 42.9 lb (19.5 kg) of contingency samples. They then deployed the TV camera, an S-band dish antenna, and a U.S. flag. The astronauts deployed an advanced lunar science experiment package about 495 ft (150 m) west of the Lunar Module and set up a laser-ranging retroreflector approximately 100 ft (30 m) beyond. The EVA lasted 4 hours 49 minutes and traversed about 1,815 ft (550 m) of lunar terrain.

The February 6 EVA, lasting 4 hours and 46 minutes, was a quest to reach the rim of Cone Crater on foot. Cone Crater was formed by a meteoroid impact creating a pit 1,000 ft (300 m) wide. Geologists hoped its natural excavation would have left bare eons of lunar geological history, possibly including the Moon's oldest rocks. For this attempt, the astronauts had a two-wheeled "rickshaw" cart named the "modularized equipment transporter" (MET) for hauling tools, equipment, and samples, but owing to the rough terrain the astronauts would end up carrying it. While the rim appeared nearby, due to the lack of Earthly visual distance references, it proved to be much farther than it appeared. The astronauts would have to terminate and return without achieving their goal. While the second Apollo 14

EVA did not reach the rim of Cone Crater, the mission returned with 94.6 lb (43 kg) of lunar samples.

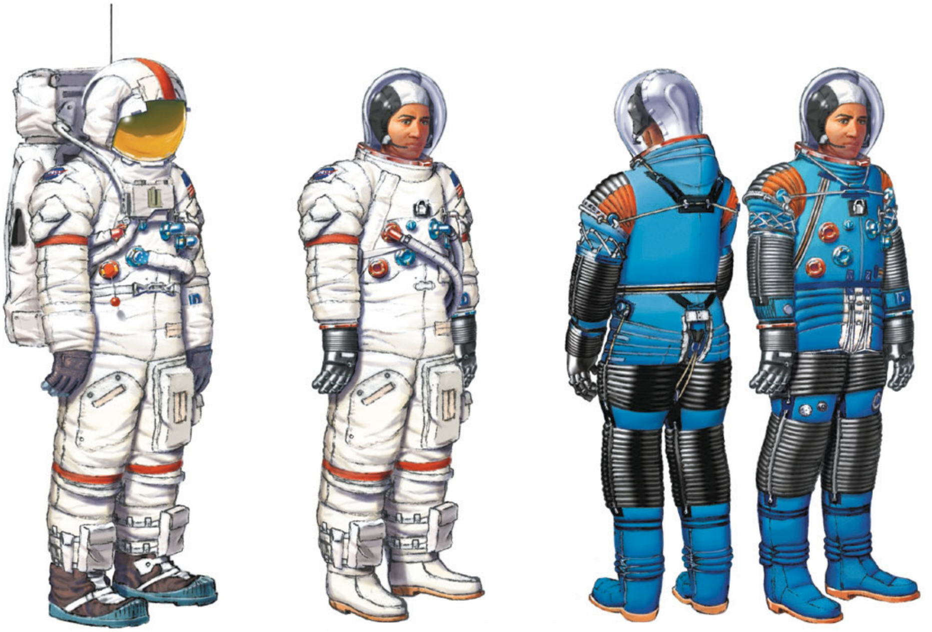
After returning to the Lunar Module, Shepard and Mitchell started their close-out activities for the EVA. During a delay, Shepard fastened an item that he had carried on his person from Earth onto a mission tool handle that had served its mission purpose and with another personally carried item in hand announced, "Houston, while you're looking that up, you might recognize what I have in my hand is the handle for the contingency sample return; it just so happens to have a genuine six iron on the bottom of it. In my left hand, I have a little white pellet (a golf ball) that's familiar to millions of Americans. I'll drop it down. Unfortunately, the suit is so stiff, I can't do this with two hands, but I'm going to try a little sand-trap shot here." The swing missed, so Shepard repeated the action and the second swing hit lunar soil. Mitchell added, "You got more dirt than ball that time." The ball moved only 2 or 3 feet. On Shepard's third try, he finally connected and the ball was sent off-camera on a fairly low trajectory. Shepard tried with a second ball and again connected. While the trajectory of the shot appeared similar to the previous ball, Shepard announced, "Miles and miles and miles," implying that it was traveling for miles and miles in the one-sixth Earth lunar gravity. While this was not a NASA-sanctioned experiment, it did earn the first U.S. astronaut to travel into space the additional distinction of being the first man to play golf on the Moon. Shepard's homemade golf club head is currently on display at the U.S. Golf Association's Hall of Fame in Far Hills, New Jersey.

Apollo 15–17: EMU—improving existing systems and use (1968–1972)

The Apollo 15, 16, and 17 configuration of EMU (Figures 6.7.12A and 6.7.12B) supported 13 EVAs for a total of 124.6 man-hours in space. The use of the "rover" on these missions (Figures 6.7.13 and 6.7.14) allowed the astronauts to travel miles rather than yards from the lunar base to perform surface exploration and collect samples. This system configuration was born out of economic, programmatic, and schedule necessities. In 1963, NASA planned to have a second-generation suit system being implemented to support lunar activities in the 1970–1973 timeframe. The challenges encountered in preparing for Apollo EVA and developing in parallel a more advanced suit system had proven greater than imagined.

With the beginning of 1968, the Apollo 9 and 10 EVA systems were delivered and the hardware for the later flights was in flow. Looking forward, NASA recognized that, starting with the mission that became Apollo 15, astronauts would be provided with the capability to travel farther and explore more with the introduction of the Lunar Rover. The AX5L had been used for the suit-to-rover interface definition and NASA was aware of visibility problems with this vehicle/suit combination. NASA did not correct this condition in the A6L and A7L suits because it intended to rectify the condition, as well as increase mobility and safety, with its next generation of suits.

Apollo 18 and later advanced suit developments that were still proceeding in parallel were not yet ready for certification and implementation. Additionally, the



(A) Lunar Module crew EMU system

(a) EVA system (b) IVA level (c) and (d) Without covers (front and rear)

(B) Command Module pilot EMU system

(a) EVA system (b) IVA level (c) and (d) Without covers (front and rear)

Figure 6.7.12. Apollo 15–17 EMU configurations.

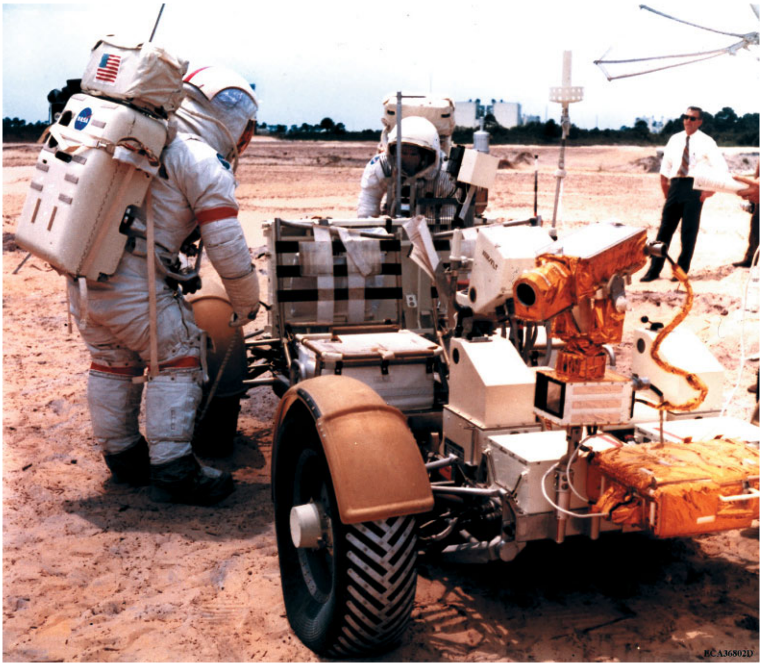


Figure 6.7.13. Earthly training prepares for lunar exploration (courtesy NASA).

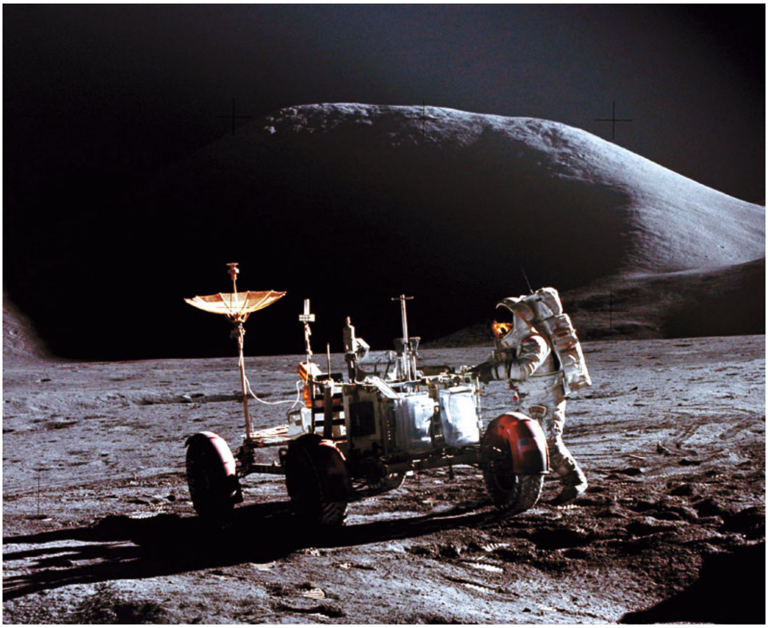


Figure 6.7.14. The rover extends man's ability to explore (courtesy NASA).

current vehicle system architecture would not support the then current advanced suit volumes and masses. Also, NASA budgets were declining, and another suit competition would cost time and funds that the Apollo program did not have. Changing suit suppliers would cause parallel suit programs and support groups during phase-out of the old configuration and the certification/implementation of the new. NASA therefore elected to embark on improving the performance of the then current EMU using existing resources to create what was hoped to be an interim suit system at minimum cost.

The suit side of this effort that would ultimately produce the A7LB started with an informal NASA/International Latex study of alternative zipper entry systems. From this emerged two entry concepts that were initially referred to as "A8L" and "A9L". In parallel, International Latex was tasked with formulating solutions to the mobility and seated visibility issues of the A7L. The participants of the internal effort proposed the creation of A8L and A9L prototypes for comparative development and testing. What NASA funded was selection of one design for fabrication and test. The selection picked the A9L concept and the resulting prototype was officially named the A7LB.

As the A7LB suit progressed in development, its manufacturer experienced a change in identity. International Latex Corporation was founded in Dover, Delaware, in 1937 and quickly grew to a diverse corporation. In 1947, International Latex split into four separate divisions. By 1955, the Metals Division had been renamed the Specialty Products Division and had become involved in pressure suit development. During the 1960s, International Latex had been acquired by a larger corporation, which was subsequently merged with yet another. In January 1969, the parent corporation made the Specialty Products Division a separate organization named ILC Industries and sold 30% of its holdings to the public. ILC stayed in the Dover (Delaware) area supporting the Apollo and subsequent space programs without interruption. In 1982, the remaining 70% of ILC shares would be publicly sold, severing all ties with International Latex.

The A7LB EVA pressure suit was introduced as part of the Apollo 15 EMU and differed from the Apollo 14 A7L in the entry zipper orientation, addition of neck and waist joints, use of lower-torque shoulder joints, manufacturing improvements in the gloves, and revisions in the brief for improved walking performance. The A7L used one set of zippers that consisted of a rubber inner pressure-sealing zipper and an outer metallic restraint zipper that ran down the back, between the legs, and up the front almost to the waist. The A7LB used two zipper sets. One set started at the left shoulder and closed diagonally across and down the chest to finish slightly above the waist on the right side. The second set started at the left front of the suit slightly above the waist and circled around the back parallel to meet the other zipper set on the right side. A special clasp held the zipper sets together when closed. The neck joint allowed the suited and helmeted wearer to look down or up by arcing around the shoulders on cable slides attached on either side of the neckring. The removal of the A7L-type rear-entry system allowed a waist joint to be added to the torso to supply the ability to bend without the need for a front drawstrap mechanism. The glove system was revised to use more bonded and molded components for greater durability and reduction of the cost of manufacture. While the walking stride of the suit was made easier with the A7LB, the Apollo astronauts would still prefer the lunar lope.

Life support also posed technical challenges. Where the Apollo 10–14 portable life support system provided six hours at 930 Btu/h (234 kcal/h) with 30 minutes of emergency backup, NASA desired an 8-hour primary capacity with 2 hours of backup. Evaluation revealed that the 8-hour capacity could be easily obtained in all but two areas: oxygen and water storage. The increased oxygen storage requirement was met by increasing the fully charged pressure from 1,110 psi to 1,500 psi (76 atm to 102 atm) by refinements in manufacturing and recertification of the bottles. The problem of increasing the water storage for extra duration was not as simple. There was not enough volume remaining in the backpack envelope to add the increased water capacity cost-effectively. A review of the Lunar Module interfaces with Grumman and NASA showed that a protrusion on the right side of the backpack would not impact the Lunar Module or cause a crew mobility constraint. A right side–mounted, auxiliary water tank (called by some a "Volkswagen" tank) was designed and added to create a retrofitable increased water capacity for the "8-hour" portable life support system.

The development of a 2-hour backup life support system, called the secondary life support system, was started. This was to provide liquid cooling and 2 hours of life support in the same volume as the existing 30-minute oxygen purge system (OPS). However, the buddy life support system (BLSS), which was first used on Apollo 14, was a simple 8 ft (2.4 m) liquid-cooling umbilical that would allow one backpack to cool two astronauts. With the OPS on its low-flow setting, the BLSS/OPS combination could provide almost an hour and a half of emergency life support. This OPS/BLSS combination was ultimately deemed acceptable and the secondary life support system was terminated while still in its design stage.

Apollo 15, the first mission to use the OPS/BLSS configuration, would have five EVAs: four on the lunar surface and one in deep space on return. The four surface EVAs would be spent surveying the Hadley–Apennine mountain range. Ground preparation for this ambitious undertaking included the development of a complete complement of 1g training systems that included Earth-operating rovers and backpacks to support astronaut comfort and rigorous/lengthy training times through functioning liquid-cooling garments (Figure 6.7.13). The Lunar Roving Vehicle would be used on the second, third, and fourth EVAs of the mission (Figure 6.7.14).

The first Apollo 15 EVA was performed on July 30, 1971, shortly after landing on the Moon. The landing site was selected for its relatively flat topography in a valley. Like Apollo 14, dust kicked up during descent obscured final landing visibility. To verify having landed in the correct location and to aid in planning the surface excursions that would follow, Commander David Scott and Lunar Module Pilot James Irwin depressurized the Lunar Module. Using umbilical connections to the vehicle's life support, Scott stood up with his shoulders through the top hatch to enable him to get his bearings. This "standup EVA", or SEVA, lasted 33 minutes.

The next day brought the first surface excursion of the mission. David Scott and James Irwin started the EVA by setting up the improved TV camera and collecting a contingency sample, respectively. The astronauts then unstowed and deployed the Lunar Roving Vehicle developed by Boeing. Irwin would lose his balance and fall several times during the deployment without harm to himself or his EMU. Although the rover was designed to have four-wheel steering, the astronauts found that the front-wheel steering was not operating, but that the use of only rear steering was adequate for the mission. About three hours into the EVA Scott and Irwin set out on a 6.2-mile (10 km) exploration heading south along the rim of Elbow Crater to the St. George Crater, near Hadley Rille. During the ride the astronauts reduced suit cooling to avoid becoming cold since their metabolic rates were low while riding on the rover. The astronauts encountered some difficulties from a condition called "zero-phase lighting"—a phenomenon that occurs when light reflected from the landscape opposite the Sun is almost as bright as from the direction of the Sun and makes obstacles difficult to discern. The astronauts used a rake to collect "walnut-sized samples" near St. George Crater before returning. On their return, the astronauts deployed an advanced lunar science experiment package. As Scott had used more oxygen than he had expected, flight controllers terminated the EVA 30 minutes early. This second Apollo 15 EVA lasted 6 hours 34 minutes.

Through the second EVA (first surface EVA) of the mission, Irwin had been extremely thirsty because his drink bag had failed to operate and did not operate during any of the Apollo 15 EVAs. Also, both astronauts suffered pain in their fingers caused by the hard contact of their fingernails with the inside of the glove fingertips. Irwin needed help to remove his gloves, and elected to trim his nails before the next EVA. Scott left his fingernails alone out of concern for reducing touch feedback. Dust from the EVA made the life support connectors tight and difficult to operate.

The third Apollo 15 EVA came on August 1. In this 7-hour 13-minute expedition, Scott and Irwin would utilize the rover to cover 7.5 miles (12.5 km), exploring southeast to Mt. Hadley Delta and deploying a heat flow experiment. For this excursion, the front steering of the rover was inexplicably operational. They traveled to the foot of the Hadley Delta mountain, passing Index, Arbeit, Crescent, Spur, and Window Craters. At Spur Crater they collected the "Genesis Rock", which today is still believed to be a piece of original lunar crust that is more than 4 billion years old. Scott called Spur a "goldmine" of interesting geological samples. Back at the lunar base, Scott had difficulty drilling a core hole, hurting his hands in the attempt. Then the 10 ft long (3 m long) core tube could not be easily removed and was left until the next EVA. The U.S. flag was planted at the end of this 7-hour 16-minute EVA.

August 2 saw Apollo 15's fourth EVA (lunar surface EVA #3). This EVA would last 4 hours 20 minutes and was Scott's fifth career EVA, establishing a world record that would not be surpassed until 1984, when Cosmonauts Leonid Kizim and Vladimir Solovyov performed six EVAs outside Salyut 7. The EVA was delayed almost two hours to let the crew rest after they experienced irregular heartbeats. This was traced later to potassium deficiency that was complicated in

Irwin's case by failure of his suit drink bag. Scott and Irwin managed to free the core tube, which became stuck on the last EVA, but could not take it apart to stow it because of problems with a malfunctioning visor. They used a wrench and 28 minutes later succeeded. Irwin and Scott proceeded west on the rover to Scam Crater, and then turned northwest to Hadley Rille. This EVA marked the first time Apollo astronauts passed out of sight of their Lunar Module.

In support of Apollo 15, the rover permitted almost 28 miles (50 km) of surface travel at an average speed of 5.7 mph (9.16 km/h). The longest single "drive" was 14 miles (23 km) with a maximum distance from the base camp of 3 miles (5 km). During the three rover excursions, the astronauts collected nearly 176 lb (80 kg) of samples.

On August 5, 1971, during the return trip, Command Module Pilot Alfred Worden performed the world's first deep-space EVA some 171,000 miles (273,600 km) from Earth. Unlike the surface-reflected warmth of lunar EVAs or orbital EVAs protected from radiation by Earth's inner magnetosphere, this was a new environment for humankind. To minimize potential radiation exposure, this EVA lasted only 41 minutes during which Worden made three round trips to the Scientific Instrument Module bay built into the side of the Service Module to retrieve film packages and check on experiments. Worden's life support was provided by a 27.4 ft (8.3 m) umbilical attached to an inlet connector of his suit and a Hamilton Standard, Apollo program, pressure control valve (PCV) attached to the outlet connector. This simple single-feed hose with PCV purge provided a pressurized environment, ventilation flow, and removal of carbon dioxide and humidity. This EVA was supported by James Irwin who guided Worden's umbilical from the hatch of the Command Module. This PCV and umbilical combination would also provide the primary life support for the Apollo 16 and 17 deep-space EVAs.

Apollo 16, launched on April 16, 1972, was the only expedition planned to the lunar highlands. John Young was the Mission Commander, and Charles Duke and Thomas Mattingly were the Lunar Module and Command Module Pilots, respectively. The mission would include four EVAs, three of which would be on the surface of the Moon. Lunar dust–related conditions such as sticking zippers, difficult working glove disconnects, life support connectors, and bearings plus difficulty in reading gauges were now becoming normal for lunar exploration.

The first EVA came on April 21 and lasted 7 hours 11 minutes. In preparing for this EVA, Duke had trouble getting into his suit because he had grown 1.5 inches (4 cm) as a result of weightlessness. This was a physiological effect of weightlessness that the Apollo program had not taken into account during suit fitting. They deployed the U.S. flag and an experiment package before preparing to depart on the rover. The rover initially started with no rear steering and indicated that one battery was low on power, but it became fully operational once under way. Young and Duke drove past Flag, Spook, Buster, and Plum Craters collecting samples as directed by videoconference with geologists on Earth. After their return, Mission Control relayed the news that the House of Representatives had approved the initial funding of the Space Shuttle. John Young leapt 3 ft (1 m) into the air and saluted the flag. This gesture would have future significance as Young became the commander of the first Shuttle mission in 1981. Duke also jumped for joy but slipped and fell on his life support backpack; although he was unharmed, this caused much concern to Hamilton and NASA personnel on Earth.

On April 22, while emerging for the second EVA, Young broke the radio antenna off his backpack while working his way out the hatch, resulting in a small reduction in signal strength. The astronauts performed geological surveys as they traveled to and returned from Stone Mountain. The EVA lasted 7 hours 23 minutes.

The next day the exploration goal was Smoky Mountain. Young and Duke performed the 5-hour 40-minute EVA successfully and without noteworthy incident. During the three rover EVAs, astronauts with tools and samples traveled 16.6 miles (26.7 km) at an average rate of 4.8 mph (7.8 km/h). The longest day's exploration distance was 7.2 miles (11.6 km), reaching a point that was 2.8 miles (4.5 km) from the Lunar Module. With the surface explorations complete, John Young and Charles Duke returned to lunar orbit and a successful rendezvous with the Command Module.

The last Apollo 16 EVA was in deep space during the return to Earth. On April 25, Command Module Pilot Thomas Mattingly performed an EVA that lasted 1 hour 24 minutes. The EVA permitted recovery of mapping and panoramic camera film packages, inspection of the spacecraft's exterior, and retrieval of a microbial ecological evaluation device. Before returning to the cabin, he opened his visor briefly to allow him to see the stars, taking care not to look in the direction of the Sun.

Apollo 17, which was the last crewed U.S. mission to the Moon, had some differences from the preceding missions. Apollo 17 had a career geologist, Harrison Schmitt, as one of the lunar explorers. The television equipment had been omitted to save weight and extend the Lunar Module's hover time before having to land or abort. Veteran astronaut Eugene Cernan was the mission commander.

The first EVA was carried out on December 11, 1972. The first crew task was the unloading of the rover, followed by experiment deployment and planting the flag, but part of the rover's fender was accidentally damaged in the process. Cernan tried to repair it with tape before starting their travels south to Steno Crater in an area called the Central Cluster, however, the damaged fender fell off before the first scheduled stop. The astronauts were showered with dust but continued and placed two explosive packages to be set off after Cernan and Schmitt departed and to be recorded by instruments in the Apollo 17 experiments package being left behind. The EVA had lasted 7 hours 12 minutes. During the Apollo 17 crew's sleep period, John Young, Apollo 16's commander, led the effort to develop a repair for the next day back on Earth.

Before the start of the December 12 EVA, the repair procedure for the rover's fender was radioed to Schmitt and Cernan. The repair would be accomplished by the use of folded maps and two lamp clamps. After completing the repair, the astronauts set off to conduct geological exploration on a path that took them to South Massif. At 7 hours 37 minutes, this EVA set a world record for the longest EVA that would stand until May 13, 1992, when the STS-49 mission astronauts Thuot, Hieb, and Akers performed an EVA of 8 hours 29 minutes using Shuttle EMUs.

On December 13, 1972, the last 20th-century human exploration of the Moon would be conducted. This day's activities would take the lunar crew to North Massif. Their EVA time would be 7 hours 16 minutes. During the three Apollo 17 sorties, astronauts explored 22.3 miles (35.9 km) of the lunar surface at an average speed of 5 mph (8.1 km/h). The longest mission sortie was 12.5 miles (20.1 km) with the greatest range from base of 4.7 miles (7.6 km). At the time, Schmitt and Cernan expected they would be the last humans on the Moon until the late 1980s. They left the Moon on December 14 carrying 253 lb (115 kg) of samples, 2,120 photos, and the distinction of being the being the last humans on the Moon in the 20th century.

During the return voyage on December 17, 1972, Command Module Pilot Ronald Evans performed a 1-hour 7-minute EVA to retrieve film from the Service Module. This had the dual distinction of being the last Apollo EVA and humanity's last deep-space EVA to date (Figure 6.7.15).

Figure 6.7.15. Apollo's and man's last deep-space EVA (courtesy NASA).

6.8 APOLLO SUIT SYSTEM REVIEW

The Apollo Extravehicular Mobility Unit (EMU) reliably and effectively supported the Apollo missions. The Apollo EMU was the first U.S. spacesuit system to use autonomous life support in EVA and had greater mobility than any preceding space pressure suit. The Apollo 9–14 configurations of EMU had adequately performed their missions and the Apollo 15–17 configurations rectified many of the shortcomings of the earlier EMUs. However, the technical approach to the pressure suits had some unforeseen and interesting nuances that became apparent by the end of the program. The following paragraphs illustrate a few of these phenomena.

Apollo Block I/II mobility elements required more effort to bend and hold bent positions than would have been acceptable for extensive lunar exploration. In a KC-135 lunar gravity simulation, the spring-back from an Apollo suit in a bent-over position was so pronounced that the suit subject thought someone else in the aircraft had kicked him. However, this was understood and was the reason advanced suits were developed for the canceled Apollo Block III missions.

Food and water accommodations were imperfect. While it was never experienced in flight, having a pass-through in the helmet for water and liquid food bottles had a risk of not sealing when the bottles were removed. A failure to reseal, due to the dusty lunar conditions, could have threatened mission success and the astronaut's life. Water bottles frequently leaked. On at least two flight occasions, orange juice that had leaked became stuck to crewmembers in unintended places. With suited astronauts not being able to wipe the orange juice off, skin irritation resulted in a matter of hours.

Another unforeseen problem with the non-redundant cable-based restraint system, used on the arms and legs of the Apollo EMU and many other suit systems of the 1960s, was the effect of cable failure under pressure during manned usage. On several occasions, test subjects were walking on a treadmill, sometimes in a vacuum chamber, when a leg cable failure would be experienced. Since the purpose of the leg cables was restraint to keep the legs from growing due to the inflation pressure, loss of this restraint on a particular leg meant that the boot would try to move down, but would be limited by the top of the foot to some degree. This was uncomfortable enough, but if the subject was walking at 3 mph on the treadmill, the resulting gait was interesting, to say the least.

On one notable occasion, a subject was exercising on the treadmill at vacuum in a chamber when, apparently, no one was aware that a leg restraint pulley had seized. The restraint cable continued to move back and forth in the now stationary pulley until it slowly sawed through the pulley's axle and restraint was lost, resulting in the familiar "growth spurt" of the leg and termination of the test. This time, however, the results were a little different. The pulley was located in the crotch area, and as the suit was deflated in preparation for doffing, the subject noticed a rapid and alarming increase in temperature in the groin area. He was removed with alacrity. Technicians noted that the pulley and surrounding components were too hot to handle. Attempts made to recreate the incident at sea level with a suit instrumented for temperature were unsuccessful.

One of the hallmarks of the Apollo flight suit program was the customization of pressure suit assemblies for the individual crewmember. In addition to making plaster hand casts, crewmembers had full body casts made, with only their necks, heads, hands, and feet extending from the cast. They stood with arms outstretched in front, gripping a horizontal bar, while a technician applied plaster of Paris to the torso and limbs. An exothermic reaction was involved, and it was incumbent on the technician to add water quickly to any areas that a concerned crewmember indicated was growing too warm. Once made, the body casts then supported the manufacture of a set of pressure suits customized to the astronaut's shape. This was usually a set of three: one to be used for training; one to be retained for flight; and a third to be held in reserve as a backup suit should the training or flight suits become damaged. At least 139 model A7L or A7LB suits were created to support the Apollo 7–17 missions. While some standard-size pressure suits were made, the custom set approach was the principal influence on Apollo suit quantities.

7

Advanced development for canceled Apollo missions

From the beginning of the Apollo contract, NASA recognized that the development of the initial suit system was only a first step for lunar surface exploration. It was believed that effective exploration would require a more specialized spacesuit than the initial system recounted in Chapter 6. This began with NASA funding Litton Corporation for advanced pressure suit development in 1962. In 1963, NASA's Manned Spacecraft Center (MSC) located in Houston, Texas, started developing requirements for a later Apollo suit system that was to commence operation in the 1970–1973 timeframe. For these later missions, NASA was planning for extended stays leading to bases to permit extensive study of lunar geography. Also in 1963, NASA's Ames Research Center located at Moffett Field, California, was tasked with advanced spacesuit development.

To understand the state of potential advanced suit technologies in 1963, it may be helpful to reflect on the suit technology approaches available and the effects of internal pressure on these systems. When a fabric suit is pressurized, it not only tends to become stiffer (hard) and hence less mobile, it also tends to change shape. This can be demonstrated by blowing into the sleeve of a latex dishwashing glove and sealing it. If you collapse the sleeve, the air pressure in the glove increases, the palm area of the glove tries to assume a round shape and the glove stiffens, and all of these tendencies resist efforts to grasp a tool. While pressure gloves are designed to generally retain shape and have features to enhance pressurized mobility, they present an area of great challenge. Minor shape changes can cause hard contacts that could result in bruising and even nerve damage. The same analogy applies to pressure suit arms, legs, and torso. As outlined in Section 7.1, most of the advanced approaches in 1963–1965 controlled shapes by using hard-shell segments in non-flex areas coupled with more effective mobility elements.

In 1965, the advanced extravehicular activity (EVA) suits gained a specific place in the Apollo program, the Block III vehicle system, and a timetable for implementation. Following this, the number of organizations involved in advanced suit

K.S. Thomas and H.J. McMann, *U. S. Spacesuits*, Springer Praxis Books,
DOI 10.1007/978-1-4419-9566-7_7,

development grew to include International Latex, Hamilton Standard, David Clark Company, AiResearch, NASA's Manned Spacecraft Center, and Webb Associates. These organizational endeavors are discussed by manufacturer in Section 7.2. While such efforts did not result in a single design model reaching space service, they would have far-reaching effects (see Section 7.3).

7.1 EARLY ADVANCED SUITS (1962–1965)

There was a window of opportunity for "advanced suits" to have been part of the original lunar missions. Pressure suit mobility and durability in the first two years of the Apollo program for the initial lunar missions did not progress as rapidly as was planned. If the parallel, advanced suit development had reached technical maturity during this period, the suit systems used on the Moon might have been dramatically different. However, this would have required either finding more volume and vehicle lift capacity for an additional, more advanced EVA suit system, or the more advanced suit system would have needed to additionally support intravehicular activity (IVA) functions, such as launch and entry. IVA suits were required to provide comfort for hours while waiting to launch and under multi-g launch loads. IVA also meant performing in extremely cramped spacecraft cabins and potential emergency pre-launch egress conditions. While advanced suit progress was made during 1963–1965, this path had much greater technical challenge and would take longer to reach an acceptable design prototype level.

The greatest amount of advanced development during this period came from Litton's Aerospace Division, whose work was based on earlier developments. In the 1950s, Litton's Dr. Sigfried Hansen developed a concept that looked something like the Tin Man in the *Wizard Of Oz* (Figure 6.1.1A) to facilitate real time vacuum tube development inside a vacuum chamber. The concept used human-shaped metallic sections where the human body does not bend, and attempted to create constant volume mobility joints where mobility was required. Constant volume is the ideal because if the joint does not change volume during movement and the center of pressure remains coincident with the center of rotation, there would be essentially no effort to move or hold position. Litton's first attempt was the Mark I pressure suit. This "hybrid" suit had a "hard" metallic upper torso and "soft" fabric hips and legs. The upper torso featured a "slash" or "bandolier" side entry body seal closure. The body seal closure effectively sealed the pressurized environment inside, unlike the constantly leaking zipper entry systems of the time.

The Mark I featured gimbaled mobility joints (cardanic linkages) that provided more mobility in most areas than the aviation-based pressure suits of the time. The U.S. Air Force was the first to see potential in this odd-looking design, and provided test personnel and technical participation from almost the beginning. By 1960, NASA had also expressed interest in this approach, even though its mobility was still inadequate for any of the then proposed space missions and the suit system did not meet the dual-purpose nature of the early NASA programs.

Figure 7.1.1. Litton's RX-1 (left) and RX-2 (right) prototypes (courtesy Hamilton Sundstrand).

In 1962, NASA funded Litton for advanced spacesuit development. The first Litton prototype was the RX-1 (Figure 7.1.1, left). Like the Mark I, the 1964 RX-1 was also a ''hybrid'' hard/soft suit that had pressure-sealed bearings in the shoulders and upper arms as well as improved design mobility joints. The lower torso assembly, made by Arrowhead Rubber Company, featured a ''soft'' waist-to-thigh assembly that used rolling convolutes for mobility.

Before the end of 1964, an RX-2 design (Figure 7.1.1, right) was also completed. The RX-2 was actually the RX-1 with an added hard lower-torso assembly. The hard lower torso allowed consideration of optionally higher operating pressures to as much as 10 psi (68.94 kPa). One novel feature of the RX-2 was a small crank at about navel height that raised an interior seat to enable head and eye position to be maintained when the occupant adopted a seated position. Two RX-2 suits were created: the first was a retrofit of the existing RX-1; the second was a completely new design.

The next NASA–MSC funded prototype was the Litton RX-2A (Figure 7.1.2). This was a major departure from the RX-1 and RX-2 suits as it employed a ''dual-plane'' closure for entry and exit, incremental sizing elements, a hemispherical

Figure 7.1.2. Litton's RX-2A suit with dual-plane closure (courtesy Hamilton Sundstrand).

helmet, and was the first suit to provide two-axis waist mobility. The RX-2A was also lighter and more mobile than its predecessors. Its construction consisted of an inner aluminum shell, an outer shell of fiberglass, with the space between the shells—consisting of composite (epoxy resin–impregnated fiberglass cloth) structure—being filled with urethane foam insulating material. The Litton prototypes that followed would continue the evolution of being increasingly lighter and more mobile.

Litton Corporation's pioneering of innovative approaches to spacesuit systems included pressure gloves. For the RX-1/RX-2 designs, Litton started with anthropomorphically shaped hard shells in the palm area with a linked series of mechanical rings to form a convolute joint in the wrist. The RX-2A came on the eve of a 1965 competition in the parallel initial Apollo suit system program. Except for refinements, the competition established the base pressure suit design that would support the early Apollo EVA missions. While this early EVA program moved to complete development, certification, and implementation of a "soft suit" into training and flight, the NASA centers continued their prototype level advanced development in parallel.

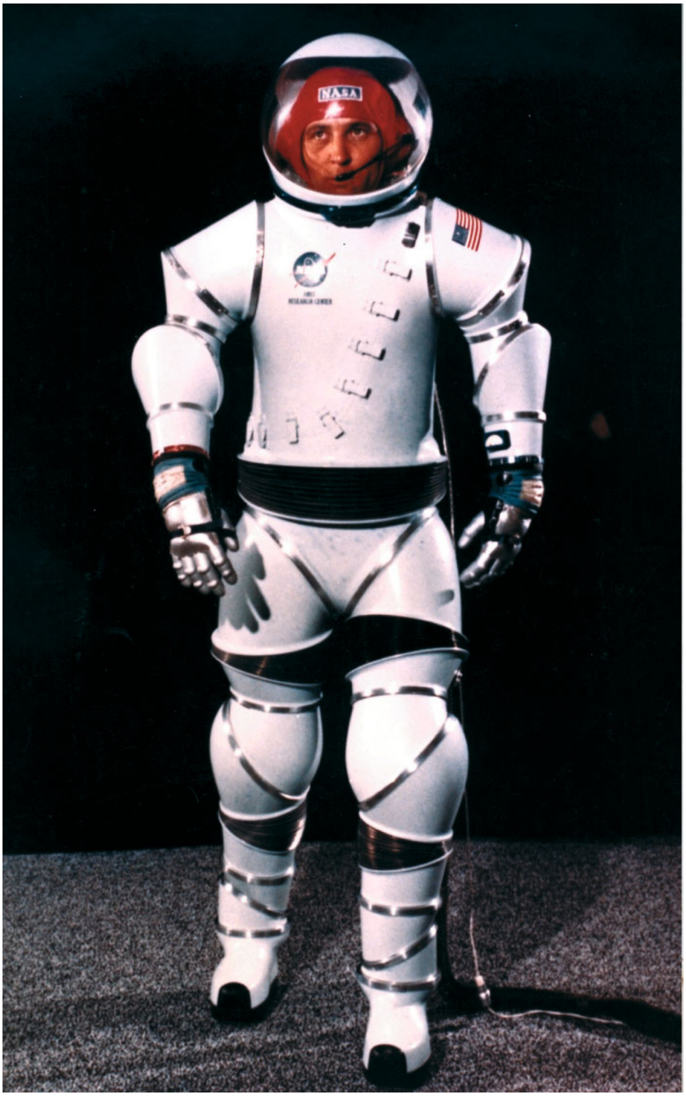


Figure 7.1.3. NASA-Ames Research Center AX-1 prototype (courtesy of NASA).

In 1964, the Ames Research Center also produced its first prototype, the AX-1 (Figure 7.1.3). In contrast to the fabric suits and Litton's hard suits with fabric joints, the Ames AX-1 was an "all hard" concept that introduced mobility through the use of multibearings. This concept by NASA–Ames engineer Hubert C. "Vic" Vykukal used hard-angled suit segments rotating on pressure sealing bearings to provide low-torque mobility. Also, the AX-1 featured metal bellows in the waist, thighs, and calves for additional mobility, and was also different in terms

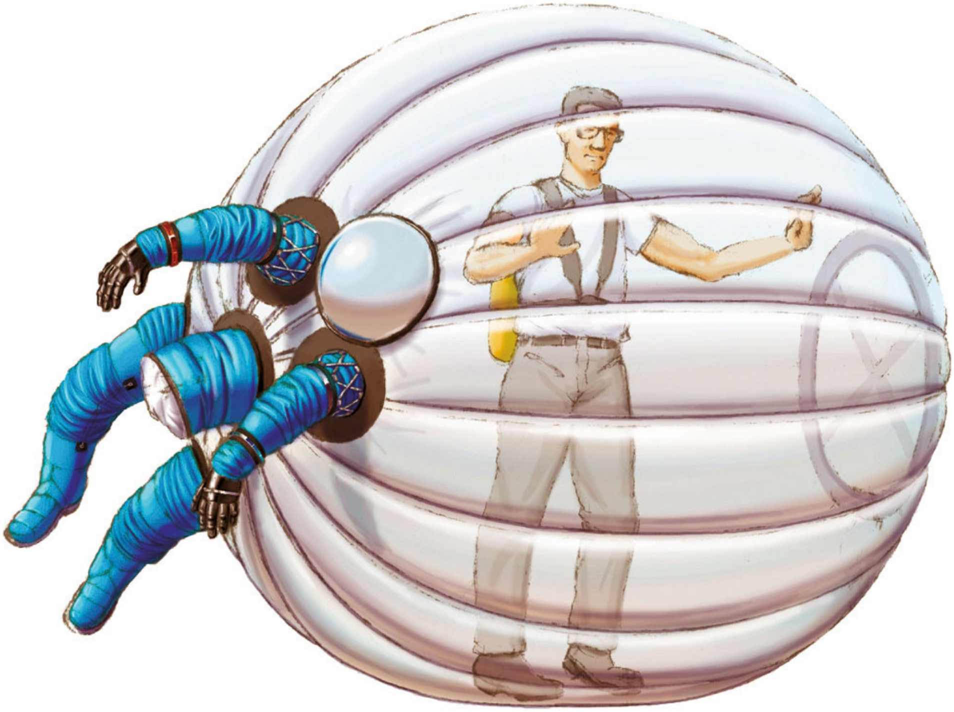


Figure 7.1.4. Johns Hopkins University spherical experiment #1 (1964).

of its manufacturing approach. Unlike the government contracting approach of the MSC programs, these AX suits were accomplished through in-house design and fabrication, with only the metal bellows and off-the-shelf bearings being supplied by outside vendors.

However, what was probably the most technically interesting lunar exploration prototype of this period was not a traditional pressure suit but rather a ball/suit. Johns Hopkins University Applied Resources Laboratory created the spherical experiment #1 (SX-1) prototype using a "gerbil-in-a-ball" approach (Figure 7.1.4). The SX-1's see-through spherical shape would allow the explorer to walk or run in any direction with no pressure suit–type mobility restrictions. The sphere had, at one location, pressure suit–type arms, legs (both Hamilton Standard), and gloves (International Latex Apollo) to permit conventional pressure suit mobility/activity for site exploration and vehicle entry. The sphere also possessed a miniature airlock to permit the pass-through of samples. The prototype was demonstrated in late 1964. Given the "limpness" of the protruding arms and legs in the surviving film footage, the demonstrated pressure was substantially less than the Apollo program's 3.7 psi (25.5 kPa). Had the SX-1 been produced in 1960 rather than made in 1964, this concept might have been viewed as a potentially credible approach instead of a novelty. This does, however, provide a reflection on how fast space exploration technology had progressed in just four years.

7.2 COMPETITION FOR BLOCK III APOLLO SPACESUITS (1966–1971)

In 1965, the Apollo suit programs became realigned with Apollo vehicle systems. Block I was for Command Module flights that did not require the Lunar Module or extravehicular activity. Block II ranged from orbital flights verifying Lunar Module abilities to the first, limited duration lunar missions. The Apollo Block III vehicle configuration was to provide a 45-day Earth-orbital or 35-day lunar visit capacity. Advanced lunar suit system development became part of the Block III vehicle system and continued under the name Apollo Applications Project. In 1965, Block III was expected to reach first flight by 1969. Following 1965, the field of participants grew, adding technical diversity and the potential for competition. As these were really separate parallel developments, they are addressed by manufacturer in the sections that follow.

The Apollo capsule fire in January 1967 caused Blocks I, II, and III to be delayed. In 1968, NASA evaluated the potentially best technologies in a constant volume suit (CVS) comparative testing effort. While the CVS prototypes were more advanced than any preceding pressure suit design, they were not compatible with the volume constraints imposed by the vehicle. The Apollo advanced suits culminated in a final advanced extravehicular suit (AES) competition and selection. However, before a winning design emerged, Apollo Block III flights would be canceled. While it was planned for the winning AES prototype to be a flight experiment on the Skylab Space Station, this would not occur. Thus, although these developments earned a distinctive place in history, they were never used in flight.

Litton Corporation

The next advanced prototype was the Litton RX-3 pressure suit that followed in 1966 (Figure 7.2.1). This was a "hard suit" concept that had an improved dual-plane closure and consisted of 20 interchangeable modules that came in various sizes and could be mixed and matched to provide sizing adjustment. This approach eliminated soft (fabric-based) suiting elements. The RX-3 was the first RX to have a thermal outer garment.

A "Mark II" derivation of the RX-3 technology was made to support NASA's "lunar shelter and extravehicular manned testing" in the summer of 1967. NASA's Manned Spacecraft Center (now Johnson Space Center) needed arms and gloves capable of being pressurized to 14.7 psi (1 atm) over atmospheric pressure for its Lunar Receiving Laboratory to eliminate the need for that unit to have antechambers, operator pre-breathing, and time-limited work periods. Litton produced this system with a derivative of the RX-3 arms/gloves. Later, Litton would use a "Slip-net" technology (a variation of David Clark Company's "Link-net") with reasonable success in the Lunar Receiving Laboratory's 14.7 psi (1 atm) pressure differential application.

A variety of suit prototypes were produced in 1967 by Litton, David Clark Company, NASA's Ames Research Center, the AiResearch Division of Garrett Corporation, and Webb Associates. Litton's next suit design was the RX-4, which

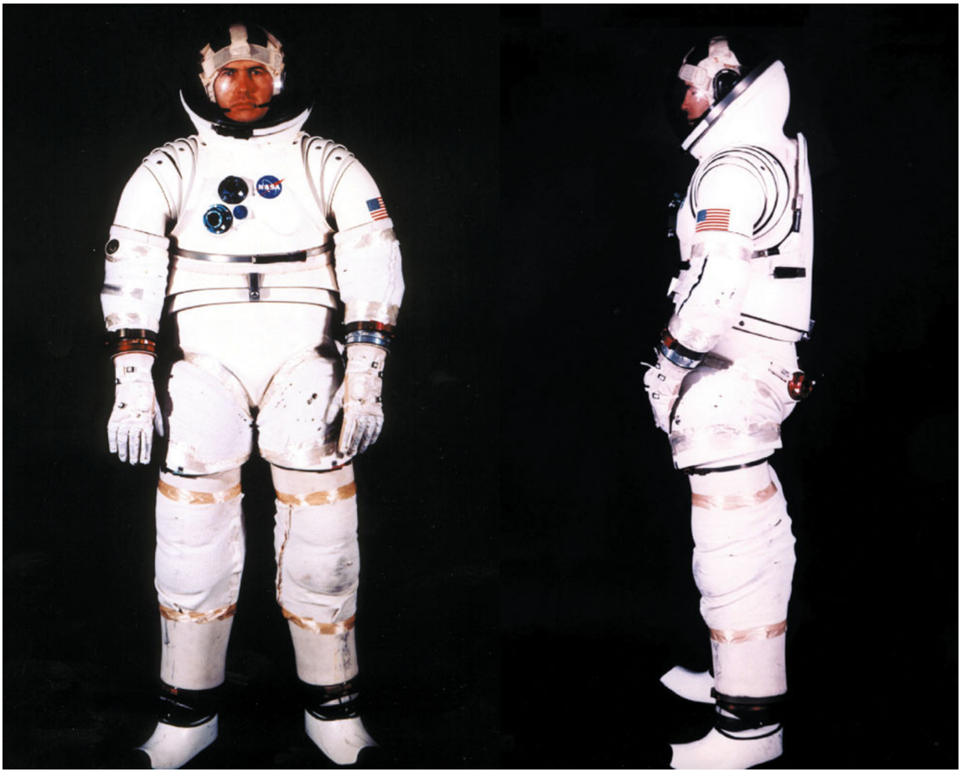


Figure 7.2.1. Litton's RX-4 prototype (courtesy Hamilton Sundstrand).

was similar to the RX-3 except that the frontal area around the life support connectors was indented to provide greater clearance when passing through hatches. The RX-4 explored a NASA concept of a hinged metacarpal (thumb to hand) joint—a concept that would reappear in advanced glove prototypes in the 1980s (see Figure 11.1.1.6).

The Litton RX-5 (Figure 7.2.2) featured a round, single-plane mid-entry body seal closure. The closure was canted higher in the back and lower in the front to minimize the suit's profile. The RX-5 also featured a three-bearing (per side) hip joint for significantly reduced effort in walking at operating pressures up to 7.5 psi (52 kPa).

The RX-5A (Figure 7.2.3) was the last RX prototype design and the last Litton prototype series of 1967. The RX-5A configuration added a waist bearing that allowed the hips and shoulders to rotate independently, had the thermal/micrometeoroid materials integrated into the shell, and featured simplified sizing elements. The sizing element simplification was based on using a slide-in wire loaded in shear to hold joints together, rather than a complex external clamp system. Almost a decade later, the prototype that won the Shuttle EMU competition

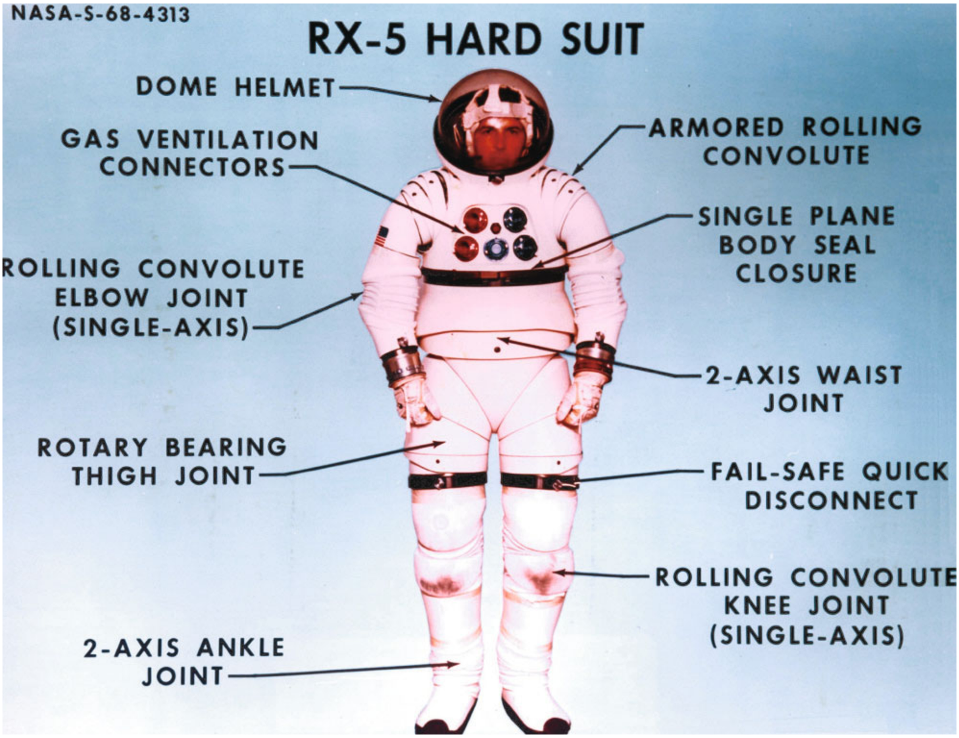


Figure 7.2.2. Litton's RX-5 suit features (courtesy Hamilton Sundstrand).

would feature a waist bearing and a canted mid-entry body seal closure. Almost two decades later, the NASA/ILC Industries Space Station *Freedom* Mark III pressure suit prototype would use a slide-in wire connection, called the "Ortman wire" connector. This approach was later considered but not used for Shuttle EMU sizing elements.

In 1968, NASA–MSC funded Litton to produce a prototype embodying the best constant volume suit (CVS) technologies. For this design (Figure 7.2.4), Litton elected to borrow from the early AX series concept of hard-angled suit segments rotating on pressure-sealing bearings in conjunction with further refined Litton-type fabric bellows joints to provide mobility. The Litton CVS was competitively tested against AiResearch's EX-1 prototype in what would later be referred to as the CVS study. While the Litton design was preferred in the evaluation, neither suit met the Apollo compactness requirements. This led to a follow-on competitive evaluation entitled the advanced extravehicular suit (AES) study.

For the AES, NASA funded both Litton and AiResearch for prototypes. The Litton AES (Figure 7.2.5) featured a single-axis rolling convolute shoulder with the hard suit segments being replaced with collapsible fabric sections that assume the appropriate segment shape when pressurized. The base shoulder

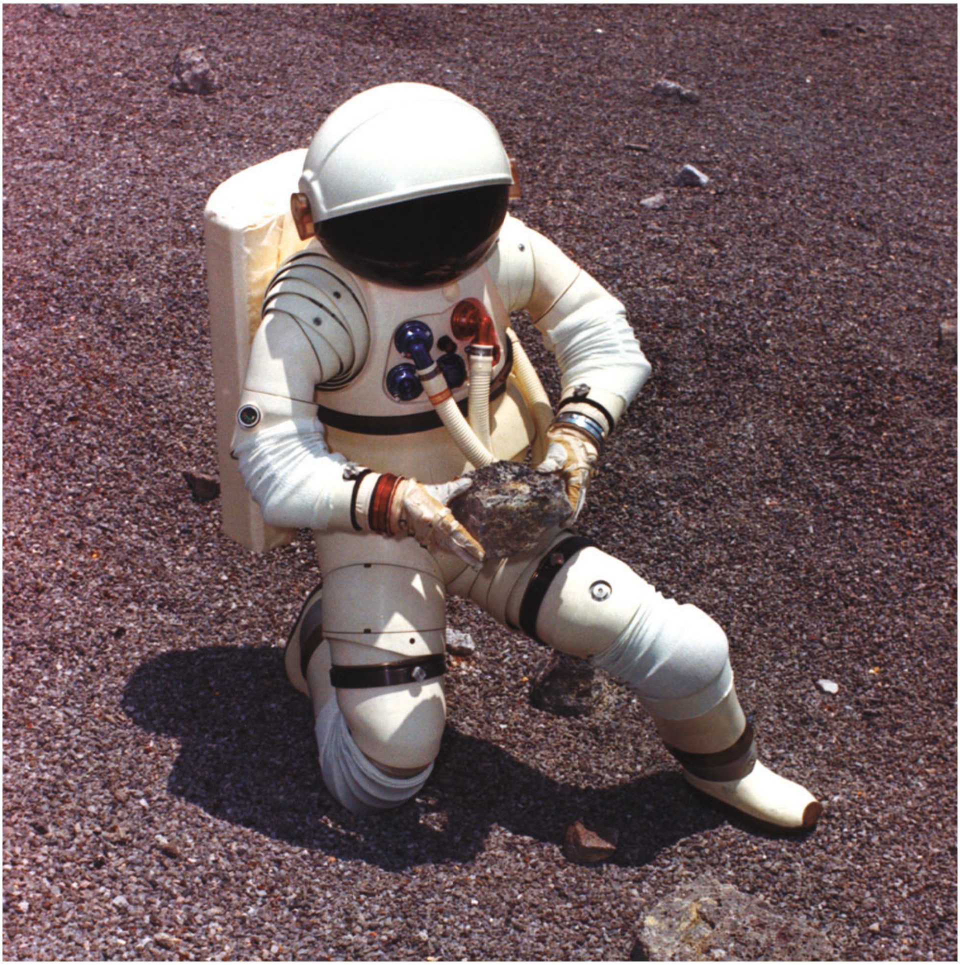


Figure 7.2.3. Open-loop portable life support system and RX-5A (courtesy G. L. Harris).

concept of the Litton AES would see reemergence in the late 1980s in the NASA/ILC Mark III prototype pressure suit for Space Station *Freedom*. Litton built multiple AES prototypes, and perhaps the most interesting was one that was built with a Chromel-R covering. Chromel-R was a "fabric" woven from extremely fine corrosion-resistant steel wire. Because it would not melt when it came in contact with high-temperature objects, this had been used on the gloves and lunar boots of the Apollo EMU and the Gemini IX-A EVA suit systems.

Apollo Block III research and development intended for Apollo 18 and later missions was not limited to pressure suits. NASA also funded limited life support activities. NASA–MSC funded Litton for the development of the open loop portable life support system in 1967–1968. This system was designed around a "breathing

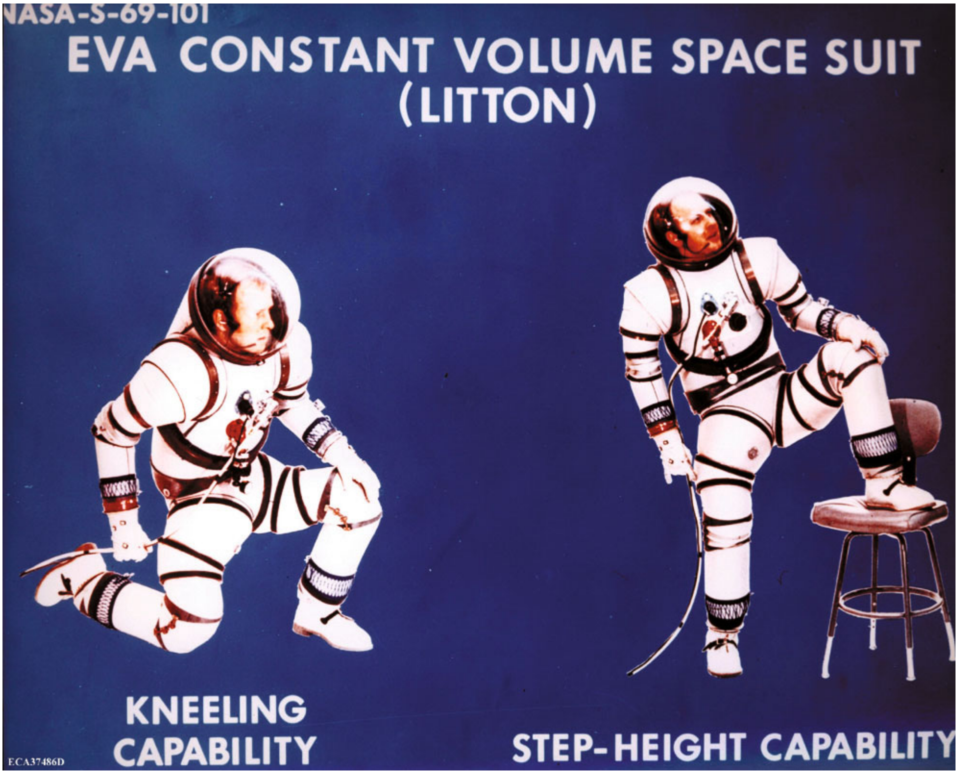


Figure 7.2.4. Litton's constant volume suit (CVS) design (courtesy Hamilton Sundstrand).

vest'' approach, which would eliminate the fan, battery, carbon dioxide removal cartridge, and humidity removal subsystem. It worked on the theory that a properly sized constant flow of oxygen into a bag-like vest—which would expand and contract between the body and the inside suit surfaces during inhalation and exhalation cycles—would provide an adequate breathing supply through a duct located in the oro-nasal area. The ''vest'' consisted of a front and back bag-like assembly made of very flexible, gas-tight material. During inhalation, the bag would be emptied by the expansion of the lungs against the bag; during exhalation, the bag would be filled by the constant oxygen inflow. Part of the flow was provided over the helmet vision area to prevent fogging. The system also featured water cooling via a conventional liquid-cooling garment. However, the water was circulated by a pneumatic pulse pump with the ''motor'' gas being the same oxygen ultimately delivered to the breathing vest. The heat rejection device was a sublimator, but one that operated without a porous plate. Expendable water was fed at four locations sequentially to the outside of the metallic sheets behind which the cooling water was circulated. Overlaying the metallic sheets was a soft foam, which acted as a pressure-restricting barrier. The expendable water would be metered, flow out over

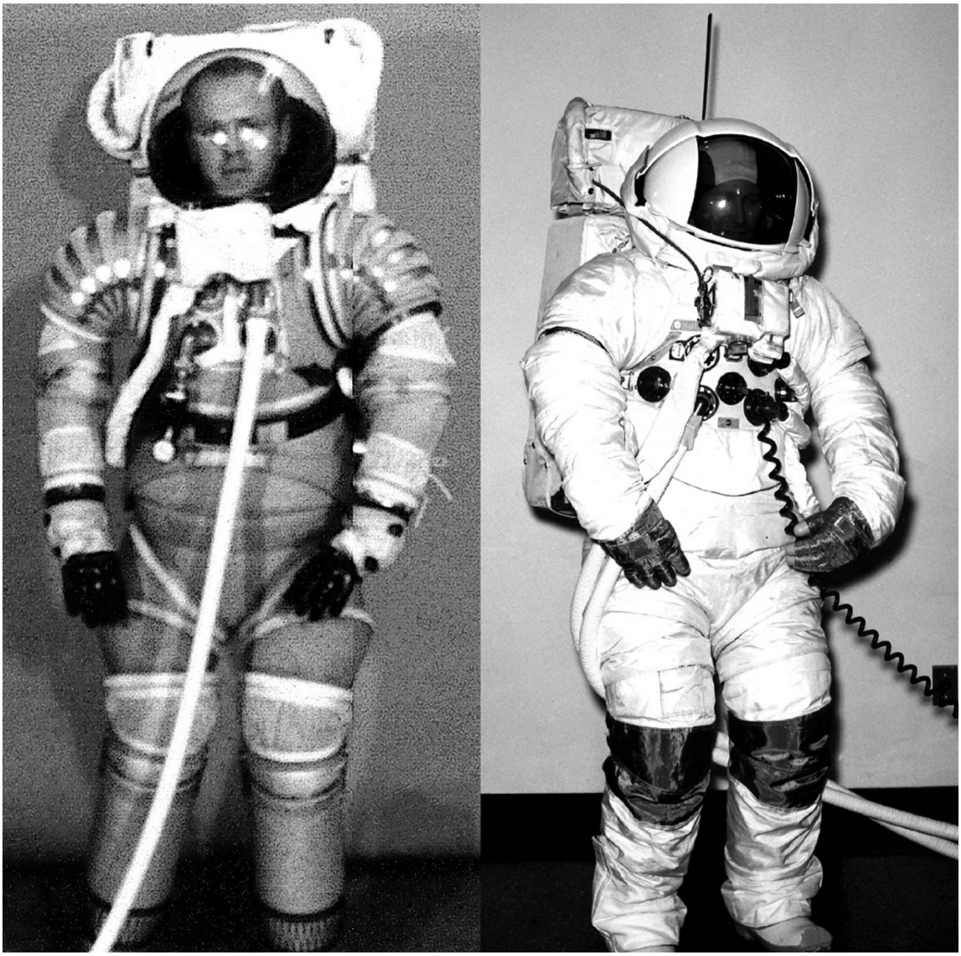


Figure 7.2.5. Litton's advanced extravehicular suit (AES) system (courtesy, left and right, G. L. Harris and NASA, respectively).

the plate, and freeze. As heat was applied, the ice would sublime and the vapor would pass through the foam. The presence of the foam imposed enough of a pressure barrier to assure that liquid water would not escape into space. If the foam became damaged, however, water loss to space would occur.

The oxygen supply system featured two tanks, which were plumbed in parallel and equipped with check valves to prevent loss of both tanks if one was leaking. Oxygen was drawn from both tanks simultaneously, and a "red-line" pressure level indicated that termination of the EVA was required in order to assure that if one tank was lost at that time, there were 30 minutes of emergency time remaining. The most unique feature of this system was that it was entirely pneumatic in operation—no electrical power was required except for communications. The system provided

4 hours of life support, weighed 30 lb (13.6 kg), and was capable of 800 Btu/h (202 kcal/h) of heat removal. However, problems with the breathing vest concept included the potential for snagging during donning, and the need for precise location of the duct at the oro-nasal area to preclude CO_2 buildup.

At NASA's behest, Litton also started development of a 45-minute version of the open loop portable life support system, called the "contingency transfer system" (CTS) for use during emergency return from the Lunar Module to the Command Module on proposed post–Apollo 17 missions. The CTS was never completed due to cancelation of Apollo 18 and later missions.

While Litton elected to withdraw from spacesuits soon after the AES competition, the AES design was not the end of the Litton suit story. Currently residing in the National Air and Space Museum's preservation collection is probably the last Litton pressure suit design (Figure 7.2.6). While the mobility systems were common to the AES, it featured a fiberglass hard upper torso and mid-entry system that were amazingly similar to what would eventually be used in the Shuttle EMU. While Litton's pioneering efforts failed to garner it a program production contract, Litton would leave yet another influential legacy. Litton was also developing a flat pattern joint system that NASA found most interesting. This appeared to offer relatively low operating effort with a simple, less expensive manufacturing technique when compared with the advanced mobility elements or molded suit joints of the time. As Litton had no further interest in the spacesuit business, NASA funded others to continue flat pattern development. A few years later, the winning Shuttle EMU prototype would feature a mid-entry hard upper torso with flat pattern mobility joints.

NASA's Ames Research Center

In 1963, NASA tasked the Ames Research Center with advanced spacesuit development that produced the 1964 AX-1. Ames's "Vic" Vykukal continued under this charter to produce the 1966–1967 AX-2 prototype (Figure 7.2.7), which was a refinement of the AX-1. For the AX-2, Ames elected to again employ metal bellows but the elements possessed greater range for improved mobility over the AX-1. While this was the last Ames prototype of the period, Ames research would be offered to and incorporated in later advanced Apollo prototypes.

International Latex

From April 1962 to March 1965, International Latex was precluded from competing for advanced Apollo and other NASA technology development contracts as it held the largest NASA suit development and production contract, which was the mainline Apollo program. In March 1965, International Latex was temporarily displaced as the Apollo suit provider. During this hiatus, International Latex successfully won a contract from NASA's Ames Research Center for exploration of a suit concept that would functionally replace the "seat" or couch in the vehicle system.

Figure 7.2.6. The last known Litton advanced suit design (left, courtesy of Smithsonian Institution).

The resulting suit system has typically been called the "lobster shell" suit (Figure 7.2.8) as it utilized removable anthropomorphically shaped fiberglass support "shell" sections designed to interface with seat mounts in the launch vehicle and provide support to arms and legs, affording some level of protection from windblast. Ironically, this development would start after International Latex regained the Apollo suit provider role, thus eliminating itself from consideration for further development contracts. International Latex delivered the prototype system in 1966.

While this concept did not proceed past a development study with NASA, Litton would offer a derivation of this approach to the USAF for the Manned Orbiting Laboratory (see Section 8.3.1).

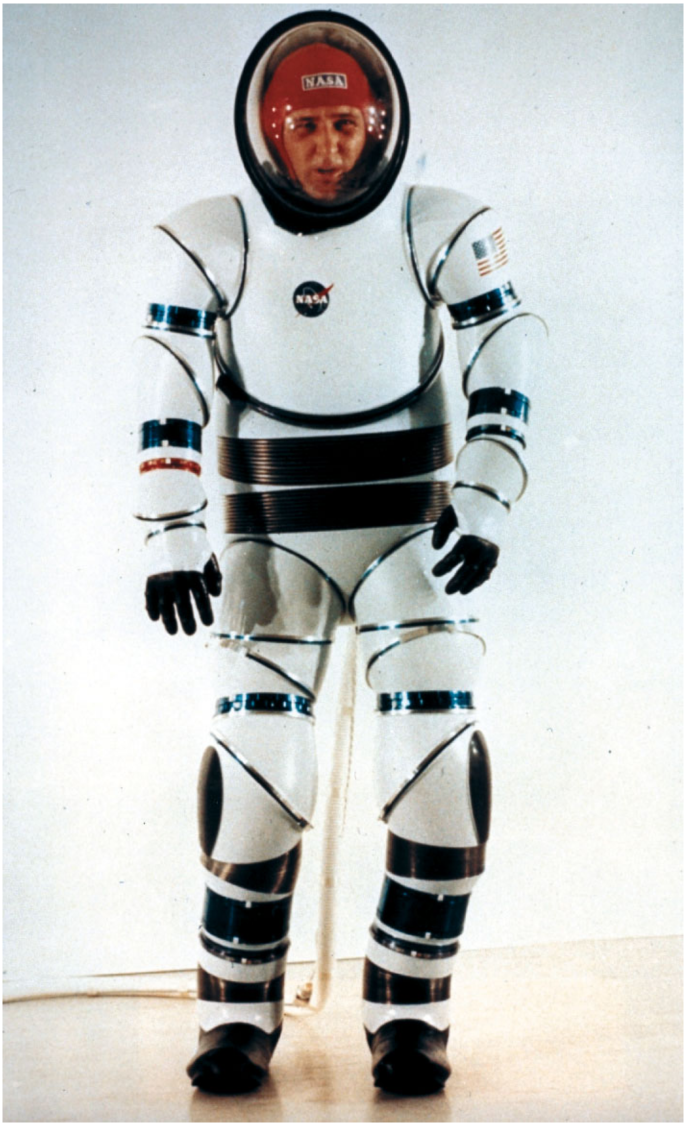


Figure 7.2.7. NASA-Ames Research Center AX-2 prototype (courtesy of NASA).

Hamilton Standard

In 1966, Hamilton joined the competition for what was believed to be the next Apollo pressure suit contract by internally funding the manufacture of an Apollo configuration prototype design model XM-2A (Figure 7.2.9, left). The XM-2A embodied advancements made from the end of 1964 to the summer of

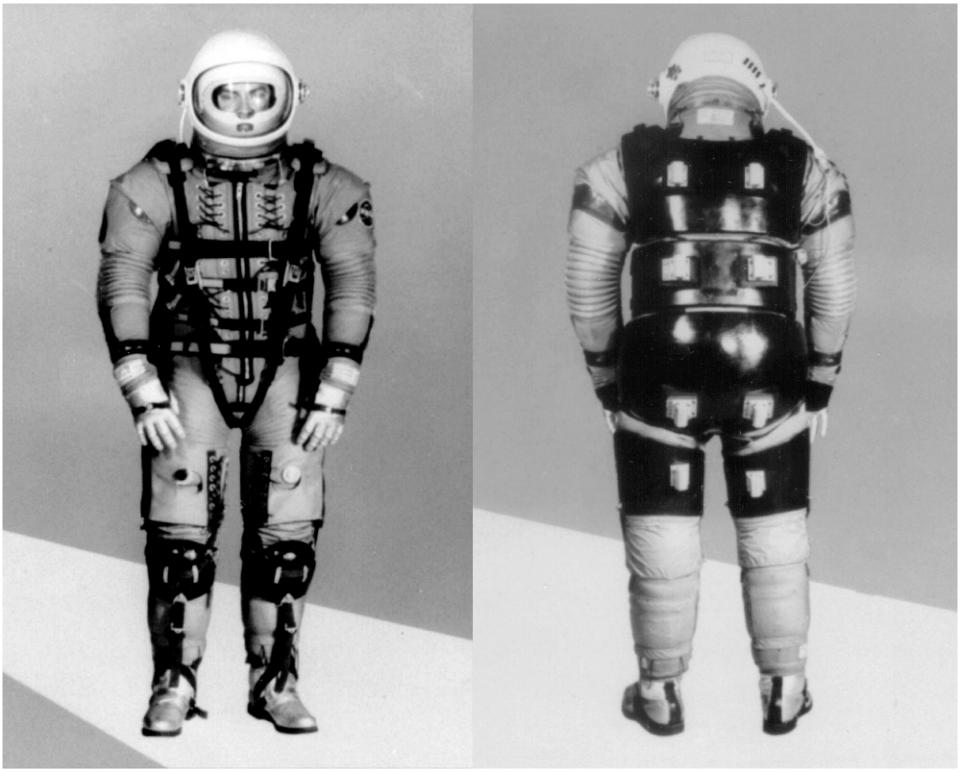


Figure 7.2.8. International Latex 1966 ‘‘lobster shell’’ ejection suit (courtesy NASA-Ames).

1966 and had been built in the hope of regaining the Apollo suit system integrator’s role and the suit production portion of the contract.

The XM-2A was the ‘‘sister suit’’ to the Manned Orbiting Laboratory XM-1A prototype that won the U.S. Air Force station suit competition in January 1967. In contrast to the Litton suits, the XM-2A was a soft suit that was designed to support launch and entry as well as EVA. The XM series utilized fabric bias directions and restraint design to achieve retention of its anthropomorphic shape when pressurized (see XM-1A in Section 8.3.1 for details). The XM-2A was designed to operate at 5.0 psi (34.5 kPa) like the other advanced Apollo suits and possessed a multidirectional waist joint and walking brief mobility system. This allowed the wearer to drop to the ground on one knee and lean forward, which was an Apollo goal at the time.

With the beginning of 1968, Hamilton Standard initiated the internal funding of three advanced Apollo soft-suit builds. The first two prototype suits were simply named ‘‘Apollo suits’’ (Figures 7.2.9, right). These were derivations of the then-in-production USAF Manned Orbiting Laboratory Model MH-7 training suits (Figure 8.3.15, left), differing only in their accommodations for the Apollo life

Figure 7.2.9. Hamilton 1966 XM-2A and 1968 Apollo suit (courtesy Hamilton Sundstrand).

support backpack. The Apollo suits were completed in April 1968. In parallel, Hamilton funded the development of a third, more advanced soft-suit prototype named the "R&D suit". This was to feature shoulder bearings, low-torque convolute shoulders, and lightweight launch/entry/EVA capability. However, in April 1968, expectations of Apollo budget and mission reductions resulted in the termination of the partially developed R&D suit and all further Apollo-related suit development.

David Clark Company

In 1965, the International Latex molded convolute joint had won the Apollo Block II EVA suit recompetition. NASA was interested in seeing if such a system would provide a mobility improvement to the David Clark torso assembly that otherwise used the Link-net restraint system throughout the pressure garment. To support this request, the David Clark Company manufactured mobility elements that were facsimiles of the International Latex Apollo systems and integrated them into a pressure garment. The resulting David Clark prototype provided no overall

Figure 7.2.10. David Clark S-1C chamber suit (courtesy David Clark Co.).

advantage over the standard Link-net system. However, NASA found the attributes of the system of interest and ordered a limited production of this design (Figure 7.2.10) for technicians supporting astronauts inside vacuum chamber events. NASA gave this technician chamber suit the designation S-1C.

Figure 7.2.11. David Clark S1021 advanced Apollo prototype (left, courtesy of Smithsonian Institution).

NASA's Manned Spacecraft Center also funded David Clark Company for an advanced concept suit that was completed in November 1967. This soft-suit prototype was officially a David Clark Company Model S1021 (Figure 7.2.11). The new features included fabric-convoluted joint systems for mobility and a horseshoe-shaped zipper closure. The horseshoe entry system, used on the USAF X-20 suits (see Chapter 8), had an entry zipper system that started on the side of the chest, ran under one arm, around the back, under the other arm, and ended on the other side of the chest. The suit's "dome" helmet featured a pressure visor that was easily replaceable in the field.

AiResearch Division of Garrett Corporation

In 1967, the AiResearch Division of Garrett Corporation (now Honeywell) elected to expand its capabilities to include entire spacesuit systems by developing an in-house capability for space pressure suit design and manufacture. To do so, AiResearch successfully recruited personnel from Litton and drew from its internal talent base. To demonstrate its ability to design and manufacture a latest technology space pressure suit, AiResearch independently produced the EX-1A prototype (Figure 7.2.12). To avoid proprietary infringement, the EX-1 featured new mobility technology referred to as the "toroidal joint" in conjunction with angled segments with pressure-sealed bearings like those of the NASA–Ames AX-1 and AX-2. In 1968, the EX-1 was evaluated against a Litton prototype in NASA's constant volume suit (CVS) evaluations (Figure 7.2.13). The CVS comparative tests showed that AiResearch had elevated itself to being a competitor to Litton

Figure 7.2.12. AiResearch EX-1 prototype with cover garments (courtesy Hamilton Sundstrand).

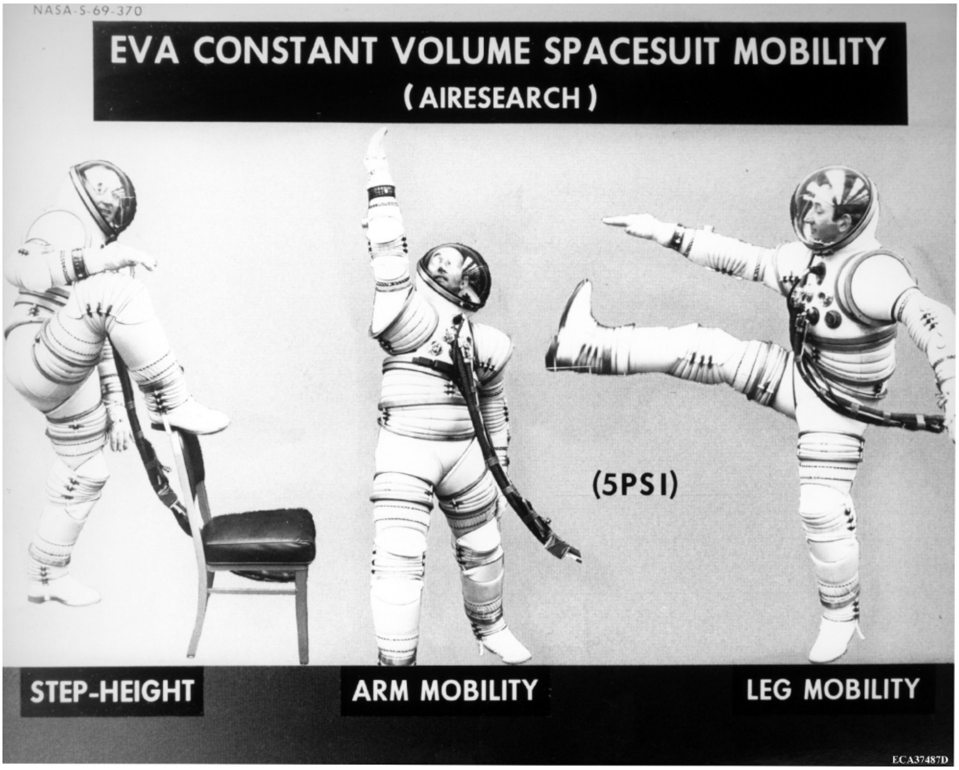


Figure 7.2.13. The AiResearch EX-1A in constant volume suit testing (courtesy Hamilton Sundstrand).

and was funded by NASA for a follow-on advanced extravehicular suit comparative test series.

Also in 1968, AiResearch won a NASA–MSC competition for the Block III portable life support. This system was named the "optimized portable life support system" (OPLSS), and was an advanced self-contained system designed to support an astronaut during an Earth-orbital or extended lunar surface extravehicular mission. The primary objectives of this program were to advance the performance and operational characteristics of the current Apollo PLSS, improve expendables servicing, reduce recharge time, and improve the suit/pack interface. The significant requirements included zero-*g* service/deservicing/operation, use of a non-venting heat sink, improved umbilical capabilities, and a greater number of EVAs per mission. The OPLSS design (Figure 7.2.14) was a further improvement over AiResearch's portable environmental control system (PECS) in areas such as packaging, checkout, servicing, performance, and duration.

In addition to the OPLSS, NASA envisioned in 1969 a family of incrementally improved life support systems. Using the Apollo PLSS as the starting point, NASA intended to first develop an improved version (IPLSS), which would be used for two

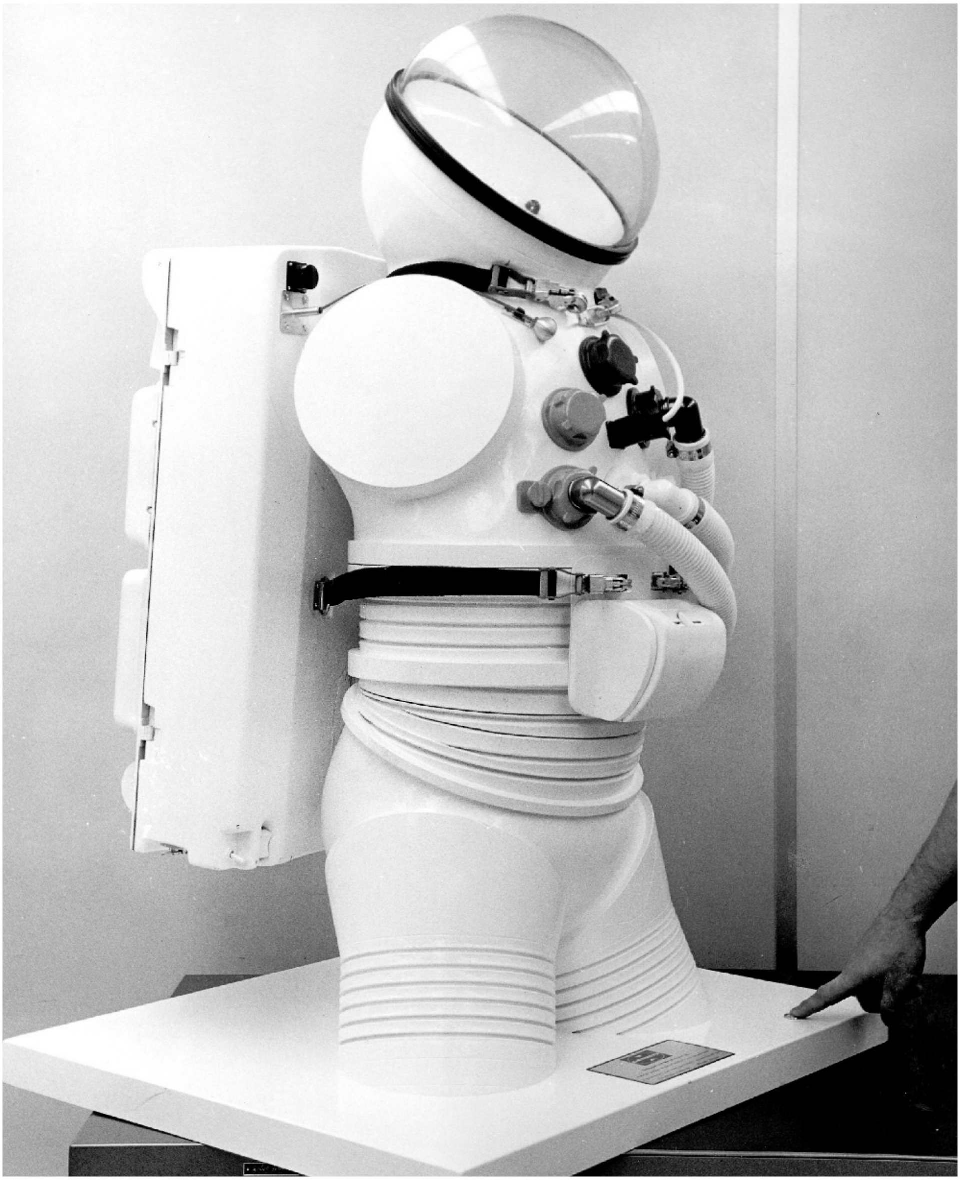


Figure 7.2.14. The AiResearch optimized portable life support system (courtesy Honeywell).

flights and include a small auxiliary water tank and plumbed-in OPS bottles. The next step would be the minimum consumables PLSS (MPLSS), which would have 7,500 psi (510 atm) oxygen storage and a plug-in emergency system. Then would come the optimized PLSS (OPLSS), and finally the advanced PLSS (APLSS), which was to have such features as a Hall effect motor for the fan.

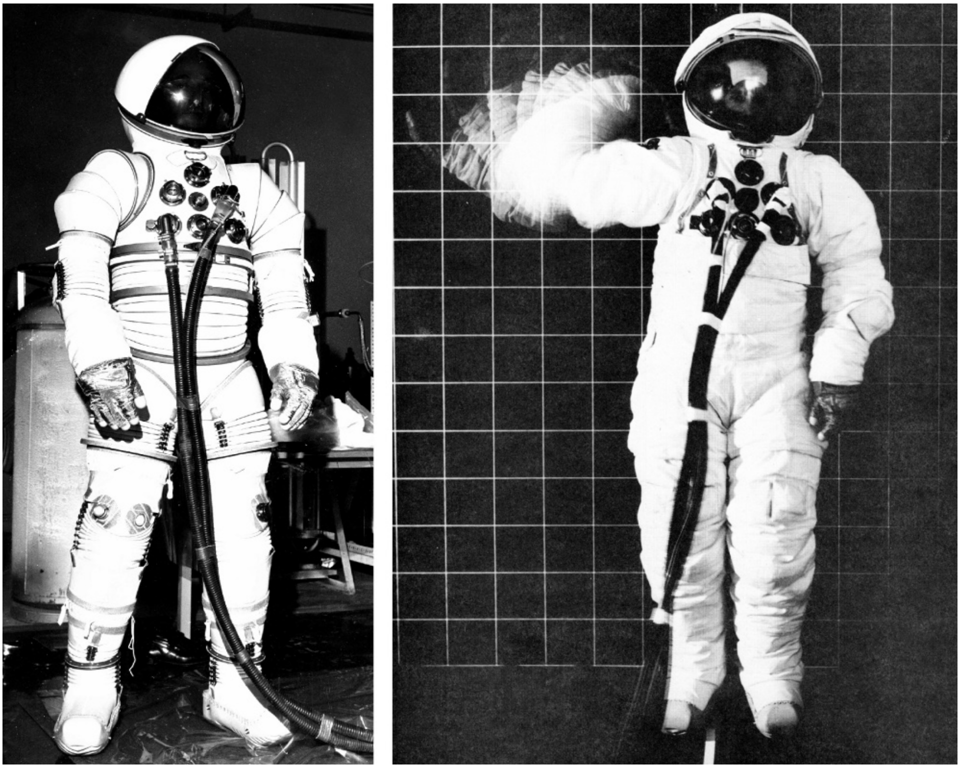


Figure 7.2.15. AiResearch advanced extravehicular suit (courtesy, left and right, Honeywell and G. L. Harris, respectively).

For the 1969 AiResearch advanced extravehicular suit (AES, Figure 7.2.15), NASA–Ames shared a five-bearing shoulder concept complete with a full scale mockup. AiResearch took the shoulder concept and brought it to fruition. In the other areas, this AES utilized refinements of its near constant volume toroidal mobility joints and bearing hip architecture that were parts of their CVS. In the AES competition, AiResearch emerged the winner.

Unfortunately, the missions for which the AiResearch AES and OPLSS were aimed were canceled, resulting in termination of these contracts in 1969 and 1970, respectively. The OPLSS did not complete its detail design phase, and none of the other PLSS "family members" saw development. The AES was planned as a Skylab flight experiment but never saw flight (discussed further in Section 7.3).

Webb Associates

Another organization with a very different approach to advanced Apollo spacesuit technology development entered the field in 1967. This was Webb Associates of

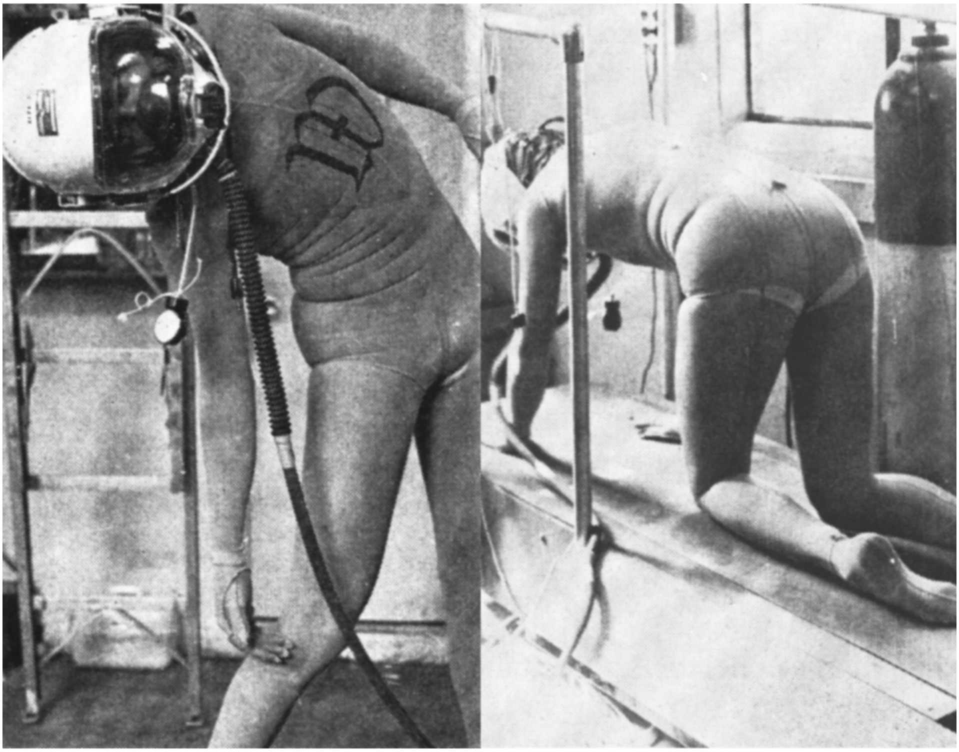


Figure 7.2.16. Webb Associates 1967 "1.9 psi" prototype (courtesy P. Webb).

Yellow Springs, Ohio, headed by Dr. Paul Webb. The preceding advanced Apollo spacesuit types were all based on the principle of surrounding the user in a fully enclosed, pressurized environment. Like the David Clark S-1 "capstan suit" of the late 1940s, the Webb Associates approach was to provide pneumatic pressure (oxygen atmosphere) to the head and lungs that was adequately matched by mechanical counterpressure being applied to the torso to support bodily functions. However, in the Webb concept, layers of elastic garments supplied the mechanical counterpressure to the torso. The development of the Webb space activity suit came in increments.

A prototype arm was fabricated and tested by 1967 and the equivalent of an approximately 1.9 psi (13 kPa) prototype suit system was made by 1968 (Figure 7.2.16). A second prototype that was the functional equivalent of an approximately 3.3 psi (23 kPa) suit was made and in test by 1971 (Figure 7.2.17). The Webb system was donned in layers and included its own Webb-designed portable life support system.

While there was a hiatus in NASA interest in this approach, the concept saw U.S. university project activity in the 1980s and 1990s. NASA's interest reemerged in

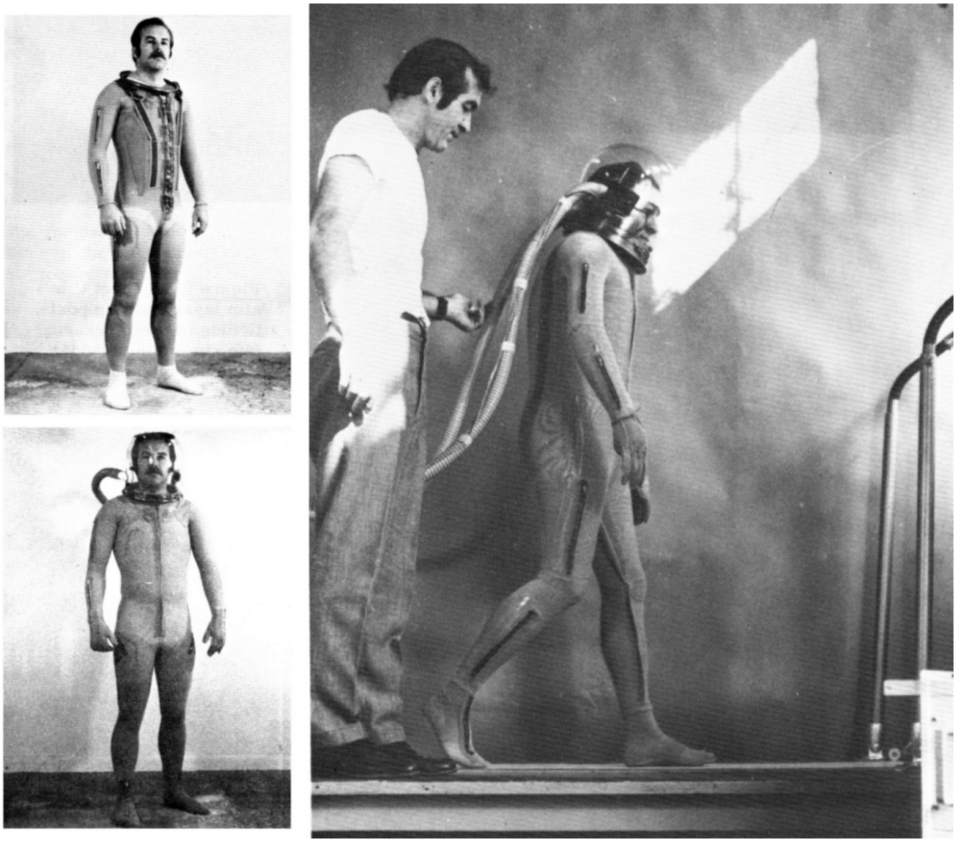


Figure 7.2.17. Webb Associates 1971 "3.3 psi" prototype with life support (courtesy P. Webb).

1999 with the funding of a Honeywell Corporation (formerly AiResearch) division-led 3-year study. Dr. Paul Webb MD, the former head of Webb Associates, was a key consultant on the project.

NASA's Manned Spacecraft Center

What is now the Johnson Space Center not only provided administrative overview for most of the advanced Apollo suits, but also provided technical contribution as NASA engineers have always had a personal interest in hands-on development. NASA in Houston was the suit and life support system integrator for Gemini, and after September 1965 for Apollo. By 1968, NASA–MSC was also attempting internal next-generation development. A reflection of this was an Apollo A7L suit that underwent extensive modification (Figure 7.2.18) to a mid-entry body seal closure. This suit had been used by Walter Cunningham on Apollo 7. Before

Figure 7.2.18. NASA's Manned Spacecraft Center mid-entry experiment suit (right, courtesy of Smithsonian Institution).

NASA became organized to preserve for posterity what are now considered national treasures, out-of-life pressure suits had little value except as test articles or to be cannibalized for reusable parts. In this experiment, a round entry closure was added, which was canted low in front, and provided a simple-to-manufacture closure with a thinner front-to-back profile. This development was similar to the entry architecture of the later Shuttle competition–winning SX-1 prototype.

Also, NASA internally performed zipper entry concepting in 1968 that additionally reflects the view and relative value of out-of-life pressure suits during the Apollo program. NASA performed entry concepting by taking several expended A6L or A7L suits, and hand-sewing heavy commercial zippers in them, to represent proposed entry configurations. The technicians then opened the zippers, cut through the torso, and trimmed the opening. The new entry locations could then be tried in very realistic don/doff simulations. This produced two entry concepts that were considered for proposed "A8L" and "A9L" prototypes that were never built. A down-select resulted in the A9L concept being chosen for what was ultimately called the A7LB design.

7.3 LATE APOLLO SUMMARY

By 1969, the space program was not the national priority that it had been in the early 1960s. The costs of the war in Vietnam, coupled with the domestic agenda of the "great society", had created financial burdens that resulted in a lessening of NASA budgets. Adjustments in NASA's strategic planning resulted in the cancelation of the later lunar missions and corresponding development programs in 1969 and 1970.

Skylab almost provided an opportunity for the AiResearch AES to be flown and tested as a flight experiment. Unfortunately, the complications of the Skylab launch and subsequent repair missions resulted in those plans never reaching fulfillment.

While the design models of the Apollo Applications Project never reached flight, the advancements from those efforts would provide strong technical influence in the EMU that would support Shuttle flights for almost three decades, and potentially on next-generation suit system developments of the U.S.A. in the early part of the 21st century.

8

U.S. Air Force spacesuits

From its creation, the U.S. Air Force (USAF) had supported advanced aircraft development, typically in conjunction with or for the National Advisory Committee for Aeronautics (NACA) and then the National Aeronautics and Space Administration (NASA). This support, which included personnel, facilities, and development expertise, started before the X-1 program and has continued to the present. The USAF assisted Litton's 1950s' development of the Mark I pressure suit in the form of funding and test personnel. In the X-15 program, the USAF provided pressure suit selection and development to NACA. While most of the X-15 flights were high-altitude applications, the X-15 was designed to travel far enough above the Earth to allow its missions to qualify as space flights. Thus, the USAF was responsible for the development of the first U.S. spacesuit design. After the founding of NASA, the USAF lent facilities and technical resources at Wright–Patterson Air Force Base in Ohio for the Mercury spacesuit selection.

In parallel with NASA's Mercury program, the USAF was directly tasked with developing a reusable X-20 spacecraft that included a supporting IVA spacesuit system. The USAF would also conduct parallel suit technology developments. In 1963, this was followed by the Manned Orbiting Laboratory (MOL). The best known "MOL" suits were the initial IEVA suits. However, there were MOL-related suit designs that included an exclusively EVA "on-station" suit system and suits to support primate (chimpanzee) testing.

After MOL was canceled in 1969, the USAF was no longer directed to produce a defense-related manned space program. However, the USAF would continue to support NASA with capabilities, technical expertise, and personnel.

8.1 THE U.S. AIR FORCE X-20 PROGRAM (1958–1963)

In the late 1950s, the USAF had space or near space missile and satellite programs. Because the Soviet space program in 1958 was principally a military effort, the U.S.

K.S. Thomas and H.J. McMann, *U. S. Spacesuits*, Springer Praxis Books,
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Defense Department tasked the USAF with a follow-on to the X-15 program. This was the X-20 Dynasoar (dynamic soaring) program. Initiated in 1958, the X-20 was to create a single-pilot, reusable spaceplane that could be launched into space by a rocket and land on conventional runways on return to Earth.

The David Clark Company was awarded the X-20 spacesuit contract for suits that were intended to support launch, entry, and parachute escape but not extravehicular activity. The X-20 configuration was a derivation of the David Clark A/P 22S-2 suit. Like the A/P 22S-2, the X-20 suit used David Clark's Link-net restraint system and featured a rear-entry "horseshoe" zipper closure (Figure 8.1.1) that started on one side of the chest, ran diagonally down the side as it wrapped around the back and then back up the other side to terminate on the other side of the chest. The X-20 suits started with a helmet similar to the A/P 22S-2 suit (Figure 8.1.2, left) but later gained a very roomy bubble helmet (Figure 8.1.2, right).

Figure 8.1.1. David Clark Co. (DCC) X-20 suit restraints and entry (courtesy Hamilton Sundstrand).

Figure 8.1.2. DCC X-20 "Dyna-Soar" suit configurations (courtesy, left and right, Hamilton Sundstrand and G. L. Harris, respectively).

The revision of Defense Department goals ultimately resulted in cancelation of the X-20 program in December 1963 in favor of a USAF space station concept named Manned Orbiting Laboratory (MOL). X-20 suits would, however, be used for early MOL evaluation and development activities.

8.2 EARLY USAF SPACESUIT DEVELOPMENTS (1959–1964)

The USAF's foray into spacesuits was not limited to specific program applications. The USAF funded two interesting efforts in its first years in the field: one was a unique approach to a mechanical counterpressure suit that was concepted and executed by Mauch Laboratories of Ohio; the other was the David Clark Company's implementation of USAF concepts for an extravehicular suit system.

In 1959, the USAF funded Mauch to explore the idea of using a passive approach to mechanical counterpressure rather than the "active" method used in the David Clark capstan tube "partial pressure" suit that was used in defense

Figure 8.2.1. Mauch mechanical counterpressure suit.

applications and in X-1 record attempts. Like the David Clark system, the head and lungs were provided with pressurized oxygen while a garment tightened on the torso, arms, and legs to provide a closely matching external counterpressure.

This Mauch suit (Figure 8.2.1) utilized the dynamics of closed-cell foam, which expands as the material decompresses. To benefit from this, the suit featured a tight-fitting garment with a layer of closed-cell foam sandwiched between two layers of fabric. The inner layer held the foam in place, while the outer layer provided the boundary against which the expanding foam reacted to provide pressure on the wearer's body.

The goal of this research was to produce a suit system that would be highly mobile and permit evaporative cooling to effectively occur at the skin level, thus avoiding body heat containment/capture typical of full pressure suits. This program, which was concluded by 1962, was successful to the extent that the suit demonstrated the ability to keep a subject alive in a vacuum chamber for hours. However, it was not the mobility and life support solution for which the USAF had hoped.

In yet another activity, the USAF explored the development of a complete spacesuit system for performing activities outside the spacecraft. In July 1962, the USAF contracted with the David Clark Company for the development, system level integration, and delivery of a pressure suit and life support system for the USAF Aerospace Medical Research Laboratory's extravehicular protective assembly (Figure 8.2.2) program which operated from the Wright–Patterson Air Force Base

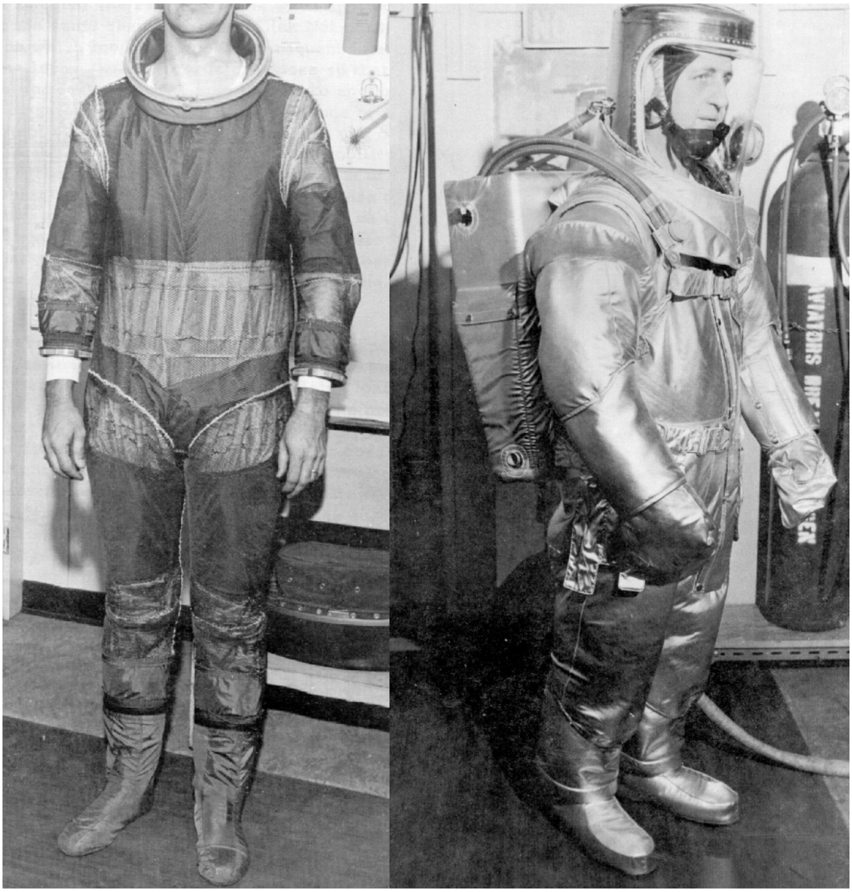

Figure 8.2.2. DCC extravehicular protective assembly (courtesy G. L. Harris).

between 1962 and 1964. The primary goal was to develop an extravehicular activity (EVA) spacesuit that would support both lunar and Earth-orbital activities.

The goal of the David Clark pressure suit assembly was to provide EVA protection in a subsystem that weighed no more than 25 lb (11 kg) and could be donned without assistance in 5 minutes or less. The helmet was cylindrically shaped and fabricated in stainless steel to Wright-Aerospace Development Division concepts and specifications. It featured a two-piece EVA sunvisor that retracted upward to be stored in the forehead area and slid down with a slight overlap between the two, to cover the field of vision. The torso pressure garment was a Gemini-like rear-entry suit utilizing Link-net technology for mobility. The EVA cover garment included integrated stainless steel plates, ballistic felt, nylon moving plates, and aluminized Mylar for micrometeoroid and thermal protection.

The autonomous portable life support system for this suit was named the "environmental control system". This was a 5 psi (34.5 kPa) system to permit up to 4 hours of EVA. The resulting prototype utilized liquid oxygen vaporization to cool the ventilation gas, and a combination of ejector drive, turbine compressor, and gas bleed-off to provide ventilation flow. The ejector provided the drive for the ventilation loop from the gas entering the loop from the tank after being vaporized. A controlled partial purge of suit atmosphere controlled the pressure and removed CO_2 and humidity. While this did not achieve all of its design goals, the life support system proved adequate for manned testing and the overall system was an innovative first attempt in its field.

8.3 MANNED ORBITING LABORATORY IEVA SUIT PROGRAM

In 1963, the Kennedy administration decided to have the USAF develop a smaller, lower cost space station in parallel with NASA's more ambitious space station efforts. While this effort was officially named the Manned Orbiting Laboratory (Figure 8.3.1), it was invariably called "MOL". Cost control was to be based on the use of previously designed vehicle systems and by the offering of fixed price "design-to-cost" contracts wherever possible. To reflect the cultural difference between NASA and this USAF program, the "astronauts" preferred to be called "MOL pilots" (Figure 8.3.2). MOL had two manned suit programs.

The first suits were to support both intravehicular and extravehicular activity (IEVA), and were to be less expensive, more compact, and more flexible than Apollo suits. These requirements were driven by the MOL program's plan to use the basic Gemini capsule design for launch/return vehicles. The cabins, hatches, and couches of Gemini were more compact than their Apollo counterparts. Also for MOL, the Gemini capsules were to gain a bottom hatch through the heat shield to allow the capsule to be launched in an already docked position and to simplify the systems needed for subsequent dockings. This meant that, in the confines of the capsule, the MOL pilots had to perform movements and activities that were not required of NASA Gemini astronauts. Unlike NASA programs where each astronaut had a custom-made set consisting of flight, training, and backup spacesuits, the MOL

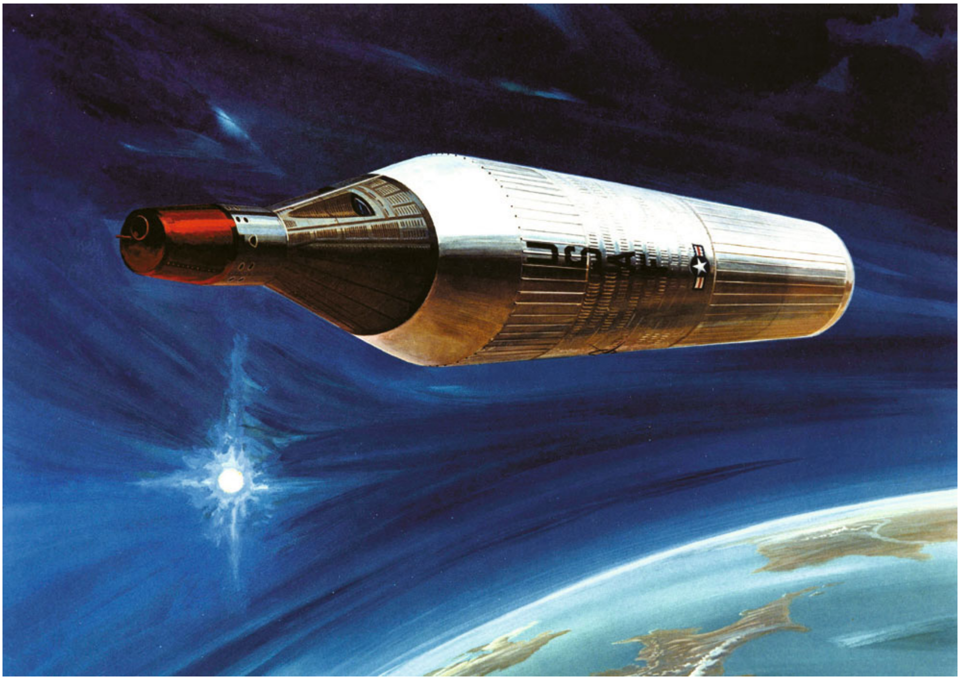

Figure 8.3.1. Manned Orbiting Laboratory (MOL) concept (courtesy Hamilton Sundstrand).

program intended that pressure suits be provided in eight standardized sizes with adjustable sizing elements to provide adequate fit for the MOL pilot (astronaut) corps.

This program had two distinct phases: the first phase was the USAF's initial development work that concluded with a formal competition; the next phase was a design-to-cost production contract to support flight. Unfortunately, the cost of the Vietnam War, coupled with the advancements in "spy satellite" technology, led to the termination of the MOL program and its related activities in 1969.

MOL IEVA developments (1963–1966)

The first steps in the MOL IEVA developments were to gain experience and evaluate potential pressure suit technologies. When the USAF's X-20 Dynasoar program was canceled in December 1963, the USAF was left with an initial inventory of suits. These X-20 suits (Figures 8.1.1 and 8.1.2) were utilized in the initial training and testing that supported the development of subsequent contract requirements and the evaluation of thermal insulation approaches (Figure 8.3.3A).

In 1964, the USAF also surveyed potential suit systems and subsystem suppliers. Their efforts principally focused on David Clark Company, International Latex (now ILC Industries) and B.F. Goodrich (now Goodrich Corporation); however,

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SEATED

Maj. L. Macleay Maj. R. E. Lawyer Maj. J. M. Taylor Maj. A. H. Crews Maj. F. G. Neubeck LCDR R. H. Truly

Figure 8.3.2. The MOL Pilot Corps (courtesy Hamilton Sundstrand).

the USAF also visited Hamilton Standard in September. While the USAF interest in Hamilton was related to life support, Hamilton had developed a pressure suit design capability to support the Apollo program, so the possibility of additionally providing MOL suits sparked Hamilton's interest.

A newcomer to pressure suit design and manufacture, Hamilton internally funded and developed four pressurizable suit prototypes specifically for MOL in 1965. The first three prototypes were the XT3, XT4, and XT6. The XT3 (Figure 8.3.3B), completed in February, was an experiment to permit the shoulders and hips to rotate independently and allow the torso to bend by providing a waist joint. It also featured a new design helmet with more side and upward visibility than NASA program helmets of the time. Another feature of the XT3 helmet was that the life support to suit connection was made through the helmet and not the torso. The XT4 suit (Figure 8.3.3C) was completed in April 1965 and embodied evolutionary improvements in mobility systems over the XT3. This suit used an Apollo C3-type helmet. In the summer of 1965, the XT3 was remanufactured to incorporate the XT4 restraint system, thus becoming the XT3/4. The last suit, the XT6, was completed in October and embodied significant improvements in mobility and durability. Creation of the XT6 (Figure 8.3.3D) coincided with Hamilton Standard learning that International Latex had won the Apollo suit recompetition. This resulted in new internal development activities that included the funding of a B.F. Goodrich prototype to evaluate the latest Goodrich mobility developments. In December 1965, Goodrich delivered their MOL "demo suit" (Figures 8.3.3E and 8.3.4). After evaluation of the suit, Hamilton elected to continue exclusively with its own in-house designs. This was the last known Goodrich involvement in a spacesuit program.

At the start of the MOL program, David Clark Company was the leader in the spacesuit industry and had been the USAF's pressure suit supplier for the X-20 and the extravehicular protective assembly. Also, MOL was using Gemini capsules as the David Clark Gemini suits had proven to work effectively in that spacecraft. In 1965–1966, the USAF evaluated David Clark capabilities by funding limited developments. There were four prototype suits in this contract that were given the designations MD-1, MD-2, MD-3, and MD-4. There were two design configurations. The MD-1/MD-2 prototypes represented the first configuration. The difference between MD-1 and MD-2 (Figures 8.3.3F and 8.3.5, left) was that they were custom-made to two specific suit subjects for the evaluation. The MD-1/MD-2 suits were similar to the Gemini G4C EVA suit system with the major differences being "dome"-type helmets, revised mobility systems, and an improved zipper system for reduced leakage. The dome-type helmets replaced the flip-down visor system, previously used for launch/entry, for greater reliability, durability, and a larger field of vision. A new shoulder system used flat pattern convolute sections restrained by a single "endless" cable system. Flat pattern convolute joints were also added to the legs. The incorporation of a BFG pressure-sealing zipper in the inboard (of the two) zippers acted to reduce suit leakage.

The other evaluation configurations were designated MD-3 and MD-4 (Figures 8.3.3G and 8.3.5, right). Like the MD-1 and MD-2 prototypes, the difference

(A) X-20 suit testing insulation

(B) Hamilton XT3 prototype

(a) External view (b) Without covers

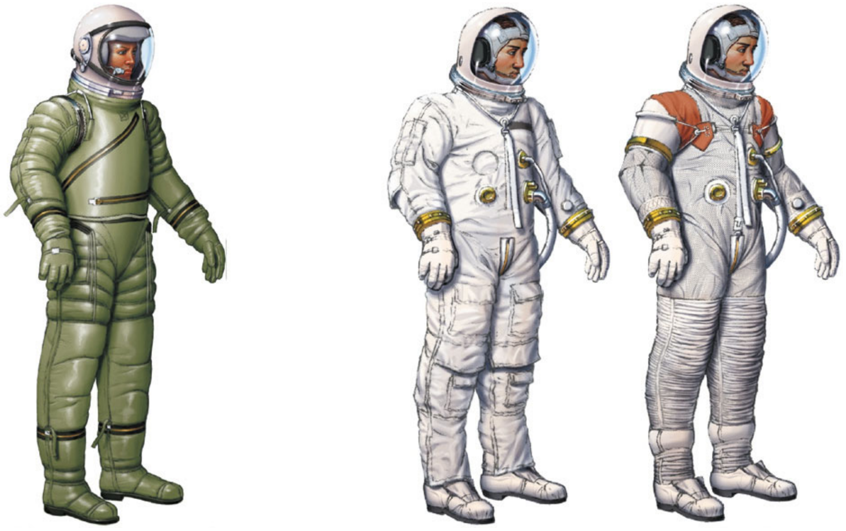
(C) Hamilton XT4 prototype

(a) External view (b) Without covers

(D) Hamilton XT6 prototype

(a) External view (b) Without covers

Figure 8.3.3. Initial MOL IEVA development efforts.



(E) BFG MOL ''demo suit''
(Hamilton funded)

(F) David Clark MD-1/MD-2 configuration
(a) External view (b) Without covers

(G) David Clark MD-3/MD-4 configuration
(a) External view (b) Without covers

(H) International Latex evaluation suits
(a) External view (b) Without covers

Figure 8.3.3. Initial MOL IEVA development efforts (*cont.*)

(J) Hamilton XM-1A competition suit

(a) External view (b) Without covers

(K) Litton's RX-3-based ejection suit

(a) and (b) Front and rear Views

(L) International Latex competition suit

(a) External view (b) Without covers

(M) Hamilton XM-3A backup suit

(a) External view (b) Without covers

Figure 8.3.3. Initial MOL IEVA development efforts (*cont.*)

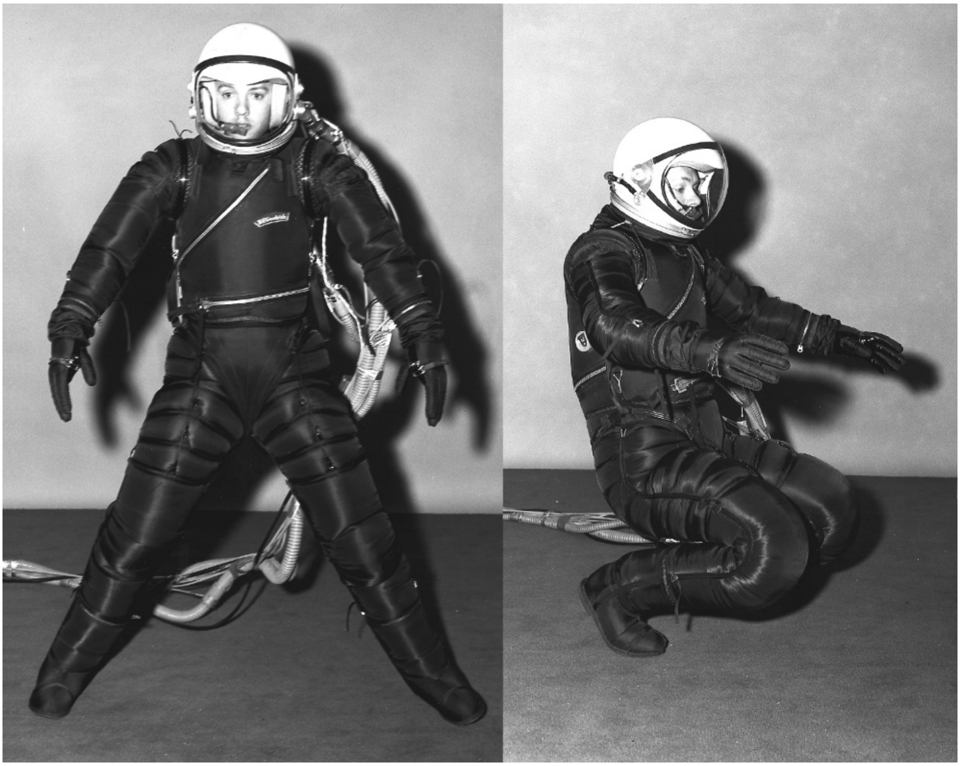


Figure 8.3.4. 1965 BFG MOL prototype (courtesy Hamilton Sundstrand).

between the MD-3 and MD-4 was related to size. MD-3/MD-4 differences from the MD-1/MD-2 prototypes included the entry closure, a revised waist/brief area, and additional helmet changes. The entry closure was revised to the X-20 style but with technical improvements. For MD-3/MD-4, David Clark developed a hip joint capable of multiaxis mobility. The helmet gained a replaceable pressure visor and improved optical quality in all visors. The sunvisor was improved for light attenuation and an antireflective coating was added.

In 1966, the USAF also explored International Latex suit technology. In 1965, NASA had evaluated Apollo-type pressure suits from all the same manufacturers that the USAF was considering for MOL. International Latex had won the Apollo competition to become the Block II suit supplier. In 1966, the USAF had purchased a limited quantity of International Latex "evaluation suits" that (Figure 8.3.3H) were based on the Apollo A5L.

In 1966, Hamilton returned with internally funded prototypes that used internal designs for the torso assembly and elected to start with the International Latex shoulder and arm design but with improvements to reduce volume and operating effort. An exclusively MOL prototype, the XM-1A (Figures 8.3.3J and 8.3.6), and an Apollo/MOL XM-2A prototype were built and campaigned by Hamilton in 1966 to

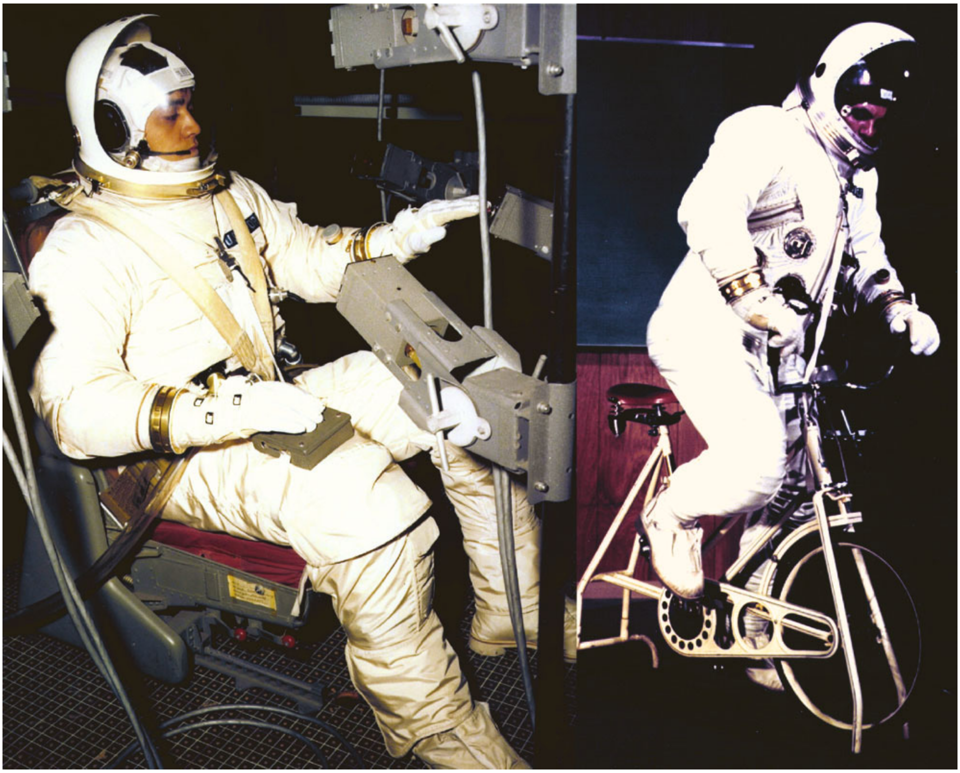


Figure 8.3.5. 1966 DCC MD-1/MD-2 and MD-3/MD-4 suits in testing (courtesy David Clark Co.).

gain entry to the MOL competition in January 1967. These suits, which shared the same mobility systems but differed in life support connection arrangements, featured a multidirectional waist joint and had the ability to operate at 5.0 psi (34.5 kPa) to offer zero decompression egress from the space station (Figure 8.3.7).

Litton also internally funded a 1966 prototype in a bid for the MOL IEVA suit contract. This was a 5.0 psi (34.5 kPa) design that was technically very different from the approaches used by David Clark, International Latex, and Hamilton Standard. Litton created a derivation of the Apollo RX-3 that had been developed for NASA (see Section 7.2.1). The principal difference between the two Litton configurations was that the hard suit for MOL was planned to also be part of the ejection seat (Figures 8.3.3K, 8.3.8, and 8.3.9). It was expected that the hard shell segments would afford windblast protection to enable MOL pilots to eject at high speeds without fracturing their arms or legs. The RX-3 probably had superior mobility to the "soft suits" being considered for MOL but could not operate in the restrictive space of the Gemini capsule.

On November 3, 1966, the USAF made its first and only MOL flight. For this unmanned mission, the USAF utilized a modified Titan 2 propellant tank to

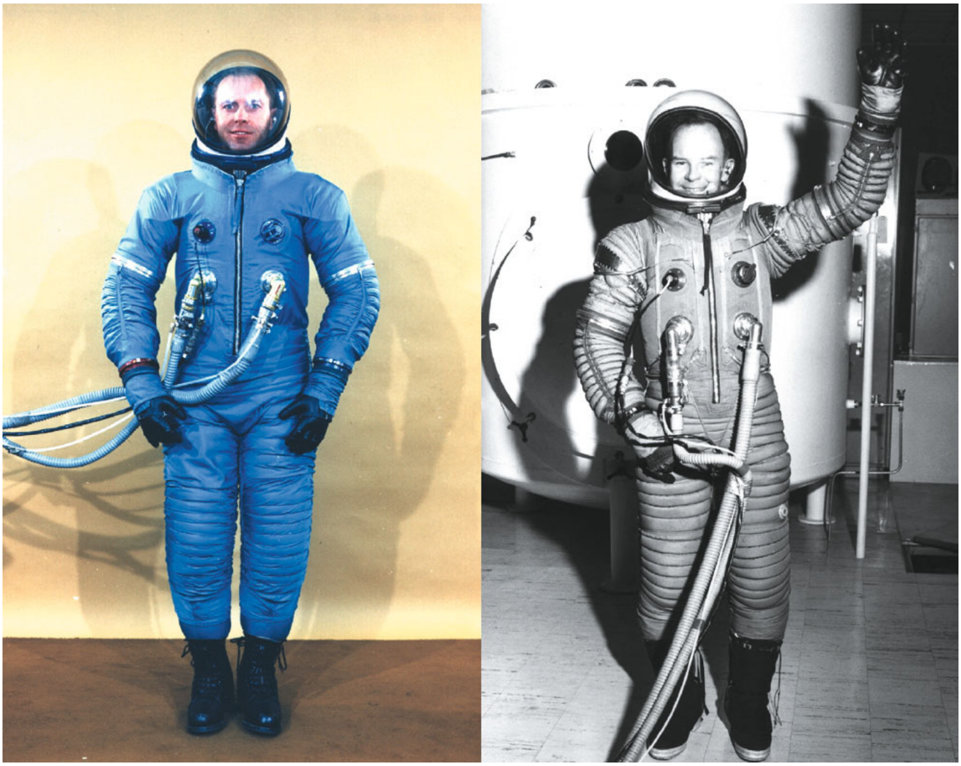


Figure 8.3.6. 1966 HS MOL XM-1A (courtesy Hamilton Sundstrand).

represent the MOL station itself. This allowed study of the aerodynamic and structural loads associated with launching the MOL station into orbit and validated the size and shape. Once the flight reached the necessary altitude, the Gemini capsule that was modified to replicate the hatch-through-the-heat-shield configuration was ejected to make a suborbital entry and splashdown in the Atlantic Ocean replicating a crew return. The capsule was successfully recovered and was found to validate the MOL design.

In January 1967, the competing manufacturers faced off in competition for the production contract for the first type of MOL spacesuits. This was held at Wright–Patterson Air Force Base. The "new suit" in this competition was a USAF-funded International Latex prototype (Figures 8.3.3L and 8.3.10) that was based on the Apollo A5L/A6L design but featured a novel elliptical, hemisphere-shaped, removable pressure visor in place of the traditional helmet. The Hamilton XM-1A demonstrated the best mobility and ability to operate within the capsule. Thus, Hamilton was selected by the USAF.

There was yet another Hamilton-funded prototype, the XM-3A (Figure 8.3.3M). This was started as a backup competition suit to the XM-1A but was

Figure 8.3.7. XM-1A mobility at 5 psi (courtesy Hamilton Sundstrand).

completed a few days after the start of the MOL competition. It was the first MOL suit to feature the shoulder and waist systems (U.S. patent No. 3,574,236, inventors Getchell, Vail, and Marroni) that would be used on the subsequent XM-4A prototype and model MH-5 to MH-8 production suits. The shoulder allowed better rotation and reach of any non-bearing cable restraint system. The multidirectional, two-phase waist joint permitted torso bending in any direction (see the XM-4A "sister suit" in Figure 8.3.12). These features greatly facilitated maneuvering in the tight confines of MOL-modified Gemini capsules. At the USAF request, the XM-3A originally had an Apollo A5H-style front yoke and torso compression strap system. These were later removed after USAF field testing; the resulting base torso assembly resembling later units.

Figure 8.3.8. 1966 Litton MOL ejection suit concept.

The MOL IEVA suit production contract (1967–1969)

The suit production contract was formally issued to Hamilton Standard in July 1967. The first suit of the contract was a pre-production prototype model XM-4A (Figures 8.3.11A and 8.3.12) that was completed in September. The changes from the XM-3A included a thermal/micrometeoroid garment coverall (as opposed to a blue nylon training cover garment), lower resistance, longer life arm bearings, larger 4 in. wrist disconnects, and new-design gloves with adjustable finger length.

During the testing of the XM-4A, a question was raised as to how much “man loading” a subject could impart into a pressure suit in addition to the load from being pressurized. Man load is produced by the forces involved in reaching, stretching, and holding activities by a suited crewmember, all of which add to the forces already caused by pressurization. The measurement of Captain Richard Lawyer, the designated MOL suit subject, brought surprise. The measurement readings were higher than any previous suit requirement or man load allowance and became design requirements for MOL suits. This requirement would later flow into the

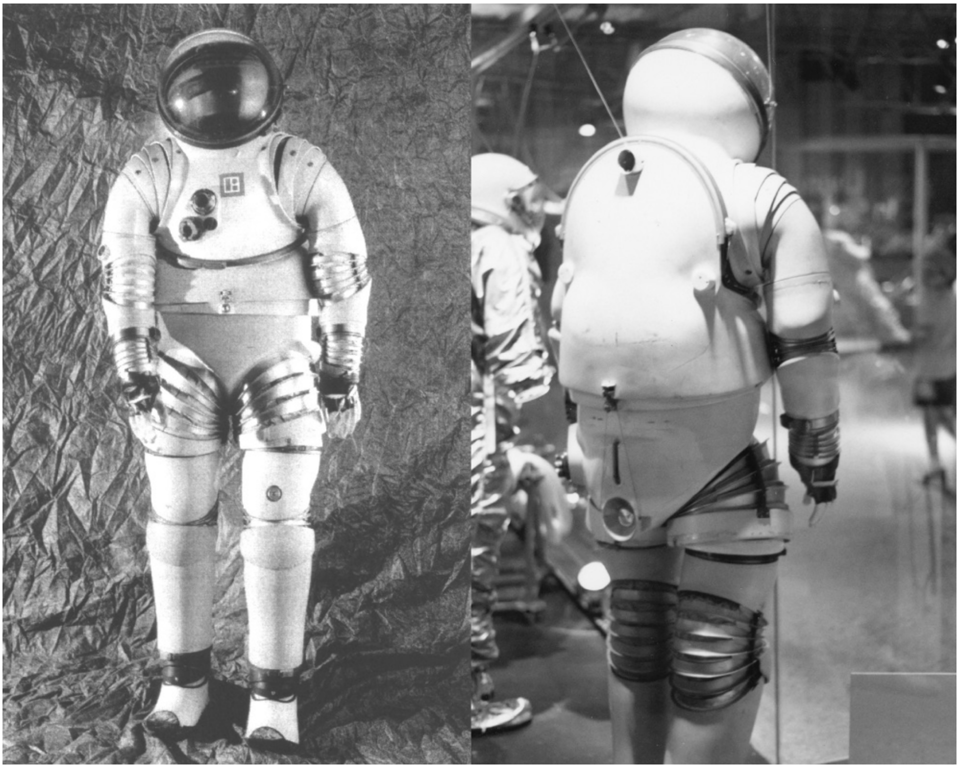


Figure 8.3.9. 1966 Litton MOL ejection suit prototype (courtesy, left and right, Smithsonian Institution and G. L. Harris, respectively).

design of the Shuttle extravehicular mobility unit (EMU). The XM-4A was followed by the MOL "production" phase (Figure 8.3.13), which started with the MH-5 and MH-6 models.

The "MH" designation stood for MOL production suits produced under the Hamilton contract. The models MH-5 and MH-6 used the same torso assembly but different cover garments. For these models, the cover garment extended down over the arm bearings. The three MH-5 suits (Figures 8.3.11B and 8.3.14), which were made for training MOL pilots, had an outer garment using a blue outer fabric with simulated bulk but no insulation for increased durability and reduced manufacturing cost.

Three MH-6 suits (Figure 8.3.11C) were also manufactured. These had an outer garment that contained aluminized Mylar space insulation and was covered by a white Teflon fabric. During this run, a "development #1" suit (Figure 8.3.11D) was also made to validate quality for cost reduction changes in the manufacturing process. The development #1 suit was provided with a XM-4A-style cover garment that was probably an earlier production leftover.

With the beginning of 1968, program delays, unrelated to the suit program,

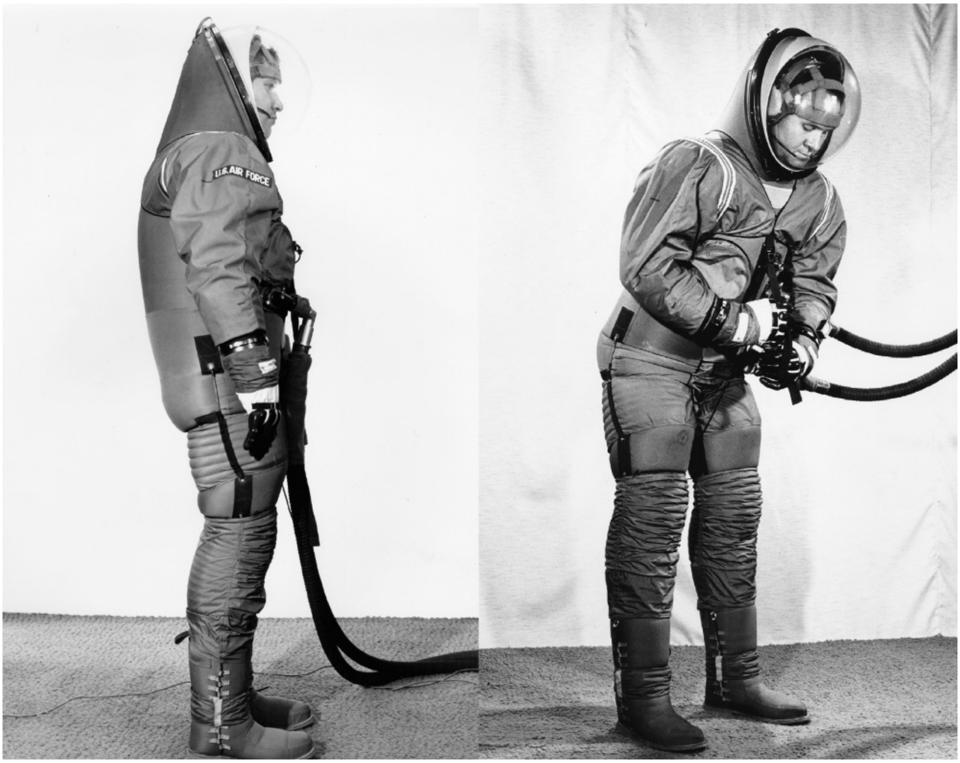


Figure 8.3.10. 1966 ILC MOL competition suit (courtesy ILC Dover LP).

allowed the USAF to implement desired changes in life support connector locations and the suit's pressure controls. This resulted in the MH-7 training suit (Figures 8.3.11E and 8.3.15, left) and MH-8 flight configurations (Figures 8.3.11F, 8.3.15, right, and 8.3.16), respectively.

At least 17 MH-7 MOL training suits were delivered between May 1968 and July 1969. The MH-7 suit principally differed from the MH-8 model in that it utilized a single-layer blue nylon cover garment that left the entry zipper and arm bearings exposed. It also lacked a pressure controller in the lower left section of the chest. At least one MH-7 was later retrofitted with thermal garments and one MH-6 was modified to later-style connections to produce near MH-8 thermal testing suits. These suits were provided with an aluminum plug in the lower left front location to replicate thermal conduction of the MH-8 pressure controller. Due to the results of flight certification testing on the MH-8 suit, MH-7 suits built after April 1969 had minor changes to improve their useful life.

The only known MH-8 suit was delivered in October 1968 for certification. Among the minor differences for flight, this configuration planned a flight helmet with a single gold visor, a drink port, a pressure relief valve, a pressure gauge on the left forearm and an emergency oxygen system (EOS) interface integrated into the

(A) XM-4A
(a) External view (b) Without covers

(B) MH-5 training suit*

(C) MH-6 initial flight configuration*

(D) Development #1*

(E) MH-7 training suit*

(F) MH-8 final flight configuration*

* Note: External view, used same restraint systems as XM-4A

Figure 8.3.11. Hamilton Standard MOL IEVA production contract suits.

Figure 8.3.12. XM-4A suit demonstrating waist mobility (courtesy Hamilton Sundstrand).

right leg of the suit. The thermal cover garment differed from the MH-6 configuration by the front zipper cover being narrower and the cover being reshaped for thermal properties. Although the MH-8 was officially certified for flight, manned testing raised additional thermal issues with gloves.

Figure 8.3.13. Hamilton's "Suit Lab" circa 1967 (courtesy Hamilton Sundstrand).

Figure 8.3.14. An MH-5 suit in zero-*g* training (courtesy Hamilton Sundstrand).

Figure 8.3.15. The MH-7 training suit (left) and MH-8 suit in certification (right) (courtesy, left and right, USAF Museum and Hamilton Sundstrand, respectively).

Through the development and certification of the MH series suit, the tradeoffs between thermal protection while handling tools under extreme conditions and dexterity in operating tools had been a challenge. Overgloves (individual fingers) that provided adequate thermal protection had too much bulk to be effective. Overmittens provided better thermal protection with less bulk but did not allow individual finger movements to operate controls. One solution appeared to be grouping two of the four fingers together. This was receiving favorable evaluation when the public announcement came in June 1969 that the MOL program had been terminated.

The official USAF notification of stopping work on MOL suit production arrived in July. MOL-related equipment items, including spacesuits, were transferred to NASA. The MOL pilots scattered: some took available positions within the USAF to continue their military careers; others were absorbed into NASA's

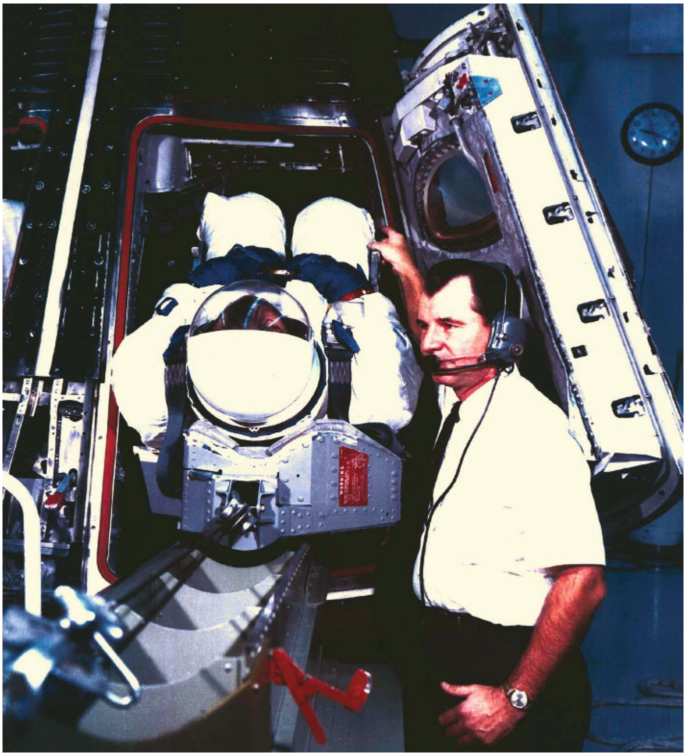


Figure 8.3.16. The MH-8 suit in certification evaluation (courtesy Hamilton Sundstrand).

astronaut corps. Due to the curtailing of plans for follow-on Apollo and Skylab missions, these former MOL pilots would not have opportunities for space flight service until the 1980s on NASA Space Shuttles.

8.4 THE "OTHER" MOL SUIT SYSTEMS

As previously discussed, the first MOL suit was an IEVA-type dual-purpose suit design that was to serve both as a launch/entry suit and as an EVA system. This provided MOL pilots with the ability to survive cabin decompression and to perform emergency EVAs. However, well before a production contract was awarded, the USAF had become aware of the functional compromises associated with the IEVA approach (see Chapter 3) and planned for the additional development of an exclusively EVA on-station suit system. While it never reached fruition, this effort had influence on later activities, as detailed in the discussion that follows.

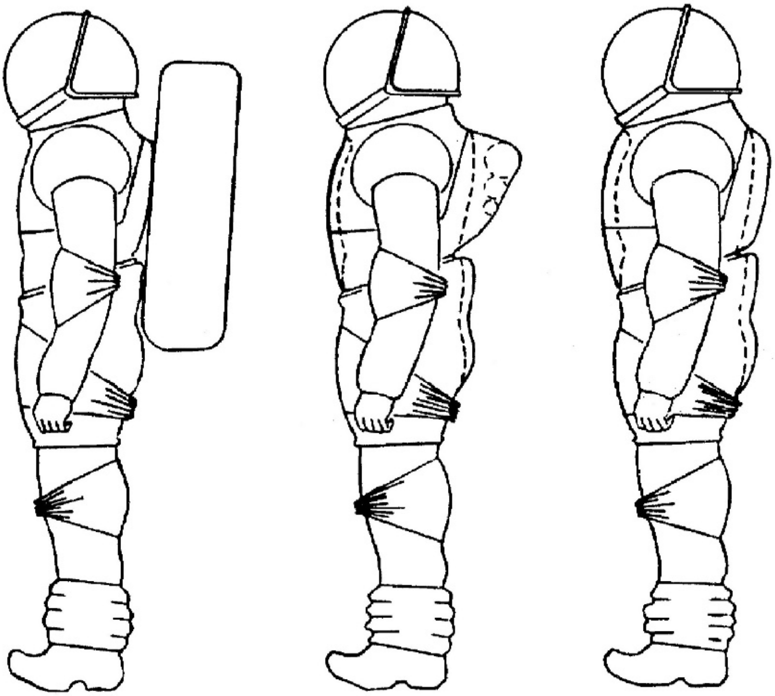
Interestingly enough, the aforementioned designs were not the only MOL suit systems. To obtain biomedical data from primate suit subjects, at least two "chimp" suits were made. These suits are discussed later in this section.

The MOL "exclusively EVA" suit development (1967–1969)

The USAF immediately followed the launch/entry/EVA suit contract award with a competition for the development of an exclusively EVA on-station suit system. This competition was held in September 1967, and the field of competitors included the Litton Corporation and the Hamilton Standard Division of United Aircraft Corporation.

Litton proposed an integrated life support/suit system building on their existing RX-4 and their RX-5 design that was in development. This concept had the advantage of being based on the most highly developed U.S. EVA pressure suit systems of the time. The MOL station was to have a 5.0 psi (34.5 kPa) (oxygen/helium) operating pressure. Litton proposed to use the same suit pressure and environment as the station, but their approach offered potential variations (Figure 8.4.1) of how the life support system might be integrated.

Hamilton Standard proposed an integrated EVA "IEVA" concept (Figure 8.4.2) with the same operating pressure and environment as Litton, but offered a specific repackaging of the existing Apollo portable life support "backpack" that would meet the more restrictive hatch clearances of MOL. The mobility systems would



RX-4 with backpack and ECS

RX with partial integration

RX with total integration

Figure 8.4.1. Litton's concept for MOL station and lunar suit (courtesy G. L. Harris/W. Elkins).

Figure 8.4.2. Hamilton Standard's competition concept (courtesy Hamilton Sundstrand).

be the same as those already in production in the MOL launch/entry/EVA suit contract.

The USAF awarded the contract to Hamilton. The preliminary design of the IEVA suit system was almost completed in April 1968 when USAF concerns developed about lost restraint tethers resulting in EVA crewmember "float-away". These concerns resulted in a redesign and the creation of the integrated maneuvering and life support system (IMLSS) concept. The redesign added a maneuvering unit that was easily removable for optional umbilical operation with a more slim profile. The maneuvering unit was to use 10 lb (4.5 kg) of oxygen at 7,500 psi (510 atm). Of this, 9 lb (20 kg) was for propulsion with 1 lb (0.5 kg) held in reserve as an additional emergency oxygen supply. This was packaged so that the center of gravity was within 1 inch (2.54 cm) of human norm, which facilitated manual control, as the IMLSS design did not include an avionics flight guidance system.

The design for the IMLSS was completed by October 1968. A full pressure prototype, less cover garments, was completed by March 1969 to support USAF testing (Figure 8.4.3). However, creation of the IMLSS cover garments was never completed due to the MOL program's cancelation in July 1969. Following

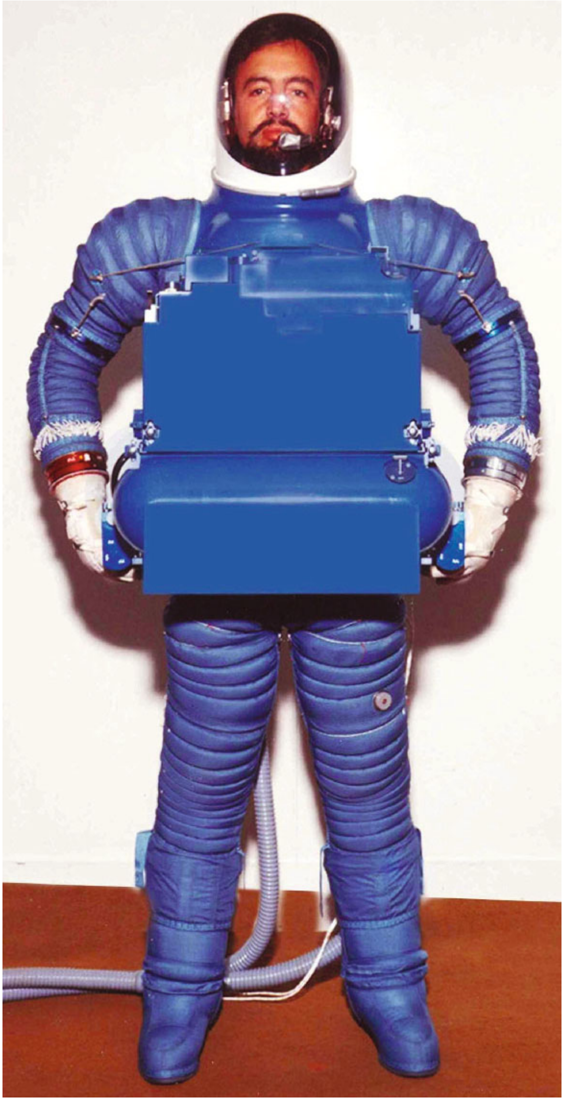


Figure 8.4.3. IMLSS semi-completed prototype (courtesy Hamilton Sundstrand).

MOL program termination, Hamilton Standard funded design improvements (Figure 8.4.4) based on the results of manned MOL evaluation. In September, with USAF permission, the MOL IMLSS prototype was used to demonstrate the spacesuit concept to NASA for Skylab consideration. In the spring of 1970, NASA funded a study of the system but, owing to the funding limitations of the period, further consideration ended in 1970. The IMLSS prototype was finally delivered to the USAF at its museum in Ohio, where it still resides.

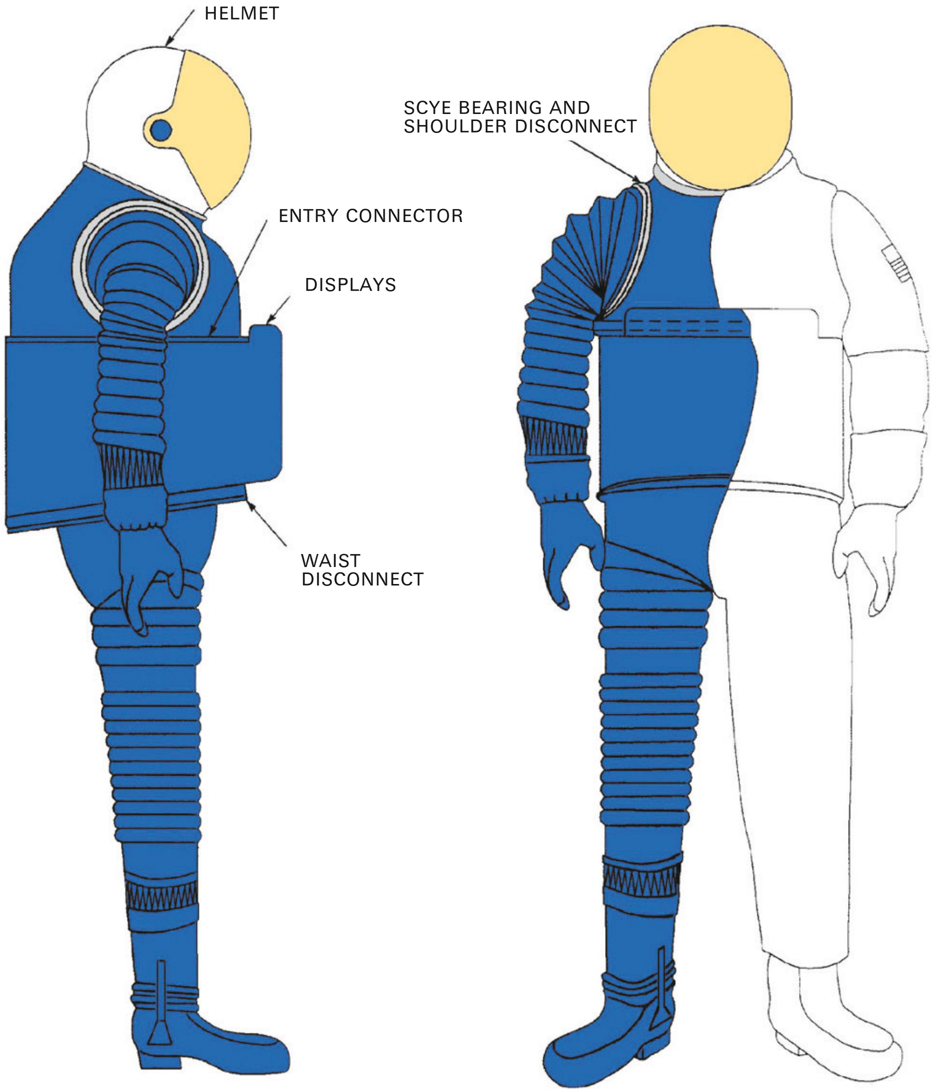


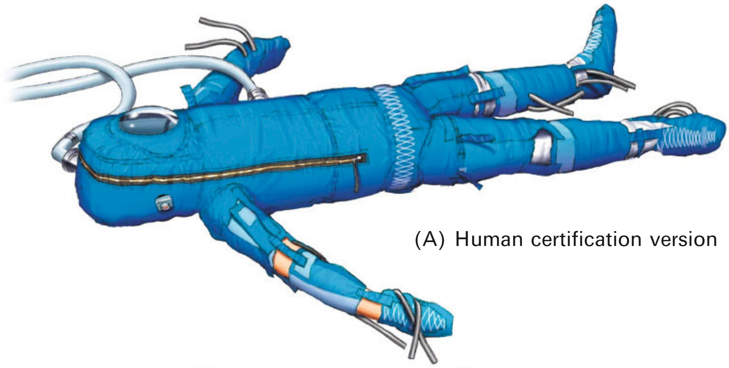
Figure 8.4.4. Final IMLSS features offered for Skylab (courtesy Hamilton Sundstrand).

MOL-related primate suits (1964–1969)

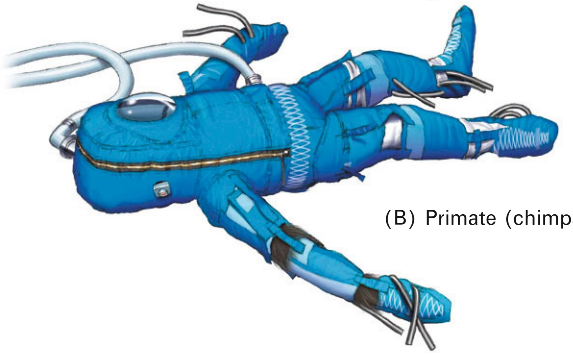
Manufacture of a third MOL-related suit was also in progress at the time of termination. However, this was not for humans. During MOL, the USAF was using primates (chimpanzees) for centrifuge, *g*-force sled testing, and other potentially hazardous, space-related activities prior to allowing human subjects to participate. This created the need for a suit-like enclosure for chimpanzees in which accurate suited information—like biomedical data such as electrocardiogram, respiration, blood pressure, body temperature, consumption of oxygen, and exhalation concentrations of CO_2 and H_2O could be collected. The only two known suits relating to this facet of the USAF space program were produced by Hamilton Standard.

The first known primate suit design came in the fall of 1964 (Figure 8.4.5). This chimp suit was internally funded by Hamilton and may have been initiated to demonstrate Hamilton's suit system capabilities to the USAF. The suit system essentially consisted of a helmet sized to fit a chimpanzee with a simple fabric coverall-type torso assembly that performed two functions: first, the coverall held the helmet in place on the suited subject; second, it attempted to keep the chimpanzee from disconnecting the biomedical monitoring devices by covering the hands with thick, thumbless mittens. The pant legs of the garment zipped

Figure 8.4.5. 1965 Hamilton Standard "chimp suit".



(A) Human certification version



(B) Primate (chimpanzee) version

Figure 8.4.6. Hamilton MOL-related SPCA suit efforts.

together to form a loop to keep the feet together and strapped in position. This kept the chimp from using his feet, which tended to be almost as adept as his hands. Finally, the torso garment contained a thick, moderately stiff "bushy" synthetic material inside the chest area to additionally provide monitor-removing impediment. The helmet had accommodations for inlet/outlet hoses to provide a recirculating atmosphere around the head. The atmosphere was captured in the helmet by a neck dam. The system included compact closed-loop life support with sensors to measure atmosphere conditions and suit subject exhalation byproducts.

Even though Hamilton had internal prototype garment-manufacturing capability, it initially funded International Latex, its Apollo suit subcontractor of the time, for fabrication of the initial torso garment. This may have been an attempt to improve relations between the two organizations; however, soon afterward, the situation degraded past the point of reconciliation. The delivery of the torso garment coincided with Hamilton's termination of International Latex as its Apollo suit provider. In March or April 1965, Hamilton replaced the original torso garment with one that was internally fabricated before the suit system was delivered to the USAF for evaluation.

Under a contract issued by the USAF in 1968, Hamilton designed and manufactured a second primate suit system. Because there was concern about

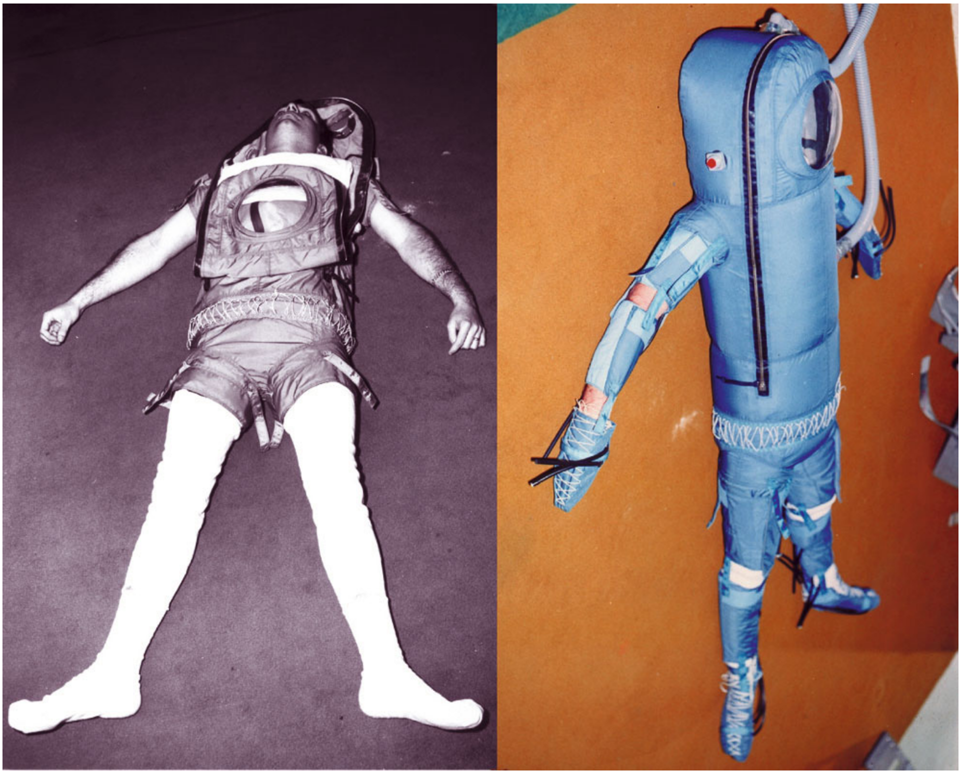


Figure 8.4.7. 1969 human testing of SPCA suit (courtesy Hamilton Sundstrand).

humane treatment of the chimpanzees while wearing the suit, a "human suit" version of the primate suit was first created (Figures 8.4.6A and 8.4.7). This was tested with independent verification provided by the Society for Prevention of Cruelty to Animals and, because the review was favorable, the resulting suit system was named the "SPCA suit". Thus, the path for chimpanzees determining the acceptability of hazardous activities for humans involved humans first verifying that the suit system was acceptably comfortable and safe for chimpanzees.

The suit was a garment that could be stored in a compact package. It had no hard structural elements and was pressurized slightly above ambient cabin pressure, being lightly sealed at the biceps and thighs. Blood pressure and biomed sensors were attached in segments down the arms and legs (Figures 8.4.6B and 8.4.7), allowing for the measurement of body pressure and vital signs at many locations on the body simultaneously during various gravitation conditions. One primate and two human versions of the SPCA suit were fabricated before the program was stopped in July 1969.

8.5 CONTINUING USAF SUPPORT OF EVA SPACESUIT DEVELOPMENT (1970–PRESENT)

NASA continues to draw on USAF expertise in many areas, including EVA, as many in the USAF have strong interest in the field of space. Indeed, many of NASA's astronauts past and present have come from the USAF. However, in 1982, this support took a more tangible form. General James A. Abramson, then NASA Associate Administrator for the Space Transportation System, directed NASA's Ames Research Center to create a prototype to embody what was judged by Ames to be the most promising high-pressure suit technology. As funding was a challenge, the USAF contributed approximately a third of the budget required for development, and the result was the Ames AX-5 prototype. The AX-5 was a significant technical departure from preceding spacesuit development as it was an all-hard-element structure, including the mobility elements (for AX-5 information, see Section 11.1.2).

9

Skylab and the Apollo–Soyuz Test Project suit systems (1969–1975)

Skylab and the Apollo–Soyuz Test Project (ASTP) built on the Apollo program by using vehicles, certified suit designs, and existing hardware. However, Skylab and ASTP were both a change in direction from Apollo. Where Apollo was a race to the Moon, Skylab was meant to establish long-duration U.S. manned presence in easily accessible space and ASTP attempted to build cooperation with a nation that was still a philosophical and potentially military adversary. The long durations in zero gravity would provide the opportunity to develop approaches to counteracting the negative effects of such an environment on spacefarers, thus enabling travel to distant places such as Mars and beyond. The cooperation was an attempt to move beyond political differences to provide potentially greater safety to spacefarers of both nations. While both programs spanned only a few years—and, in the case of ASTP, one mission—these programs represented the beginning of activities that are still currently evolving.

9.1 PLANNING FOR A SPACE STATION

Although the possibility of an orbiting space station had captured the imagination of space aficionados for decades, it was not until 1959 that officials of the newly formed NASA presented the agency's view of long-range objectives, including plans for a manned orbiting space station. It was also at this time that Wernher von Braun suggested using a spent booster stage as such a station's primary structure.

The evolution of early plans for the space station is breathtaking in retrospect. In 1961, a one-man station fashioned from a Mercury spacecraft with an attached cylindrical laboratory capable of 14 days' habitation was proposed; but, by 1963, this had grown to a 24-person orbital laboratory capable of 5 years of continuous orbital operations. The studies were carried out under the Apollo Extension Program, which was changed to the Apollo Applications Program in 1965. At this

K.S. Thomas and H.J. McMann, *U. S. Spacesuits*, Springer Praxis Books,
DOI 10.1007/978-1-4419-9566-7_9,

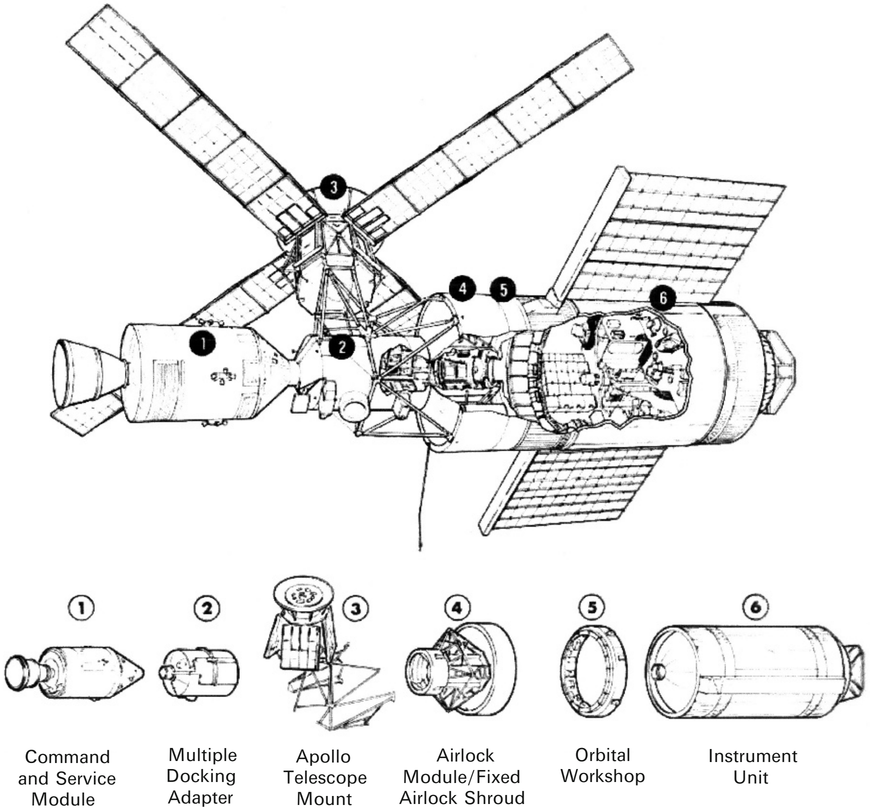


Figure 9.1.1. The Skylab cluster (courtesy NASA).

time, planners began looking seriously at the use of a spent Saturn S-IVB stage as the core of the space station and, by 1969, the concept of an orbital workshop (OWS) was proposed.

At first, the S-IVB stage was to be used along with the S-IB as part of the booster assembly, and vented of residual hydrogen and oxygen before crew outfitting and habitation. This was called the "wet" workshop approach. In mid 1969, however, the "dry" workshop became the approved approach due to the fact that the highly successful Saturn V launch vehicle could be used, rather than the smaller S-IB, thus enabling not only a workshop outfitted for use pre launch, but also the capability to carry many more experiments. In February 1970, the name of the program was changed from Apollo Applications to Skylab.

The entire assembly, called the "Skylab cluster" (Figure 9.1.1), consisted of the Command and Service Modules, followed by the Multiple Docking Adapter, Airlock Module, Instrument Unit, and, finally, the Orbital Workshop (OWS). Jutting out at right angles to the side of the Multiple Docking Adapter and Airlock Module was the Apollo Telescope Mount—which housed the solar observation cameras—from which extended the four large solar arrays. With respect to EVA, the decision to use a Gemini hatch on the airlock module was pivotal in assuring a proven egress/ingress technique for spacewalking crewmembers.

The cluster had a total length of about 117 ft (35 m) and its launch weight was around 199,750 lb (90,606 kg). The orbital paths of Skylab would sweep out an area covering 75% of the Earth's surface, 80% of its food-producing regions, and 90% of its population.

The science to be carried out on board Skylab included biomedical and behavioral performance studies designed to evaluate human responses and capabilities in space under zero-*g* with progressively longer durations. Other experiments and work tasks explored human–machine relationships, aimed at developing and assessing techniques for sensor operation, maintenance and repair, assembly and setup, and the mobility required for the various activities.

Experiments in solar astronomy, Earth resources, science, technology, and applications rounded out Skylab's investigative agenda. As a byproduct of operating for extended periods of time, information on how to increase the life of the various spacecraft operating systems would be gained.

EVA would figure prominently in the conduct of Skylab's mission, not only as a means of conducting experiments and retrieving data, but also as a means of assuring the very survival of the Skylab program.

Prior to adoption of the "dry" workshop approach, astronauts would have had to perform many hours of EVA assembling the "wet" workshop to the rest of the cluster. The initial configuration had over 70 bolts around the circumference of the hatch between the workshop and the airlock that needed to be assembled and tightened during EVA. Early neutral buoyancy testing indicated that almost one-and-one-half hours per bolt would be required, meaning that over 100 hours of EVA would be consumed in that activity alone. The move to the pre-assembled approach using the greater launch capacity of the Saturn V greatly lessened the need for tedious and tiring EVA.

EVA was to be the prime method of retrieving film canisters, cameras, and experiment packages from various locations on the Skylab cluster. EVAs would be conducted by two-person crews; one person performing the tasks and the other standing by to aid and tend to the umbilicals.

Skylab also provided the capability to conduct EVA-related experiments in zero gravity without the hazard of direct exposure to space. The large open volume of the OWS afforded the opportunity of evaluating maneuvering systems while suited or unsuited.

9.2 PRESSURE SUITS: "PIGGYBACKING" ON APOLLO

In December 1968 and January 1969, Skylab planners were part of the Apollo Applications Program (AAP) Block III designs. The pressure suits considered for Skylab were the then current ILC Apollo A7L, the ILC "omega" suit, the Hamilton Standard USAF Manned Orbiting Laboratory (MOL) suit, the Litton constant volume suit (CVS), and the AiResearch CVS (EX-1A). Funding of the ILC omega suit, which included making "A8L" and "A9L" prototypes, was in question. The MOL suit was effectively ruled out due to its perceived lack of fire protection. The 1968 CVS evaluations had not produced an acceptable candidate for Apollo extended duration and lunar base missions (which were later canceled) and the CVS configurations were not compatible with launch and entry use. Thus, the Skylab program initially baselined the A7L pressure suit for Skylab.

During 1968–1969, what had been proposed as the Omega suit was descoped into the former A9L concept being prototyped as the A7LB for Apollo evaluations. In a 1969 parallel activity, Litton and AiResearch were funded for a second iteration of prototypes under the name of the advanced extravehicular suit (AES). The Apollo Block III missions were canceled before the evaluations could occur, but the AES evaluations were conducted nevertheless. The AiResearch AES emerged the winner, and NASA decided to use this suit as a flight experiment on Skylab once the station was operational. However, owing to budget challenges on the Skylab program, this would never occur.

In 1970, the Apollo program accepted the A7LB for the Apollo 15 and later flights. With the mainline Apollo program funding the development, certification, and implementation of an improved EVA pressure suit, Skylab adopted the A7LB as its pressure suit. Since the Skylab requirements were different, NASA directed ILC to make minor changes from the Apollo 16 A7LB configuration. For Skylab, the front upper life support system bracket was revised to improve the umbilical tether attachment. The front lower life support system bracket was eliminated (Figure 9.2.1), and the boots were revised to support usage in foot restraints. As the thermal requirements were less stringent, the visor assembly and pressure suit insulation layers were both revised. The Apollo 14–17 lunar extravehicular visor assembly (LEVA) was transformed into the Skylab extravehicular visor assembly (SEVA) by relocating the opaque center visor under the visor shell and discarding the thermal outer cover on the visor assembly. The SEVA attachment approach was also revised to facilitate donning and removal. The thermal layers of the pressure suit were reduced from two layers of aluminized Kapton separated by Beta marquisette and five layers of Mylar separated by non-woven Dacron as used in Apollo, to three layers of aluminized Kapton separated by Beta marquisette for Skylab. To make it easier and faster to don and doff the pressure suit in zero gravity, the wrap-around zippers in the entry system were relocated lower on the torso. This sacrificed waist mobility, but the waist mobility that had been critical for the Apollo surface missions was not deemed critical for orbital EVA.

The Skylab A7LB flight suits represented the "600" series, in that the three digit serial numbers started with the number 6. While there are currently no known surviving examples of an ILC 500 series, since the 300 and 400 series suits were late Apollo configurations, there may have been a prototype configuration that led to the Skylab A7LB flight configuration. Also at least eight "700" series prototype suits were made. While definition of this configuration is unknown, this design model was also associated with Skylab. For additional Skylab A7LB suit information, see Appendix A, pp. 434 and 435.

Figure 9.2.1. ILC's Skylab pressure suit assembly (courtesy Hamilton Sundstrand).

9.3 EVA LIFE SUPPORT SYSTEM DEVELOPMENT: THE UMBILICAL MAKES A COMEBACK

The selection of an EVA life support system concept for Skylab was somewhat more complicated than that for the suit. Even though the CVS had been planned in the early stages, after some time there was never any doubt that the Apollo suit would be used with only slight modifications for Skylab. This was not the case for the EVA life support system.

In the 1967 timeframe, there were at least four systems in the running for Skylab EVA/IVA: the Apollo PLSS/OPS combination with an associated IVA gas and electrical umbilical; the AiResearch portable environmental control system (PECS) backpack with a similar equipment adjunct; a pressure control unit (PCU) with associated emergency oxygen supply and umbilical that could be used for both EVA and IVA; and, finally, a resurrection of the Gemini ELSS with a special umbilical to provide cooling, oxygen, and electrical services.

The Skylab EVA problem statement for the life support system was complicated by the fact that there were suited EVA-related maneuvering system experiments to be conducted inside the OWS, and one of these—M-509—was contained in a backpack. This alone would rule out use of the Apollo PLSS backpack, and the fact that the PLSS needed a vacuum to provide cooling to the astronaut was also a negative factor. Use of any backpack for EVA, then, would require some other sort of pressurization, ventilation, and cooling system for suited intravehicular activity (IVA) exercises.

The PECS was the most unusual of these systems. It had been under development by the Crew Systems Division (CSD) for years. Originally planned for later Gemini missions, the PECS was then planned for late Apollo missions. When the later Apollo missions were canceled, CSD wished to find the PECS a home in Skylab. It featured four sodium chlorate "candles" (one in each corner of the backpack) as the oxygen supply for both normal and emergency use, built-in facilities for umbilical operation, a fan plus an ejector, and a compact control module, designed to be plucked from a stowage location on the arm and worked by one hand. The control module was nicknamed the "dogbone" because of its ergonomic shape.

Problems with the chlorate candles plagued the project from the start. In order to assure adequate oxygen makeup for high metabolic rates, each candle output was fixed at a high number, since output was not variable. This meant that at low metabolic activity rates, oxygen would be vented overboard. Oxygen purity was another problem. The chlorate candle had an igniter that started combustion of a dense material that then promoted decomposition of the sodium chlorate body to produce oxygen. Filters had to be provided to remove the "dirty" products of combustion of the igniter and other chemical constituents. As the problems mounted and the schedule slipped, the tradeoff changed to favor high-pressure (7,500 psi, 510 atm) gas storage.

The Gemini ELSS was eliminated from consideration fairly early, mainly because of its limited heat removal capability and limited mission duration.

Although CSD and the then AAP Office liked the PECS, there was too much uncertainty in its development. In December 1968, AAP decided to plan for the PCU and umbilical for AAP missions 1 and 2, to be followed by use of the Apollo PLSS without an umbilical for missions 3 and 4. However, by January 1969, the PCU/

umbilical was baselined for all missions, with the A7LB suit and the PECS and/or Apollo PLSS carried as possible alternatives.

This decision led to the preparation of a specification for the Skylab astronaut life support assembly (ALSA), which consisted originally of the PCU and the secondary oxygen package (SOP). The 60 ft umbilical—which would carry supply and return lines for cooling water, oxygen for pressurization and ventilation, electrical and communications lines, and a tether—was to be built by McDonnell Aircraft Corp. (now Boeing).

In January 1969, a preliminary requirements review was held for the ALSA, and in June of that year Martin–Marietta, McDonnell–Douglas, and Litton Systems of Beverly Hills, California, declared interest in the procurement. AiResearch and Hamilton Standard also stated their intent to bid. Lockheed and Aerojet decided not to submit a proposal.

As it turned out, only AiResearch (now Honeywell) and Hamilton Standard (now Hamilton Sundstrand) submitted proposals on the ALSA. AiResearch (soon to become part of AlliedSignal as a result of a merger) won the competition in November 1969 with a design that featured the use of an Apollo Command Module environmental control system demand regulator as the heart of the system.

ALSA hardware and operations description

As mentioned previously, various system concepts from the ‘‘always a bridesmaid’’ PECS to the Apollo PLSS to the Gemini ELSS had competed at an earlier stage for a role in Skylab EVA. The presence of a spacecraft ECS with the capability to pump cooling water, the predictability of the planned EVA paths, and the ability to carry a large amount of oxygen weighed heavily toward a simpler system than the PECS or PLSS—one that could also be utilized for IVA experiments.

The ALSA concept featured an open-loop oxygen flow, cooling water recirculated by means of the water pumps in the spacecraft, and spacecraft electrical power. The two initial components of the ALSA were the pressure control unit (PCU) and the secondary oxygen package (SOP). The life support umbilical (LSU) was added to the AlliedSignal (previously AiResearch, now Honeywell) contract as part of the ALSA in June 1970.

Pressure control unit description

The PCU (see Figures 9.3.1–9.3.3) was mounted on the astronaut’s suit at the waist area, and had top-mounted controls and displays. Oxygen was fed to the PCU from either the LSU or the right leg-mounted SOP. Supply pressures from the LSU varied from a low of 65 psi (448 kPa) to 176 psi (1,213 kPa) maximum. SOP supply pressures ranged from 27 psi to 45 psi (186 kPa to 310 kPa). Oxygen could also be introduced through a recessed auxiliary connector, which was a holdover from earlier concepts for providing emergency oxygen. A schematic of the PCU is shown as Figure 9.3.4.

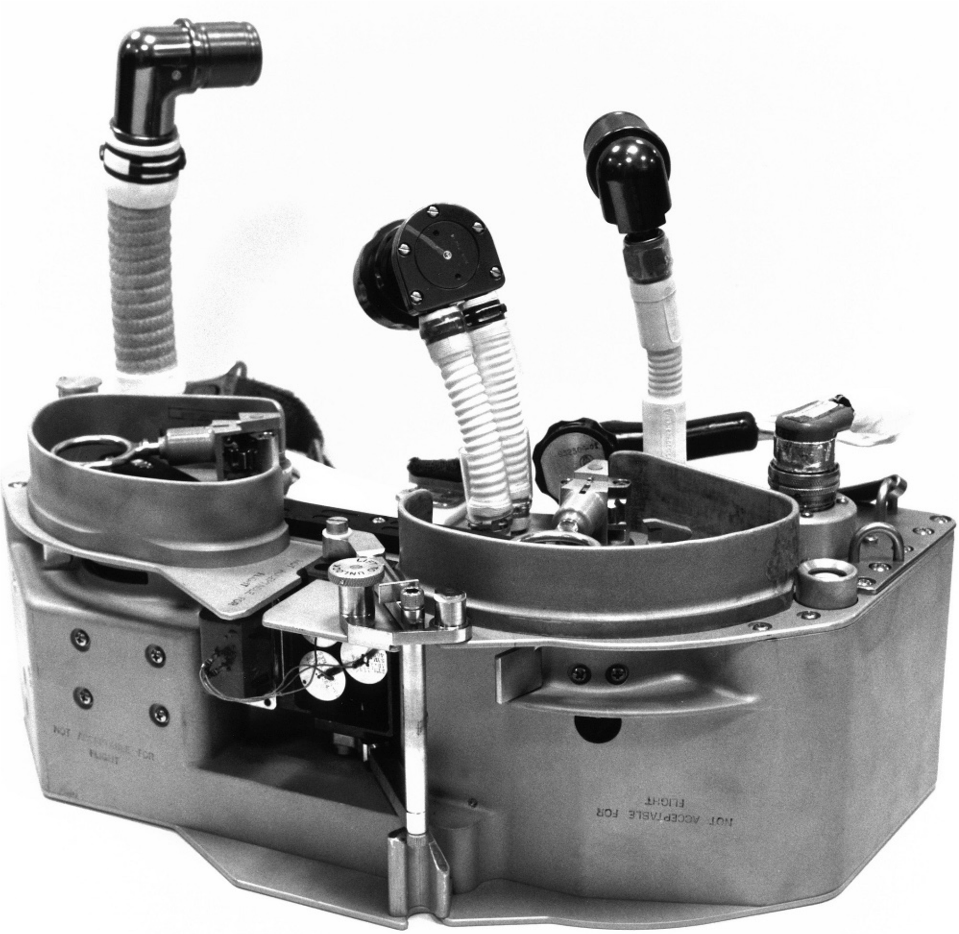


Figure 9.3.1. The AiResearch pressure control unit (courtesy Honeywell).

The PCU operated with a redundant demand regulator system that essentially "fed" a calibrated orifice at the outlet of the suit. The primary regulator controlled the suit to a pressure range of 3.42 psi to 3.80 psi (23.6 kPa to 26.2 kPa), and the secondary regulator was set to 3.07 psi to 3.4 psi (21.2 kPa to 23.4 kPa). Proper functioning of the primary regulator would then keep the secondary on standby in the event of failure. Either one or both regulators could be selected, allowing for isolation of a faulty regulator side.

The crewmember could select two operational modes: "ABS" for absolute pressure operation; and "Delta P" when he wished to pressurize the suit above normal ambient pressure for carrying out pressurized suited experiments. This control was mounted on the front face of the PCU, on the astronaut's left. For normal EVA use, ABS mode was selected. This allowed the EVA crewmember's suit to remain at about 3 inches of water (0.75 kPa) positive pressure during

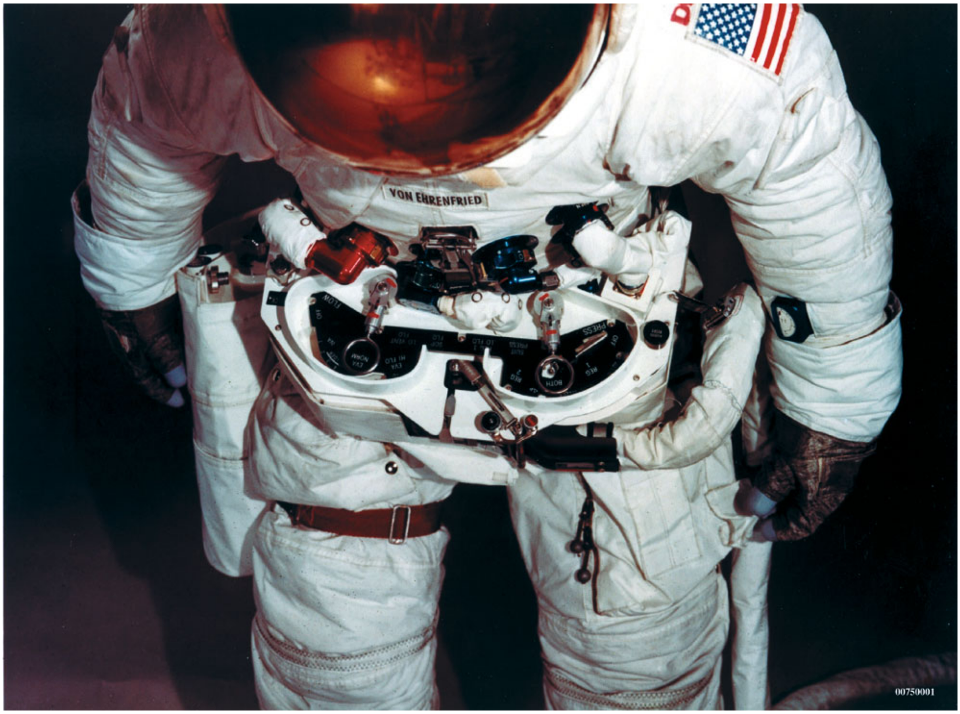


Figure 9.3.2. Skylab PCU attached to suit showing controls (courtesy NASA).

pre-EVA suited operations, allowing more freedom of movement than when fully pressurized. Aneroid (partially evacuated) sensing elements operated to maintain the suit at around 3.61 psi (24.9 kPa) when the local ambient pressure was lowered during depressurization for EVA.

This dual-regulator combination was a direct utilization of the Apollo Command Module ECS regulator, slightly modified for EVA use. Either one or both regulators could be selected by moving the top-mounted regulator selector control lever. The actual regulator internal configuration featured a tiny "peel" valve, which consisted of a thin silicone flap, which was peeled away from tiny holes by a sensitive linkage of pressure-sensing components that responded to very tiny changes in pressure due to breathing demand, even when those changes were superimposed on the normal constant flow demand. During manned chamber development testing, this sensitivity was so marked that an astute test conductor correctly deduced that the engineer participating as the test subject that day was slightly congested. He was able to tell this by the difference in flow demand pattern as traced on the oxygen supply instrumentation, as opposed to previous tests using the same person.

The outflow control valve (see Figures 9.3.3 and 9.3.4) had three settings, selectable by the crewmember: "EVA High" provided a flow rate of about

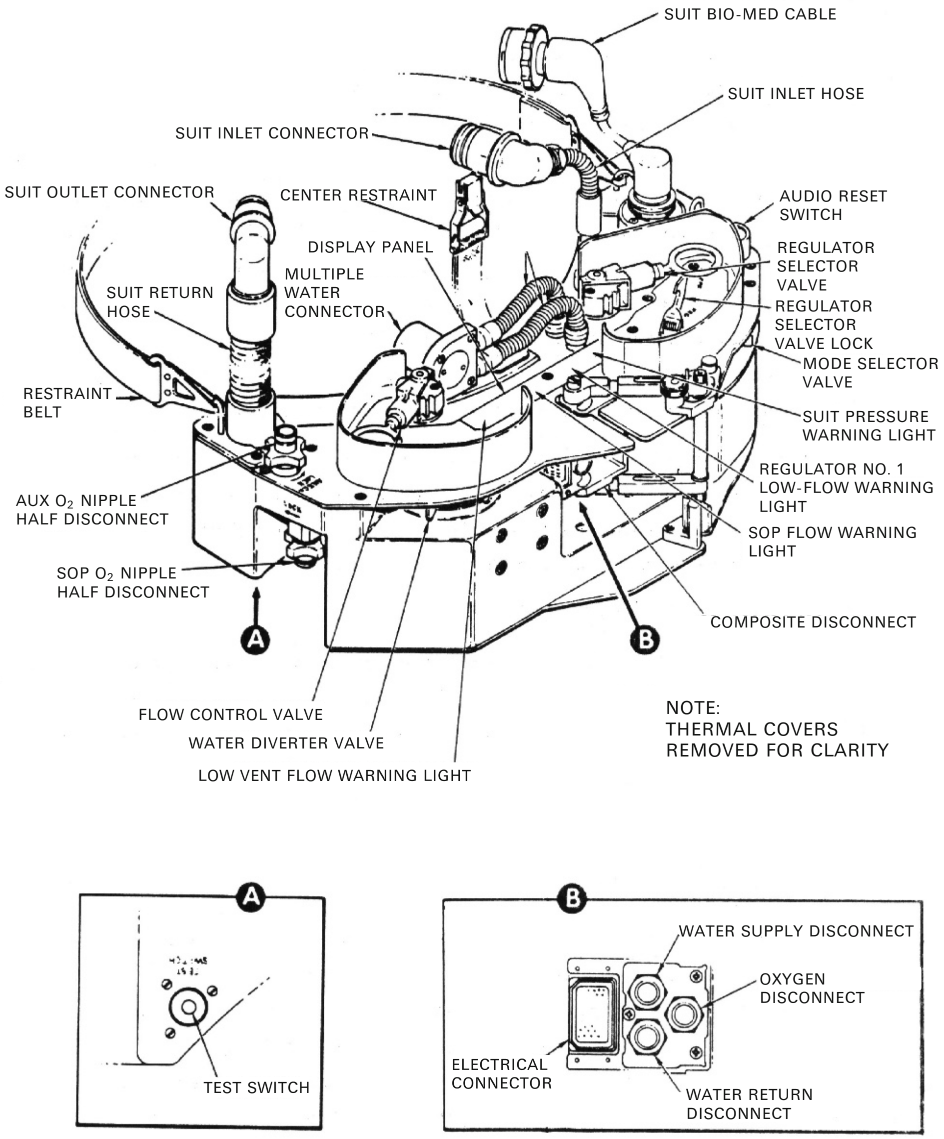


Figure 9.3.3. PCU features (courtesy NASA).

12.5 lb/h (5.7 kg/h); "EVA Norm" about 8 lb/h (3.6 kg/h); and "IVA" about 10 lb/h (4.5 kg/h) in a pressurized suit with 5 psia ambient pressure. The selector lever was mounted on the top of the PCU. For EVA, EVA Norm was the setting used, with EVA High available in the event of loss of water cooling or at crewmember discretion.

This approach to controlling suit pressure and flow was radically different from that of either Gemini or Apollo. In Gemini, flow was fixed at the inlet to the suit by a

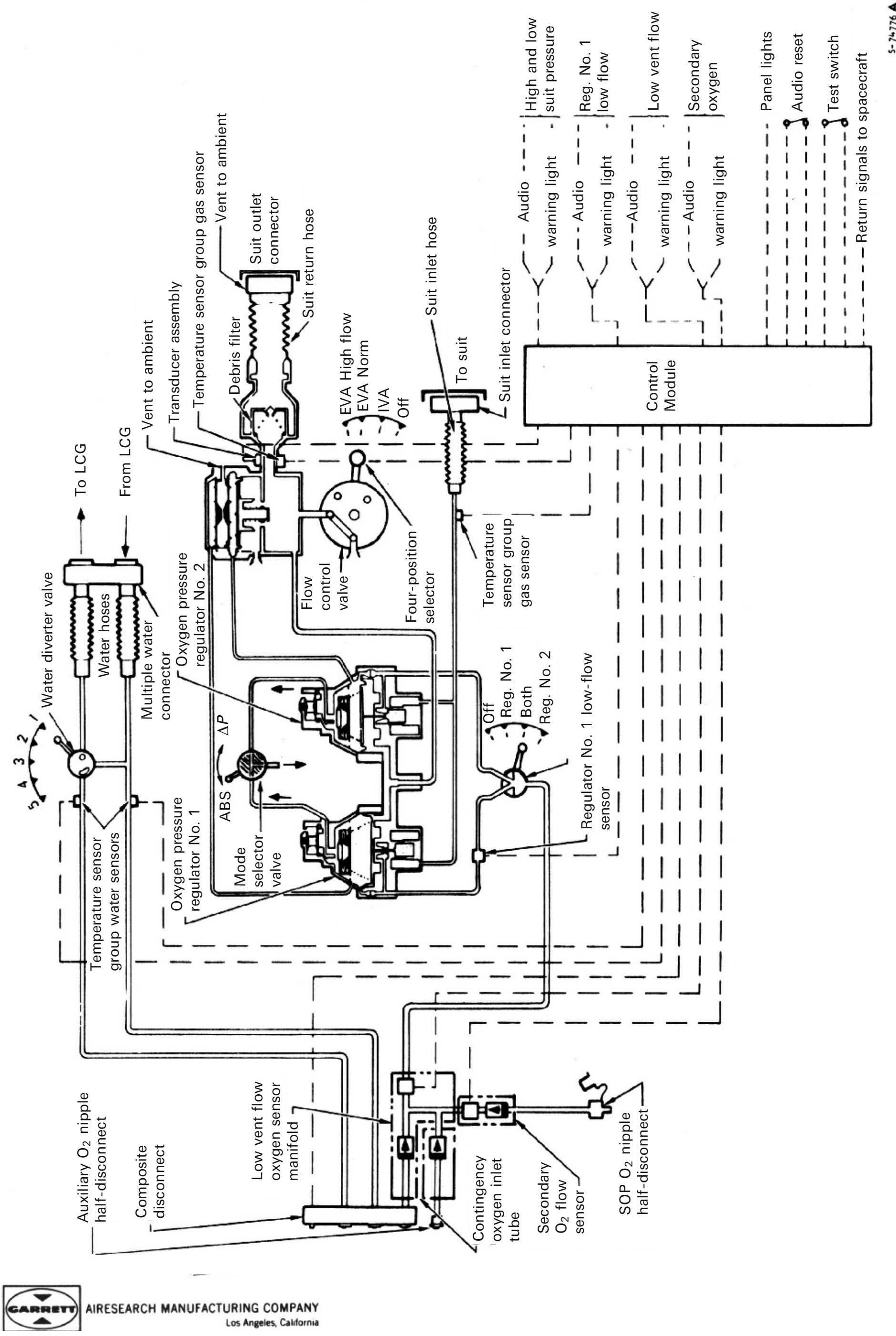


Figure 9.3.4. PCU schematic (courtesy NASA).

Figure 9.3.5. PCU debris deflector in EVA (Alan Bean pictured) (courtesy NASA).

throttling orifice and a pressure control valve at the suit outlet maintained the suit at the proper pressure by venting gas overboard. In Apollo, the loop was closed and a pressure regulator maintained suit pressure by providing makeup oxygen for that lost by leakage and metabolic usage. In the case of the Skylab system, it can be easily seen that a malfunctioning regulator or a suit puncture could be disastrous, hence the need for the redundant regulator.

This open-loop approach also dealt with the problem of carbon dioxide control along with respired moisture removal, since the exiting gas carried these constituents with it. In Apollo, the closed-loop PLSS contained a lithium hydroxide cartridge for conversion of the carbon dioxide to lithium carbonate and water vapor. This moisture along with respired water vapor was removed by means of a condensing heat exchanger.

One problem that open-loop (i.e., venting) systems caused in zero-*g* was that of unwanted thrust. The Gemini ELSS attempted to negate or at least lessen any thrust due to exiting gas by using a poppet-type relief valve that vented gas in a 360 degree arc at the bottom of the chestpack. However, there was still a resulting net force on the chestpack bottom surface. During Ed White's Gemini IV EVA and the remaining EVAs of the Gemini program, this thrust was not noticeable due to the predominance of other forces (e.g., umbilical torquing, the hand-held maneuvering unit or HHMU, etc.). In Skylab, PCU exhaust was vented through the three sides of the PCU housing. However, mission planners and experimenters were concerned that tiny particles and water vapor in the overboard venting gas stream could contaminate sensitive instrumentation on the ATM, so CSD engineers were tasked with devising some sort of deflecting shield that would divert exhaust gases to the rear of the EVA crewmember. The first concept was a hard shield that would be mounted around the front and sides of the PCU, but this proved to be unworkable due to its bulk and its interference with controls. The final configuration was a soft cover that effectively routed flow to the rear of the crewmember, while allowing operation of controls through the material (Figure 9.3.5). This meant, however, that there was a definite potential for forward thrust of the EVA crewmember, and this was experienced during the second EVA of Skylab 4 by firing of the Skylab attitude control system thrusters to maintain cluster orientation when the EVA crewmember was at the ATM, essentially at the end of a large lever arm.

Cooling control was accomplished by means of a water flow diverter valve located on the as-worn right front face (see Figures 9.3.2 and 9.3.3) of the PCU. Almost 100% of inlet flow (204 lb/h out of 240 lb/h) could be diverted around the liquid-cooling garment (LCG) worn by the crewmember (a small flow was necessary to prevent freezing in the lines). This again was a departure from the liquid-cooling temperature control in Apollo. The Apollo PLSS diverter valve bypassed water around the sublimator, keeping a relatively constant flow to the LCG at varying temperature. In Skylab, the crewmember received a relatively constant temperature at varying flow rates. The difference was noticeable when the Skylab crewmember moved the valve to increase water flow—there was a definite "cold spot" where the water was introduced to the LCG. The Gemini IV system and the Gemini ELSS relied, albeit rather unsuccessfully, on cooling by evaporation of sweat into the oxygen ventilation flow.

Secondary oxygen package description

The ultimate configuration of the secondary oxygen package (SOP; Figure 9.3.6) was a twin-tank package, mounted on the EVA crewmember's right leg (Figure 9.3.7). This was not the first approach proposed. In the early ALSA concept phase, designers reasoned that a small, 15-minute duration oxygen supply package should be carried by the crewmember, and larger—30 minutes or longer—packages be stationed at pre-selected locations along the EVA path. Several of these packages, called the "secondary oxygen supply" (SOS), could be placed during early EVAs and left there for the duration of the program, unless used.

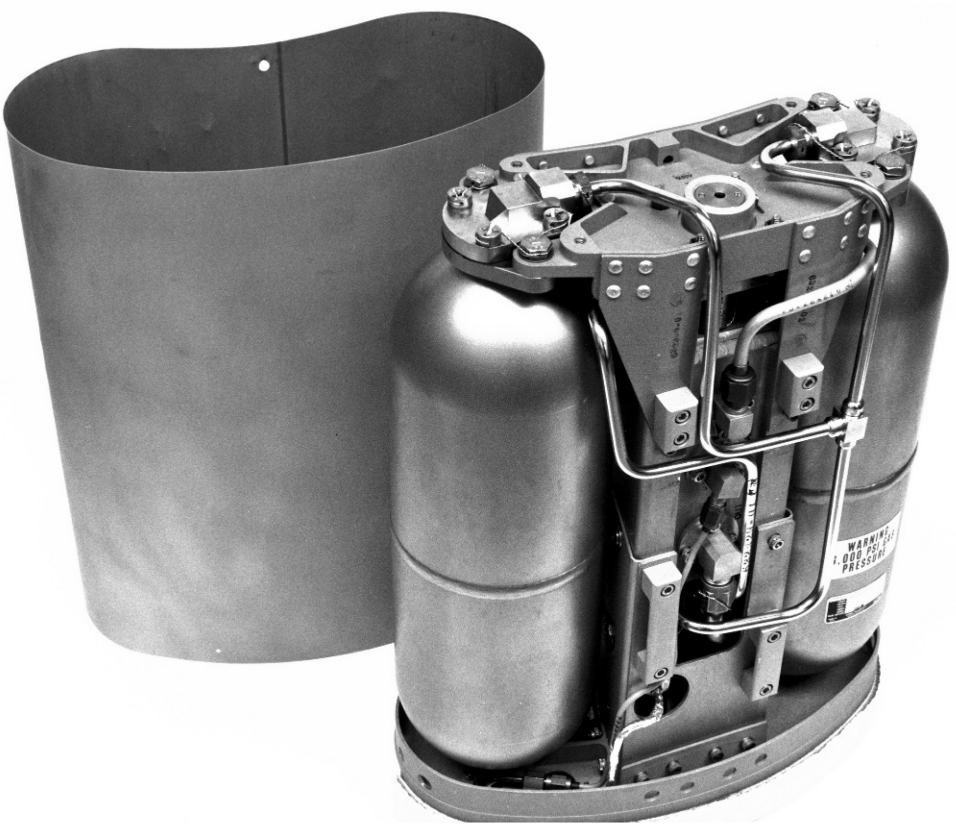


Figure 9.3.6. The AiResearch secondary oxygen package (courtesy Honeywell).

Operations specialists and the crewmembers argued against this approach, postulating that an undetected leakdown failure of the pre-stationed SOS or any difficulty attaching to it in the stress of an emergency could be disastrous. The advocates for a 30-minute supply kept by the EVA crewmember won, resulting in the SOP configuration used for Skylab EVA.

In the event of loss of oxygen supply from the Airlock Module (AM), or any other off-nominal condition resulting in the lowering of the umbilical supply pressure flow from the leg-mounted SOP to the PCU regulators was automatically initiated. Normally held closed by the higher pressure from the umbilical, the SOP would commence flow at a pressure as low as 27 psi (186 kPa) at the umbilical outlet.

The SOP consisted of twin cylindrical gas storage cylindrical tanks, containing a total of 4 lb of usable oxygen at around 6,000 psia (408 atm). The tanks were manifolded together and the supply line led to a manually activated shutoff valve, then to a single-stage regulator that controlled supply pressure from 27 psi to 45 psi (186 kPa to 310 kPa). This regulation range was held until a final tank pressure of about 350 psi (24 atm) was reached, resulting in a residual of about three tenths of a

Figure 9.3.7. SOP shown on Owen Garriott's EMU during a Skylab 3 EVA (courtesy NASA).

pound (0.14 kg) of oxygen. A pressure gauge at the manifold and a pressure gauge at the regulator were the instrumentation on the SOP. The sides and bottom of the package were thermally insulated.

SOP flow rate capability varied from 2 lb/h to 13 lb/h (0.9 kg/h to 5.9 kg/h), as determined by demand from the PCU. At the EVA Norm setting, the SOP provided about 30 minutes of operating time. At EVA High, the time was reduced to 18.5 minutes.

At even moderate flow rates, the Joule–Thomson cooling effect resulting from the expansion of the oxygen from the 6,000 psi (408 atm) storage pressure to 45 psi (310 kPa) or lower resulted in the need to warm the gas before it reached the PCU.

Accordingly, the SOP contained two features aimed at reducing the severity of the temperature drop. Inside each SOP storage tank were brazed V-shaped copper fins (vertex toward the center of the tank), and mounted just downstream of the regulator was a thermal storage unit, consisting of an aluminum block with 21 0.25 in. holes drilled through it.

Oxygen from the SOP flowed through an insulated, wire-reinforced silicone-lined hose to the PCU where it tied in just upstream of the selector valve through a self-sealing quick disconnect (Figure 9.3.8, SOP schematic).

The SOP was mounted via three straps: an upper restraint and two straps that wrapped circumferentially around the crewmember's right leg. The upper restraint clipped to the existing ring on the suit, and provided support in 1*g* conditions; the other two straps were of different lengths to allow for leg taper. They fastened by means of a simple hook and clip with an adjustment buckle.

Life support umbilical description

The 60 ft life support umbilical (LSU) provided the vital life support, tethering, and electrical links from the spacecraft to the EVA crewmembers. The LSU provided oxygen supply through a 60 ft (18.3 m), 0.25 in. (7.6 mm) diameter silicone-lined hose, which was reinforced with a spiral wire wrap and covered with a Beta-glass/Viton wash coating. Hoses 0.38 in. (11.4 mm) in diameter of the same general construction made up the cooling water supply and return lines. Electrical services provided by the 23 Teflon-coated conductors included electrical power for the ALSA caution and warning system, communications, and instrumentation lines. At the AM panel, separate fluid and electrical connectors conveyed services to the LSU, while at the PCU a composite connector allowed simultaneous hookup of water, oxygen, and electrical lines (Figure 9.3.9).

A tether provided structural integrity. It consisted of a rectangular cross-section of Nomex ribbon for the portion of the tether under the thermal protective cover, and a short length of PBI material where the tether exited the LSU at the spacecraft end. The tether was approximately 58 ft (17.5 m) long, allowing for stretch under load without putting strain on fluid or electrical connectors. The tether attached to an existing ring on the suit at the EVA crewmember end and to a rod on a panel at the AM end.

The hoses, wire bundles, and tether were enclosed in a cover assembly that provided thermal and micrometeoroid protection. The outside cover was Teflon-coated Beta fabric that overlaid four layers of gold-coated Kapton film, six layers of aluminized Kapton, and two layers of Teflon-coated Beta cloth. Beta marquisette scrim spacer material was inserted between the Kapton film elements to prevent direct contact and thus assure the efficacy of the thermal radiation shielding provided by the Kapton.

It was important for EVA crewmembers to identify each LSU readily and to determine how much of the 60 ft (18.3 m) length was extended at any time. LSU identification numbers (i.e., "1", "2", etc.) were stitched in orange, while footages in 5 ft (1.5 m) increments were stitched in green (see Figure 9.3.9).

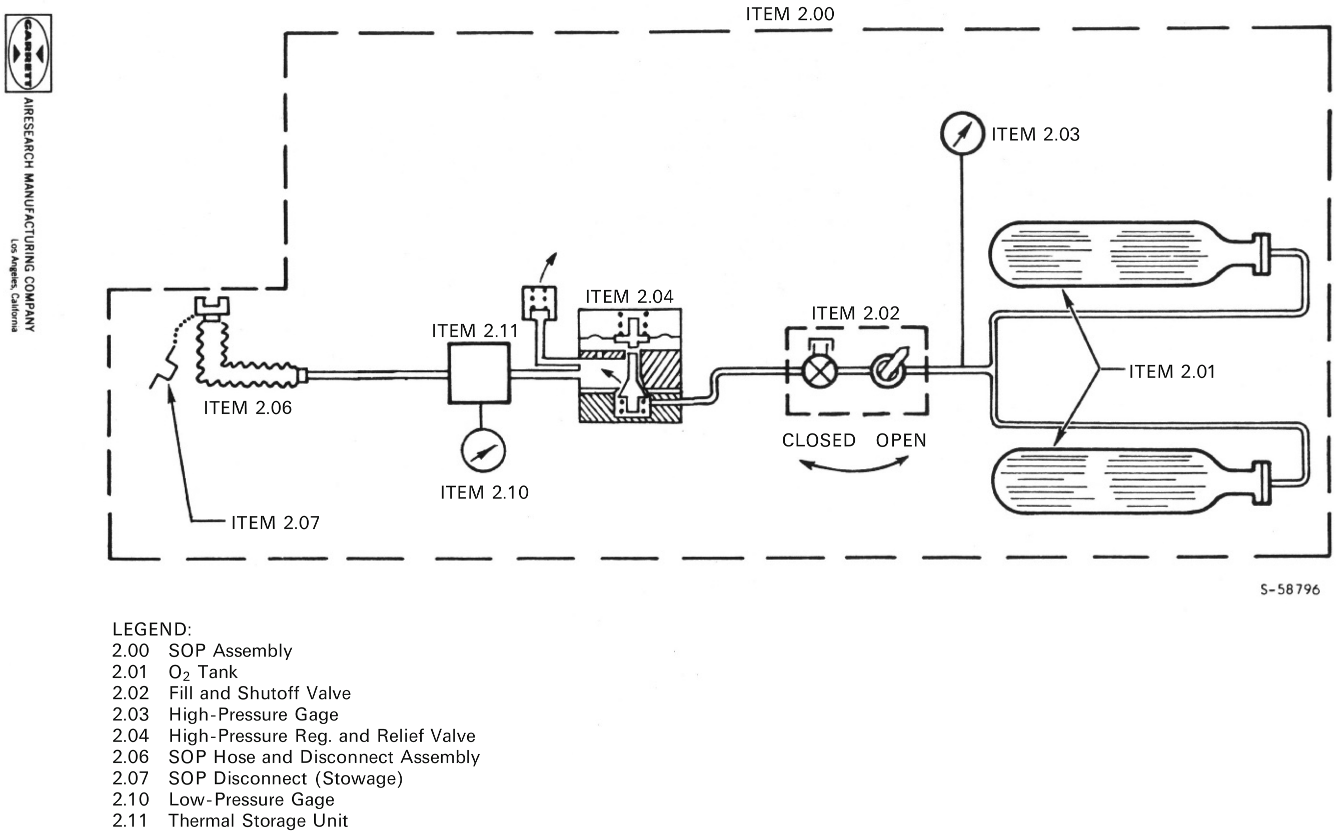


Figure 9.3.8. SOP schematic (courtesy NASA).

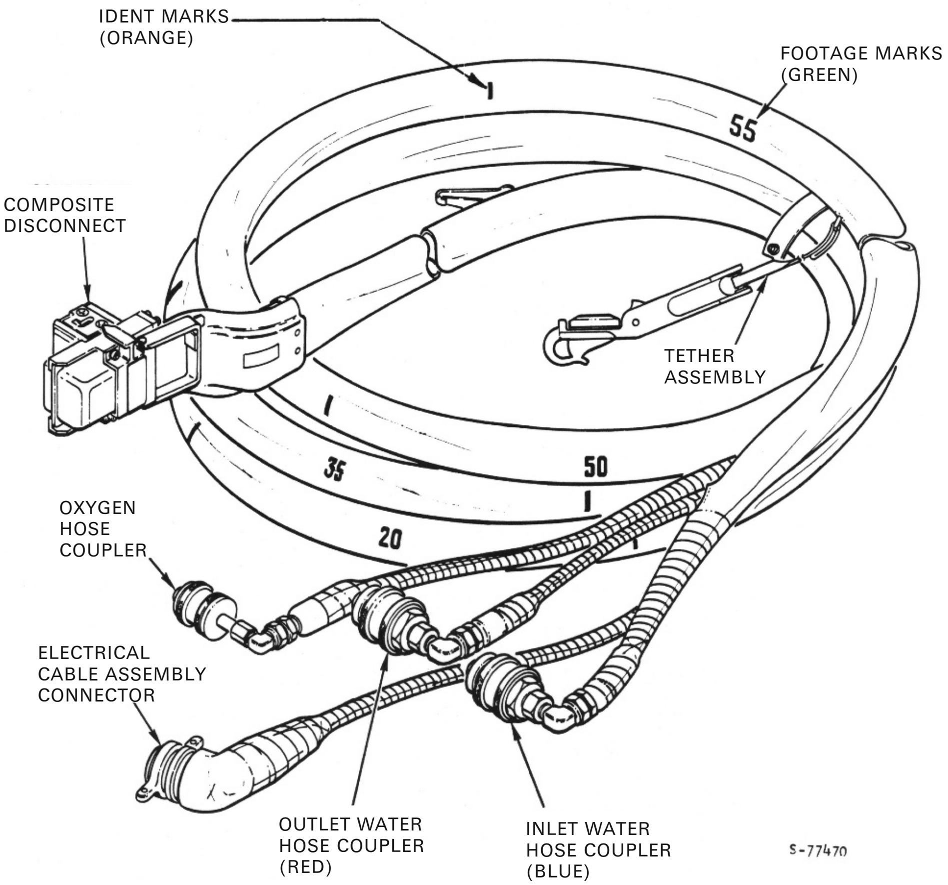


Figure 9.3.9. Life support umbilical features (courtesy NASA).

Umbilical handling had presented some irksome problems during the Gemini program. Initial stowage was accomplished on the ground and, although the umbilicals were jettisoned after EVA use, collecting 25 ft (7.6 m) to 50 ft (15.2 m) of the fairly stiff hose in the cramped cabin prior to tossing it overboard during a subsequent EVA made the confined conditions in the Gemini spacecraft even more difficult. The Skylab LSU, with three hoses instead of one and 60 ft (18.3 m) of length, required a better means of stowage and restowage. The Skylab AM location within the cluster allowed the use of two spherical stowage containers—thought to be about 40 in. (1 m) in diameter—mounted exterior to the AM with openings through the AM wall. The spacecraft end of the LSU was connected to the various connectors on the panel and the bulk of the LSU was pushed into the sphere. The composite connector (PCU end) was plugged into a mating fixture for launch and stowage between uses. For EVA, the required length of LSU was pulled out of the container as needed and pushed back into the sphere when the EVA was completed.

During EVA, the extended portions of the LSU were kept in place by V-shaped clips placed along the EVA "trail".

Instrumentation system, and caution and warning system

The PCU contained all the instrumentation and electronics necessary to operate the caution and warning system and provide performance information. Sensors measured suit pressure as well as suit inlet and outlet temperatures for both the ventilating oxygen and cooling water circuits. These data were sent via umbilical to the spacecraft and, ultimately, to the ground monitors. In addition to these automatic measurements, EVA crewmembers were requested to tell the ground the setting that had been selected for the water flow diverter valve and report any time they changed outflow valve settings.

Safety instrumentation provided audible and visible warnings of high or low suit pressure, low flow from the primary PCU regulator, flow from the SOP, and low ventilation flow to the suit. The gas and water temperatures along with diverter valve settings and flow control valve position provided information to the ground as to the EVA crewmember's thermal status, thus letting them know if there were indications of incipient thermal problems.

The EVA crewmember could take the following actions in the event of emergencies: switch from the normal setting of both regulators to either regulator 1 or regulator 2, increase gas flow to the suit in the event of overheating or low vent flow, and terminate flow out of the suit in the event of low suit pressure. SOP flow was initiated automatically if the LSU oxygen supply pressure fell to the 27 psi to 45 psi (186 kPa to 310 kPa) range mentioned previously.

9.4 SKYLAB EVA AND IVA EXPERIENCE

The Skylab cluster was launched without crew as Skylab 1 (SL-1) on May 14, 1973. About one minute after liftoff, an inability to adequately vent atmospheric gases under the micrometeoroid shield during ascent caused it to separate and damage solar array wing No. 2's tie-downs. This resulted in partial premature deployment, and subsequent impingement of the rocket plume on the solar array wing which caused its loss. Although solar array No. 1 was still present it could not be deployed on orbit because of a metal strap holding it almost completely folded closed. Without power and insulation, the onboard systems of the U.S. station would soon become seriously damaged from excessive heat. This turned EVA into the key element in a space station rescue.

Eleven days after Skylab was launched, the rescue mission, Skylab 2 (SL-2), lifted off in what was tantamount to an experiment in space repair. The first Skylab EVA was actually a 40-minute "standup EVA" conducted on May 25, 1973, from the SL-2 Command Module. The crew had moved the CSM as near to the OWS as safely possible, and Astronaut Paul Weitz stood in the CM hatch receiving life support from the CSM environmental control system. He attempted

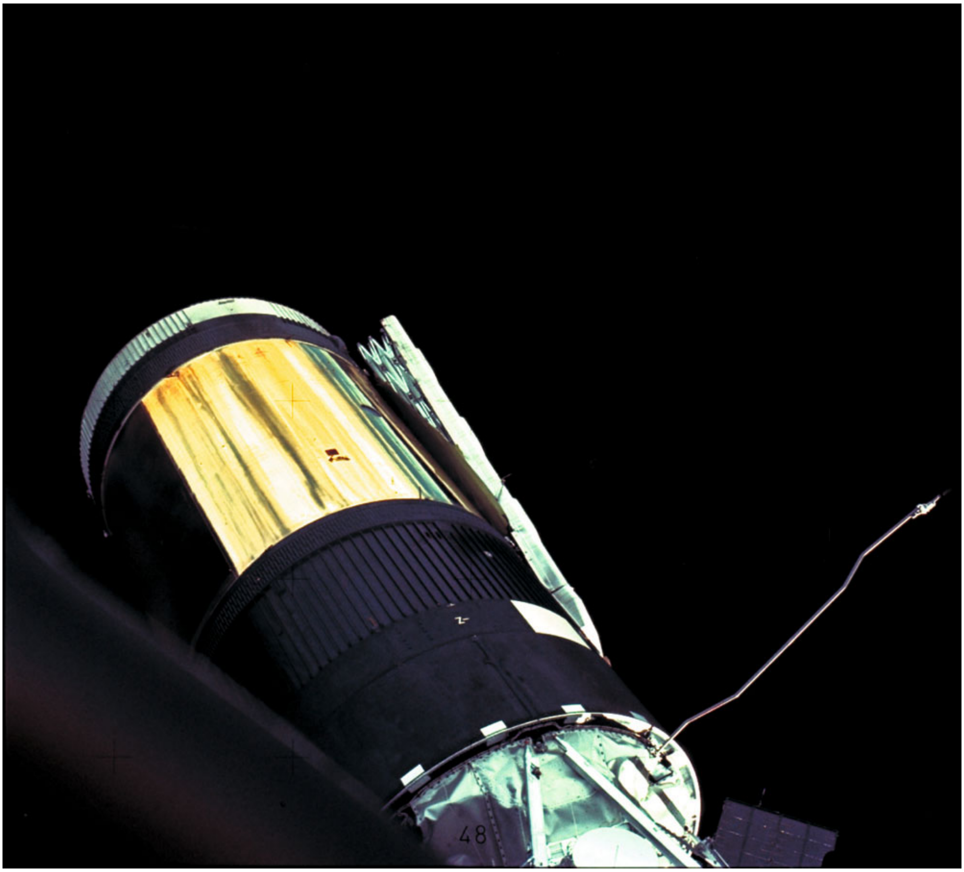


Figure 9.4.1. Skylab's remaining solar array shield beam (courtesy NASA).

to free the bound array by pulling on it using a 15 ft (4.6 m) pole with a crook at the end that he had assembled from 5 ft (1.5 m) sections during the EVA. This was unsuccessful, so he next tried to free the jammed array using a prying tool, but this too proved to be a futile effort. The EVA was ended after about 40 minutes with the array still in the undeployed position. The crew then docked with the workshop. Once inside, they deployed a parasol sunshade by pushing it out through the scientific airlock in the side of the workshop and unfolding it. This allowed the workshop interior temperature to decrease to tolerable levels.

Freeing the jammed solar array wing—called the "solar array shield"—beam (Figure 9.4.1) was the immediate priority of the first EVA from the Skylab AM. This was also the first on-orbit use of the ALSA. Astronauts Pete Conrad and Joe Kerwin conducted the next EVA (SL-2/EVA 2) on June 7, 1973, which lasted some 3 hours 25 minutes. There was a slight delay in depressurizing the AM since a large block of ice formed on the inside of the overboard dump valve.

Based on successful tests performed by a team of ground-based astronauts and engineers and using up-linked instructions, the astronauts on orbit assembled a strap-cutting device made up of available tools and equipment. Basically, it was a cable cutter mounted at the end of a 29.5 ft (9 m) rod and actuated by a rope. Ground control personnel surmised that another problem faced the astronauts: a hydraulic damper was probably frozen in position and the crew would need to exert considerable force to free it. The technique developed by the ground consisted of the crewmembers pushing up against a rope strung from the solar array to a tie point on the vehicle.

In actuality, the cable cutters were used to clamp onto the strap and Astronaut Conrad translated along the rod and ended up cutting the strap with a surgical bonesaw. In order to free the frozen actuator, both crewmembers strained upward against the rope and freed the beam. When it let go, both astronauts "took off", in Conrad's words. The newly freed array started generating power immediately, indicated by the ground's terse but happy announcement: "SAS amps!"

In addition to freeing the solar array shield beam, the astronauts changed out a film magazine for the extreme ultraviolet coronal spectroheliograph and pinned open the door for the X-ray spectrographic telescope. The only EVA equipment–related problem worthy of note was some difficulty experienced by the astronauts in restowing their LSUs in the stowage spheres.

The next EVA (SL-2/EVA 3) was carried out by Astronauts Paul Weitz and Pete Conrad on June 19, 1973, and lasted 1 hour 36 minutes. By this time, with power now at acceptable levels, EVA plans were returning to original goals. The primary objectives of this EVA were changeout and retrieval of film magazines for seven experiment packages. Secondary objectives involved attempting to start a reluctant battery charger and cleaning contamination from a camera lens. It took the crew only 1 hour and 16 minutes to service all seven experiment packages and another 20 minutes to coax the reluctant battery charger to life by the judicious use of a hammer. They also cleaned the camera lens. SL-2 returned on June 22, 1973.

No anomalies were noted with any of the EVA suit or life support equipment during SL-2. The crew returned to Earth after 28 days in space, which set a very short-lived world record for the longest time spent by humans in space.

Although the parasol that had been erected during the early days of SL-2 had reduced OWS inside temperatures to bearable levels, ground testing had shown that the parasol's Nylon fabric could deteriorate due to ultraviolet light exposure. Also, the parasol did not cover all the exposed area of the OWS exterior. Accordingly, a thermal shade was fabricated by Marshall Space Flight Center and launched with Skylab 3 (SL-3) on July 28, 1973, to be installed over the parasol.

Although PCUs and SOPs had been launched on board both SL-1 and SL-2, the trouble-free performance of these items during the first series of EVAs led flight planners to reallocate CSM storage space on SL-3 previously planned for PCUs and SOPs to allow stowage of tools and a rate gyro "six pack" to be installed during one of the EVAs. The decision to limit SOPs launched on SL-3 to one unit ultimately limited IVA experiments, as discussed on p. 265.

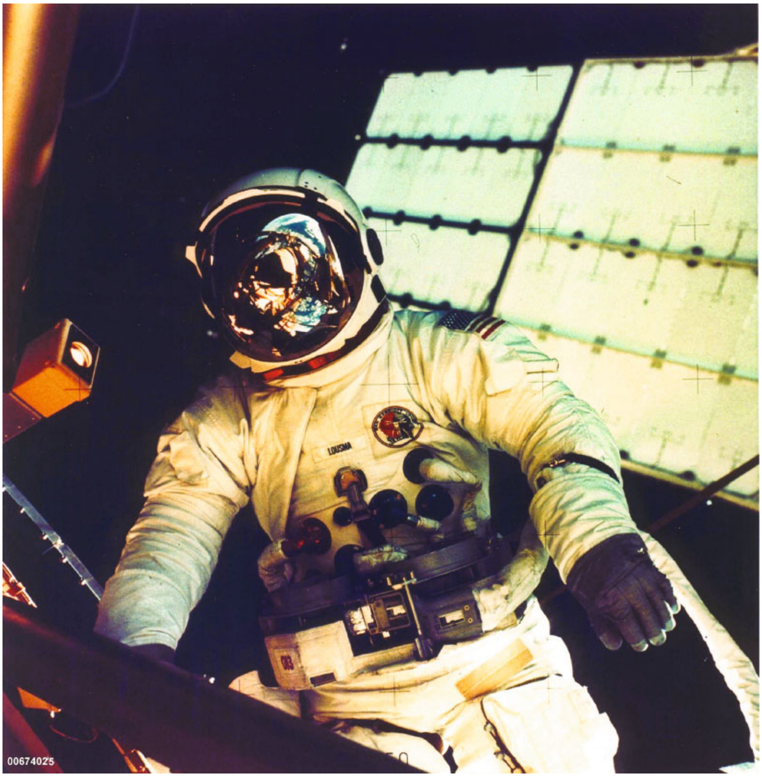


Figure 9.4.2. Jack Lousma in a Skylab 3 EVA (courtesy NASA).

Skylab 3 (SL-3) launched on July 28, 1973. On August 6, 1973, Astronauts Owen Garriott and Jack Lousma (Figures 9.3.7 and 9.4.2) undertook a 6-hour 31-minute EVA (SL-3/EVA 1) to install the thermal shade and service a number of experiments. Once again, ice partially covered the airlock depressurization valve, slowing the depressurization sequence.

The shade was installed over two poles, assembled in orbit out of 5 ft (1.5 m) sections mounted in a V shape and extending some 55 ft (17 m) over the OWS exterior. The tendency of the folds of the thermal shade material to stick together owing to rigidity in the cold of space caused some difficulty in extending the shade to its full coverage. After heating in the Sun, the material became more pliable; however, it never lost any of its accordion-like pleating.

Around five hours were spent in erecting the thermal shade (Figure 9.4.3), examining an experiment door, and checking for possible leakage of CSM attitude control thrusters. The remaining 1 hour and 31 minutes were spent installing cameras and film magazines, retrieving an experiment package, and deploying an experiment. The crew were also asked to look for any evidence of leakage from the coolant loop for the Apollo Telescope Mount's controls and displays, but none

Figure 9.4.3. Thermal shield in place on Skylab (courtesy NASA).

was noted. Once again, the suits and life support systems performed without incident.

On August 17, 1973, while inside the OWS (SL-3/IVA 1), Astronaut Bean donned the automatically stabilized maneuvering unit (ASMU) as part of experiment M-509 while wearing the ALSA and a pressurized suit to simulate EVA conditions. The ASMU (Figure 9.4.4) was a multipurpose experimental vehicle, having internal control moment gyros (CMGs) for stabilization (without the use of thrusters), rate-sensing gyros, a thruster system, and a gas (nitrogen) supply. As part of the overall M-509 experiment, a version of the Gemini HHMU was also evaluated. During the 2-hour 20-minute exercise, he first practiced flight maneuvers with the LSU attached. The LSU provided cooling, pressurization, ventilation, and communications. The rigidity of the LSU interfered with the ASMU's operation by continually torquing the experimental assembly out of plane. This resulted in "saturation" of the CMGs, which caused excessive thruster activity to maintain attitude. Next, he flew without the LSU using the SOP for about 19 minutes as a source of pressurization and ventilation.

After experiencing the now familiar ice on the depressurization valve screen, the crew carried out a 4-hour 31-minute EVA on August 24, 1973 (SL-3/EVA 2).

Figure 9.4.4. Alan Bean in IVA test of the automatically stabilized maneuvering unit (courtesy NASA).

Astronauts Lousma and Garriott serviced eight experiments by changing out and installing film canisters, installing cameras, deploying experiments, retrieving experiment packages, and performing minor repairs. They also performed a critical installation of the previously mentioned rate gyro "six pack". This activity was necessary because several anomalies had been experienced with the originally launched gyros, which provided small but precise control of vehicle attitude for conduct of certain experiments. The actual EVA task involved disabling the current cabling and installing a 24 ft cable that connected to the new rate gyro package, contained within the pressurized confines of Skylab.

Aside from some umbilical management to eliminate kinks, suit and ALSA performance was uneventful, marking some 16 hours accumulated on the same ALSA equipment with no problems.

On September 13, 1973, Astronaut Bean again conducted an IVA experiment (SL-3/IVA 2) aimed at increasing the EVA maneuvering unit knowledge base. This time he evaluated experiment T-020—the foot-controlled maneuvering unit—while suited and pressurized. This device did not require use of the astronaut's hands as did the ASMU and the HHMU. As the name implied, the astronaut's feet operated the controls. Again, he was suited and pressurized for the 3-hour test and, although he operated using an umbilical gas supply, all hoses and cables except the oxygen hose and tether were stripped out to reduce torquing effects. This solved that problem, but the lack of communication between the suited crewmember and the observer caused some delays. Garriot also performed T-020 evaluations, but was unsuited (Figure 9.4.5).

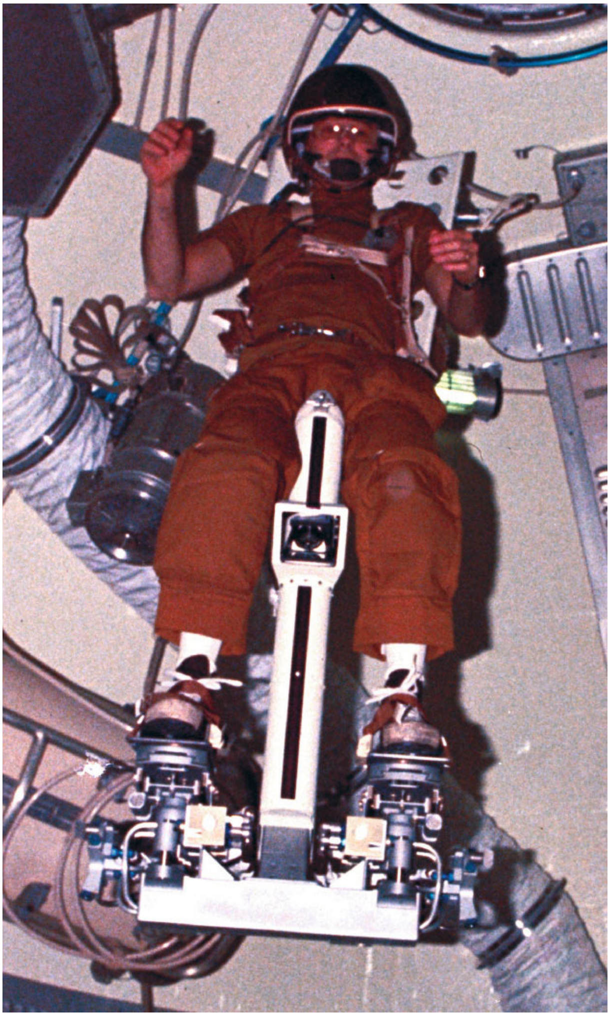


Figure 9.4.5. Owen Garriott testing the foot-controlled maneuvering unit (courtesy NASA).

Troublesome coolant leaks in the spacecraft systems finally resulted in the decision to leave the water loop inoperative during the next EVA (SL-3/EVA 3) and have both EVA crewmembers rely on gas cooling only, utilizing the high-flow setting—that is, receive about 12.5 lb/h (5.7 kg/h) of oxygen, rather than the normal 8 lb/h (3.6 kg/h). Astronauts Garriott and Bean conducted the 2-hour 41-minute EVA on September 22, 1973. In 2 hours and 10 minutes they serviced 10 experiments and spent the remaining 31 minutes cleaning a camera lens.

Ground monitors had been concerned about the potential for overheating in the absence of water cooling, so the heart rates of the EVA astronauts were closely monitored in order to give an indication of how hard they were working. The flight surgeon had set a limit of 4 hours' maximum duration for the EVA and the crewmembers were required to carry a candy bar and a 32-ounce drink bag mounted in the helmet (both were accessible by mouth without the need for handling). Rates ranged from about 1,000 Btu/h (252 kcal/h) to 1,300 Btu/h (328 kcal/h). No adverse effects were noted. Garriott indicated that, although the gas flow mode was not as cool as the liquid-cooling garment, it was satisfactory. Bean commented that his hands were warm for the whole EVA, but otherwise he felt all right.

There were no significant problems with the EVA equipment, although a little time was spent in untangling LSUs. It was noticed that the crew expended quite a bit of energy in restowing the LSUs in the stowage spheres. The 59 days that the astronauts of SL-3 spent on the OWS before their return on September 25 set another short-lived world record.

Skylab 4 (SL-4) launched on November 16, 1973, carrying a coolant-reservicing kit, which the crew used successfully to restore the cooling loop to operation three days later. The coolant was replenished using a saddle-type valve. The technique used was similar to recharging a closed air-conditioning loop, whereby a line is pierced inside a sealed compartment clamped onto the line and fluid is allowed to flow into the line under pressure. The leak source was never identified or fixed; however, the decision was made to resume usage of the cooling loop.

Restoration of the ability to provide water cooling to EVA crewmembers allowed EVA planning to return to normal. The first EVA of this last Skylab mission (SL-4/EVA 1) was carried out by Astronauts Bill Pogue and Ed Gibson and was 6 hours 33 minutes in duration. They serviced 10 experiments in about three hours and then spent the next three and a half hours repairing an antenna and pinning a door to a telescope.

Once again, irksome problems with managing the LSUs were encountered. The crew had difficulty separating the two umbilicals and reported one instance of a crewmember getting tangled up in them. Although these were not major problems, umbilical management continued to consume time and effort. The remaining elements of the EVA system continued to perform excellently.

On December 25, 1973, Astronauts Bill Pogue and Gerald Carr performed the longest EVA of Skylab (SL-4/EVA 2): 7 hours and 1 minute. During depressurization the crew remarked that the screen on the depressurization valve was 75% to 80% covered and was a "good garbage collector". They didn't specifically mention ice buildup, but it is surmised that the presence of ice plus miscellaneous debris made up the content of the material on the screen.

Once again, some 10 experiments were serviced and conducted, including photography of Comet Kohoutek. Both astronauts were busy during the EVA. In parallel with the experimental tasks they realigned the auto-rotation mechanism for a photographic filter wheel.

About three hours into the EVA, the crew were requested to remove the cloth debris deflectors (Figure 9.3.5). At this time they were performing film retrieval at the Apollo Telescope Mount and the forward thrust caused by the debris deflectors was causing the Skylab thruster attitude control system to fire in order to maintain orientation. Later in the EVA the deflectors were reinstalled.

At about four hours into the EVA, Carr reported seeing yellow ice crystals coming from the front of the PCU where the LSU composite connector mated to the PCU. The yellow color arose from the chromate-based corrosion inhibitor contained in the water coolant loop. He sensed no change in cooling and reported that ice crystals were being "thrown out" and carried along with him.

After repressurization the debris deflector was removed and Carr reported ice present on the composite connector. At the time it was surmised that the leakage was probably caused by inadvertent side-loading of the water connectors within the composite assembly, as had been the case during previous leakages at KSC and at AiResearch's Torrance, California, plant. To be on the safe side, both the LSU and PCU used by Astronaut Carr were removed from service and substitute hardware was used for subsequent EVAs. No problems were incurred with the suits during this EVA.

On December 29, 1973, Astronauts Gibson and Carr performed a 3-hour 29-minute EVA (SL-4/EVA 3) during which they conducted two experiments and performed more observation of Comet Kohoutek. No further coolant leaks were experienced and the suits continued their trouble-free performance.

On January 17, 1974, an IVA (SL-4/IVA 1) was conducted to repeat the M-509 experiment of SL-3 using the ASMU in combination with a suit and the ALSA. Astronaut Pogue used both the "stripped" LSU and the SOP as gas supplies throughout the 2-hour 30-minute exercise. Some battery problems with the ASMU were encountered and it was desired to repeat the exercise using the LSU only, since the SOP was completely discharged.

The previous experimental procedures were repeated on January 20, 1974 (SL-4/IVA 2) by Astronaut Pogue over a 2-hour 30-minute period, using only the LSU. Lack of an SOP was the result of the earlier decision to forgo launching additional PCUs and SOPs in favor of other equipment.

Skylab's final EVA (SL-4/EVA 4) was performed on February 3, 1974, by Astronauts Carr and Gibson. During the 5-hour 19-minute EVA, the crew retrieved film magazines and cameras, conducted and deployed experiments, and retrieved the AM thermal/micrometeoroid shield.

They employed a continuous belt ("clothesline") device to aid in transferring the film magazines. Apparently, during this activity the locking tab on the handle of the LSU-to-PCU composite connector on Gibson's PCU became snagged by the clothesline and the handle ultimately became rotated about five degrees. Further rotation could have disengaged the connector, which would cut off oxygen, cooling water, communications, and electrical power. Automatic actuation of the SOP would have then occurred, leaving the crewman with 30 minutes to either reattach the connector or terminate the EVA. The only immediate warning of this event would have been loss of communications, since the PCU did not carry an internal battery to power the warning system.

About 3 hours and 21 minutes into the EVA, Astronaut Gibson experienced a repeat of the coolant (“yellow ice”) leakage first encountered by Carr about four hours into SL-4’s second EVA. Different PCUs and LSUs were involved in this instance and Astronaut Gibson reduced his coolant diverter valve setting which reduced the leakage. He then selected the EVA High flow of 12.5 lb/h (5.7 kg/h) of oxygen vs. the normal 8 lb/h (3.6 kg/h) for the duration of the EVA. Restowage of LSUs at the end of the EVA was complicated by the clothesline getting tangled with one crewmember’s SOP. All in all, it had been a taxing day and Astronaut Gibson remarked at the completion of the EVA that he was “tired and hungry”.

The PCU/LSU combination with the leak was left attached for possible post-flight troubleshooting. While the side-loading theory had lost credibility, no on-orbit testing was performed. SL-4 returned on February 8, 1974.

Thus, the Skylab EVA program had come to a successful conclusion, albeit with a couple of water leaks that remained unsolved. The pressure suits performed exceptionally well throughout all the EVAs.

9.5 SKYLAB REVIEW

During the 41 hours and 46 minutes of elapsed EVA time, the two-person EVA crews of Skylab not only fulfilled the original plans of servicing and conducting experiments, but also performed repair and outfitting tasks that guaranteed the program its very existence.

Findings from the standpoint of EVA suits and associated life support equipment were mostly positive. The A7LB suit in particular performed in an outstanding fashion. The program doubtless benefited in large measure from the years of development and flight use during Apollo.

The ALSA, a new system utilizing features of both Gemini and Apollo, was also very successful. The two instances of water leakage were investigated subsequent to the completion of the Skylab program and were found to be due to gradual shrinkage of an O-seal material after chill-down during EVA, probably coupled with tolerances toward the high (loose) side. The leakages were repeated with the same hardware. When the O-ring material was replaced by one with less shrinkage, the leakage could not be repeated.

The major finding concerning life support equipment was that umbilical management was time-consuming and troublesome. A good part of one of the EVA crewmember’s time was spent in assuring that neither umbilical was in the way or in danger of becoming tangled or snagged. However, use of an umbilical lends great flexibility to the EVA time available—stays can be extended without fear of using up expendables carried with the EVA crewmember. Also, the use of an umbilical minimizes mass on the crewmember himself. All the results of the M-509 and T-020 experiments were considered to be successful, with the ASMU of M-509 providing the basis for the future manned maneuvering unit of the Shuttle program.

The value of the Skylab EVA program was perhaps best summed up by a viewgraph that made the rounds of the Shuttle program at JSC during the time when the value of providing EVA on Shuttle was being hotly debated. On one half of the page the graphic showed a picture of the crippled OWS with the parasol and the single extended solar wing; on the other side were the words in large, bold print: "EVA—Would you want to fly without it?"

9.6 APOLLO SOYUZ TEST PROJECT

The Apollo Soyuz Test Project (ASTP) had practical technical motives for linking up the two predominant spacefaring nations in the first international manned spaceflight. Verifying the compatibility of rendezvous and docking systems for American and Soviet spacecraft previewed the path taken for the International Space Station docking systems, as well as presenting the possibility for international space rescue. In 1970, early planning included the possibility of docking with the Skylab space station, and as late as 1972 there was consideration of docking with the Salyut space station. The approach ultimately chosen focused on the one-time docking of an American Apollo Command and Service Module (CSM) with a Russian Soyuz.

There were formidable challenges to this endeavor. Aside from the politically adversarial positions of the two nations, there were language and geographical barriers, plus radically different approaches to life support and vehicle design.

In addition to differences in oxygen storage (the Soviets used a chemical, potassium superoxide, for generating oxygen, while the Americans used gaseous storage), cabin pressures were very different. Soviet technology was based on sea level pressure and composition—that is, 14.7 psi (1 atm) and an 80/20 nitrogen/oxygen ratio. The Americans used a 5 psia (34.5 kPa) pure oxygen atmosphere with trace amounts of carbon dioxide and water vapor being present.

The air mixture used by the Soviets presented a minimal fire hazard; however, loss of pressure in the cabin could induce decompression sickness (DCS). The pure oxygen atmosphere of the CSM represented a fire hazard made all too real by the disastrous Apollo 1 fire of January 1967. The Americans relied not only on ignition control, but also on a rigorous materials selection process to minimize the flammability hazard.

To resolve the issue, the Soviets voluntarily offered to reduce their pressure for the docked portion of the program. The plan was for two of the U.S. crew to enter the docking module, close the hatch to the CSM, and raise the pressure by using nitrogen. The Soyuz would lower its pressure until the two would equalize at about 9.9 psia (68 kPa).

Figure 9.6.1. Donald K. "Deke" Slayton in an A7LB Apollo–Soyuz test project suit (courtesy NASA).

Consideration of EVA for ASTP occurred early in the program. In 1970, five concepts for ASTP operations were proposed by MSC, ranging from docking with a third module to permit shirtsleeve transfer, to an extravehicular transfer. Ultimately, an approach featuring an internal transfer without pre-breathing was selected, which ruled out the need for EVA capability. However, EVA remained a consideration for ASTP until 1974. Discussions as late as May 1974 involved a standup EVA during a revisit to Skylab in order to photograph the condition of the assembly and, although the photography aspect was subsequently canceled, revisit to the Skylab still remained an option for a bit longer before EVA was deleted from the ASTP mission.

The ASTP crew of Tom Stafford, Deke Slayton, and Vance Brand utilized slightly modified Apollo-type A7L suits officially designated A7LB for the mission (Figure 9.6.1). Since there was no EVA, the suits were modified to reduce weight and cost. The normal outer cover layer of Teflon Beta cloth with underlayers of aluminized Kapton with nylon spacers was replaced with Teflon Beta polybenzimidazole (PBI) fabric, which increased its durability. Also, extravehicular gloves, the suit's positive pressure relief valve, the extravehicular visor, and the connectors for the liquid-cooling garment and emergency oxygen system were removed for this flight. The helmets and boots were of the Skylab variety.

The single ASTP mission launched on July 15, 1975, and marked the successful debut of the first international cooperation in manned spaceflight through the linkup of the Russian and American vehicles. During entry on July 24, 1975, the failure of the crew to activate the Earth landing system sequence at the appropriate time resulted in the inflow of propellant gases into the Command Module cabin. The crew were not wearing helmets and inhaled some of the noxious propellant gases before they could don oxygen masks. However, no lasting damage was experienced from this occurrence and, from the perspective of spacesuit performance, the mission was a total success.

10

The Space Shuttle program: Orbital EVA comes of age

The Shuttle extravehicular mobility unit (EMU) was conceived to be a reusable spacesuit system for the Space Shuttle. To that end, it was designed as an integrated suit system that would be more robust, compact, mobile, maintainable, and universally sizable than any preceding flight EVA system. However, what it would be, who would make what, who would act as integrator to design and deliver a certified system, how many suit systems might be implemented or even if there would be EVA suit systems were all unknown at the beginning of the Shuttle program.

When the Apollo 18 and later missions were canceled, a reusable spacecraft called the Shuttle was nothing more than a concept that was part of the larger manned spaceflight plans. Planning in the mid to late 1969 timeframe envisioned the Shuttle performing such tasks as crew transfer, cargo delivery, and satellite capture. EVA on the Shuttle was to be for emergency use only. Space stations were projected for both Earth and lunar orbits. The "standard" Shuttle would service the Earth-orbital station and a nuclear-powered Shuttle would visit the station in lunar orbit. The lunar orbit station was to be a 50,000 lb (22,727 kg) structure, 22 ft (6.7 m) in diameter, and be operational in late 1975. This would be visited up to 18 times a year by the nuclear Shuttle.

An initial space station named Skylab was the next goal, but it was to use existing technology wherever possible. Thus, development of any new suit systems would be associated with whatever would come next. In 1970, NASA-Ames commissioned an in-depth study of suit system technologies for potential forthcoming spacesuit systems. If the order of applications to be addressed was a reflection of expectations, a Shuttle spacesuit was the last of five applications immediately following a Mars exploration suit system. However, by 1971 the next spacesuit systems were clearly tied to Shuttle applications.

Development of the Shuttle EMU was based on the advanced Apollo development (Chapter 7) and supplemented by a great number of influences through the 1970s (Section 10.1). This culminated in the "baseline" EMU config-

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uration that served the Shuttle program through the 1980s and 1990s (Section 10.2). The introduction of additional technologies and higher operating pressures was attempted in the 1980s, first through evolution and later by an all new "station" advanced EMU effort (Section 11.1). While this would not be successful, improvements generated from these efforts would flow into an "enhanced" EMU that was phased in as suit system module updates (Section 10.3).

The enhanced EMU continues to be the U.S. EVA spacesuit system, and it is planned for continued use throughout the remainder of the ISS problem.

10.1 DEVELOPMENT OF THE SHUTTLE EXTRAVEHICULAR MOBILITY UNIT (1971–1979)

The development of the Shuttle EMU occurred in three phases: the first two were development of requirements/key technologies* and contractor developments in support of contract competition*; the third phase came after the contract was awarded. This was due to changes in requirements and from NASA-desired changes resulting from crewmember evaluations.* These three phases combined to create the Shuttle (baseline) EMU (Section 10.2). These activities paralleled the Martin Marietta development of the manned maneuvering unit* and NASA/Lockheed development of EVA lights and helmet TV camera.*

Development of requirements and technologies

During 1971 to 1974, NASA searched for the best technical options related to the potential uses of spacesuit systems. The options included: (1) no spacesuits; (2) one dual-purpose launch/entry/EVA system, as had been used in the Apollo/Skylab missions; (3) two suit systems, one launch/entry and the other EVA. Since the Shuttle was conceived as a high-reliability carrier of passengers and cargo to orbit, the need for crew survival/escape or to perform EVA was questioned. Volume and weight constraints lent strong support for a compromise suit system that could adequately support EVA and crew survival/escape. Additionally, budget constraints required that the latter two approaches would utilize minimal or no new technologies.

The process that sorted out these various options started with NASA funding a study entitled "Shuttle EVA/IVA Support Requirements". In 1971, NASA issued a request for proposal (RFP) for the study to identify all the requirements imposed by the Shuttle concept that NASA had defined, evaluate those requirements, and propose a spacesuit system concept accompanied by more refined requirements to support the subsequent design of the Shuttle EMU. AlliedSignal (now Honeywell), Hamilton Standard (HS, now Hamilton Sundstrand), and others submitted proposals. The proposals gave the responders the opportunity to share their vision of what a Shuttle EMU might be and to identify considerations leading to a require-

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* Detailed in topics that follow.

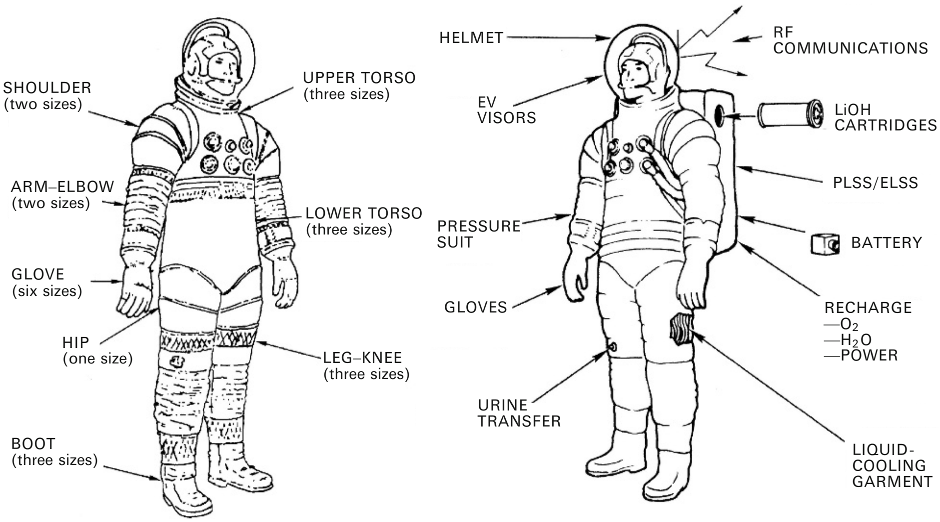


Figure 10.1.1. 1973 requirements study illustrations (courtesy Hamilton Sundstrand).

ments document to aid in the definition of the subsequent EMU. HS won this competition.

HS submitted the resulting study in April 1973. It recommended requirements for volume, weight, communication, and operational parameters for subsystems, as well as processing, cycles, and loads for the Shuttle EMU. It also recommended a modular system architecture to balance cost with adequate sizing options (Figure 10.1.1). Most of these recommendations were accepted and became the basis of Shuttle EMU design requirements.

The requirements study also recommended an 8 psi (55 kPa) operating pressure. This was to allow rapid decompression from the Shuttle's 14.7 psi (1 atm) cabin pressure to support an emergency EVA capability without an oxygen pre-breathe delay or risk of decompression sickness. Here, budget limitations and development risks would be key factors. The greater the challenge to development, the more development usually costs. This relationship has been so consistent that government contracting has a formulation for development risk that permits an approximation for the unforeseen costs of development. Previous operational EVA system experience was with a 3.7 psi (25.5 kPa) operating pressure. Hence, in order to minimize development risk, the initial Shuttle EMU contract requirement was for a 4.0 psi (27.6 kPa) suit system.

One organization that influenced Shuttle EMU development was Litton Corporation, but it did not directly participate in the program. In 1969, Litton had internally funded the experimental development of flat pattern fabric joints and NASA had an interest in Litton's flat pattern approach as a potential lower cost way of making pressure suits. Litton additionally made an advanced EVA-type prototype (Figure 7.2.6) with a hard upper torso and mid-entry body seal closure,

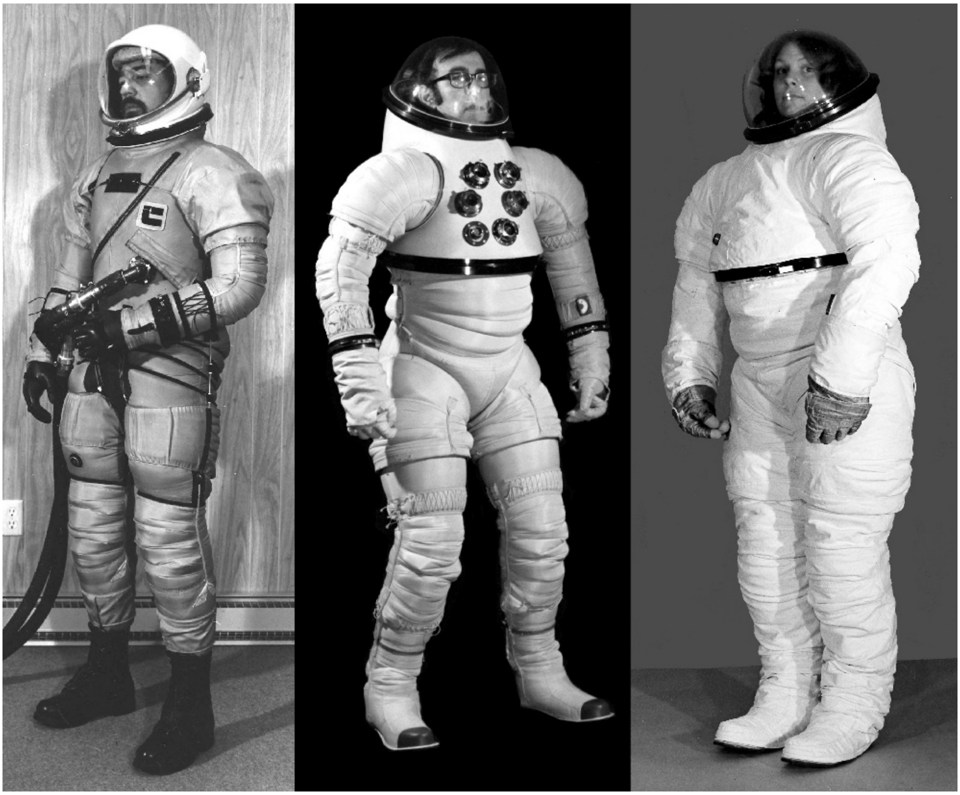


Figure 10.1.2. Early ILC Shuttle prototypes (courtesy ILC Dover LP and Hamilton Sundstrand).

similar to what the Shuttle EMU would ultimately become. As Litton withdrew from spacesuits in 1969–1970, NASA funded Space Age Control and ILC Industries in 1971–1972 for launch/entry-type prototypes using flat pattern technology (discussed in Section 4.4). In parallel, ILC internally funded a flat pattern EVA suit prototype in 1973 (Figure 10.1.2, left), which may have contributed to NASA's funding of ILC for the orbital EVA suit (OES).

The OES resulted in two known prototypes. The first OES prototype utilized an existing NASA/Litton hard upper torso to explore flat pattern technology (Figure 10.1.2, center). This was followed by a build-from-scratch complete prototype (Figure 10.1.2, right), which featured the use of Kevlar as the restraint fabric.

By 1974, budget limitations had become a major consideration in the Shuttle EMU design. To explore what a possible low-cost Shuttle EMU might be, NASA-JSC modified the second OES prototype using on-site resources and Apollo (mockup) training life support units to create a full pressure EMU prototype (Figure 10.1.3). This became NASA's concepting aid for creating the Shuttle

Figure 10.1.3. 1975 NASA-JSC Shuttle prototype (courtesy G. L. Harris/J. Kosmo).

EMU contract competition RFP requirements. It is unclear, however, if NASA shared the resulting prototype with the Shuttle EMU competitor teams.

During the 1970s, NASA's Ames Research Center (ARC) explored 8 psi (55 kPa) pressure suit technologies which would allow zero pre-breathe when decom-

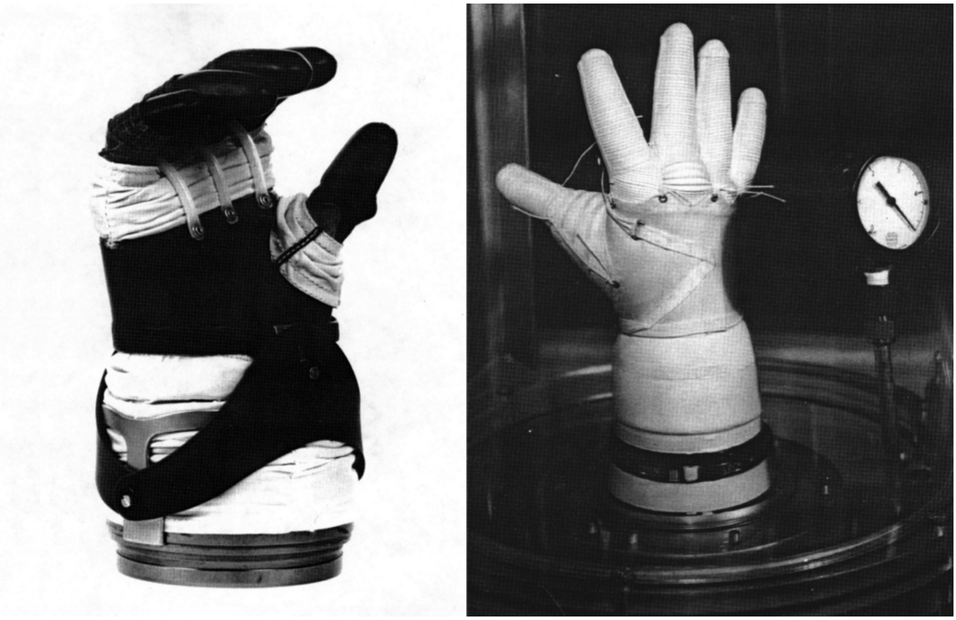


Figure 10.1.4. ARC-funded ILC and Space Age Control 8 psi gloves (courtesy NASA).

pressing from 14.7 psi (1 atm) Shuttle or station cabin pressure. This included both potential glove technologies and a complete prototype suit. Examples of ARC-funded high-pressure glove efforts included prototypes from ILC and Space Age Control (Figure 10.1.4).

In 1975, ARC undertook to build an 8 psi suit named the AX-3 to demonstrate to NASA management that a higher operating pressure was possible for the upcoming Shuttle program. ARC, which was the designer and system integrator, also fabricated the double-walled fiberglass upper torso and brief structures, all the mobility joints and sizing hardware, and all the master plaster patterns used for fabric laminate lay-up. Aerotherm manufactured all the fabric structures and sealed bearing assemblies and assembled the mobility joints. Air-Lock fabricated the dual-plane torso disconnect to Ames's design, along with the dome helmet, helmet disconnect, and glove disconnects. The AX-3 used single-wall laminate structural fabrics with a modular mix-and-match sizing system (Figure 10.1.5). The AX-3 utilized an Acurex Corporation bearing and seal design that substantially reduced leakage and minimized rolling resistance. It also employed a combination of toroidal, rolling convolute, and multibearing mobility systems.

The Shuttle EMU contract competition (1976–1977)

The 1975–1976 Shuttle EMU competition was in many ways the culmination of activities and events that had occurred in the preceding four years. In 1971,

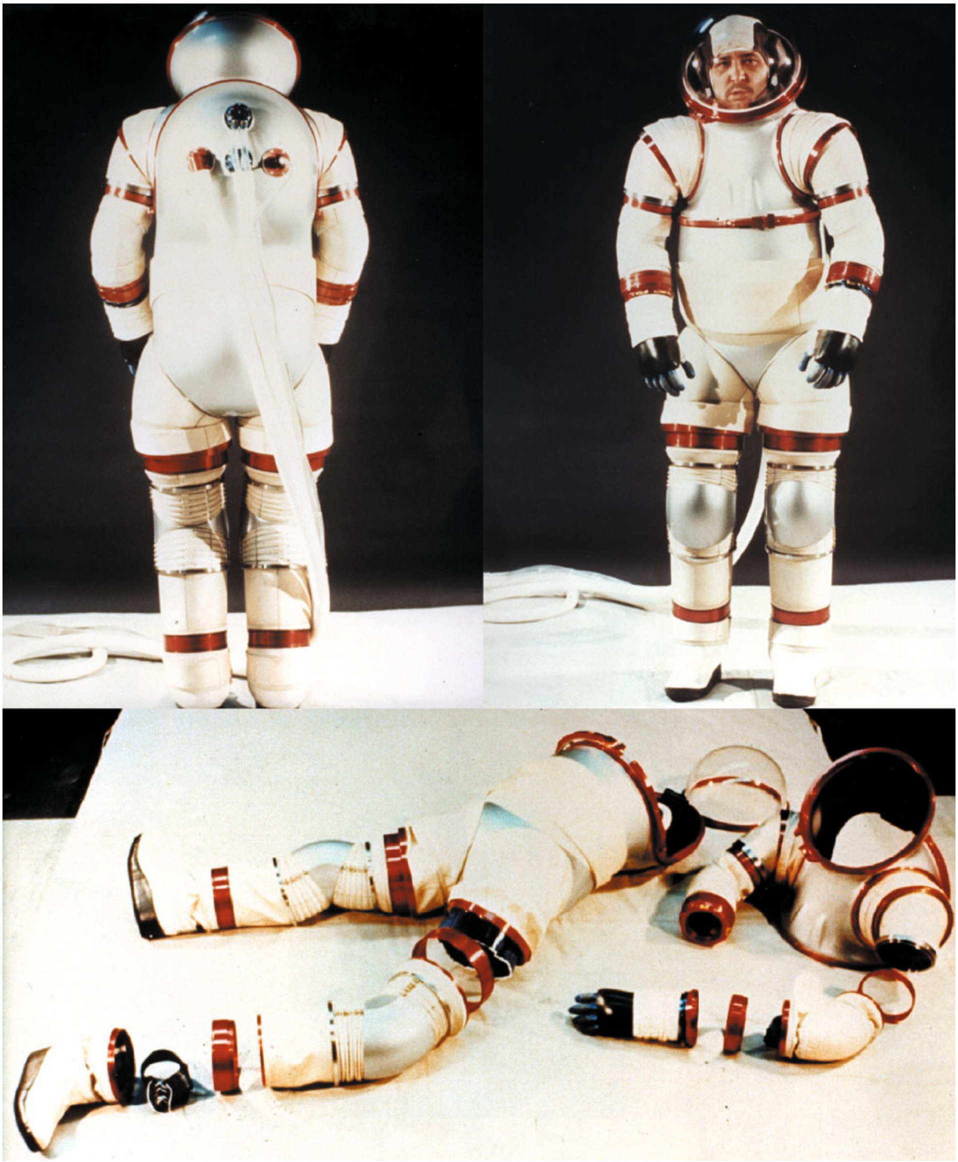


Figure 10.1.5. 1975 NASA-Ames AX-3 prototype (courtesy Hamilton Sundstrand).

NASA did not know which organizations would be responsible for the creation of the EMU. If NASA had made the EMU an element of the vehicle contract, the suit system contractor would probably have been Boeing, Grumman, Lockheed, Martin Marietta, or North American. NASA could have elected to be the system integrator, as it had for Gemini, the later part of Apollo, and Skylab. NASA also could select a contractor team headed by organizations such as AlliedSignal, Ling–Temco–Vought, General Electric, or Hamilton Standard. By the time the technology and requirement developments matured into a formal Shuttle EMU contract competition in 1976, the competitor field had narrowed to essentially two teams. These teams were headed by AlliedSignal (now Honeywell) and Hamilton Standard (now Hamilton Sundstrand).

In the early 1970s, the Garrett Corporation with its AiResearch Manufacturing Division had joined in a merger with AlliedSignal continuing under the name of AlliedSignal (now Honeywell). AlliedSignal teamed up with the Aerotherm Division of Acurex and David Clark Company (DCC) to compete for the Shuttle EMU contract. At this point, key Aerotherm individuals included former AiResearch advanced pressure suit design personnel.

For Apollo, Hamilton Standard (HS) and ILC (originally International Latex Corporation, but after 1969, ILC Corp.) had been forced together in 1962. The two organizations were never able to form an effective working relationship and by 1965 had become space pressure suit design and manufacturing rivals. In 1965, ILC would win the Apollo EVA suit in competition against HS and DCC. In 1967, HS defeated ILC and DCC for the Manned Orbiting Laboratory suit. Ironically, this provided a foundation of mutual HS/ILC respect. Also through the late 1960s and early 1970s, many HS and ILC personnel worked together on a daily basis on the Apollo program, which cultivated friendships across company lines. Additionally, mergers in the ILC parent organizations and the passing of time had resulted in almost a complete replacement of the 1962–1965 top management in both organizations. In 1974, ILC and Air-Lock Inc. (A-L) joined with HS to pursue the Shuttle EMU contract.

The competition process started with NASA issuing a request for proposal (RFP). In the RFP, NASA specified an EMU that would be a compact, reusable, robust, cost-effective system with standardized sizing to support 5th percentile female to 95th percentile male users. The EMU was to have a 6-year useful life on pressure suit elements and a 15-year life on life support systems. The life support system was to have a 7-hour capacity with a 30-minute backup. A 33% reduction in the maximum front-to-back dimension from the Apollo EMU was dictated by a desire for an ability to exit through all Shuttle internal and external hatches. The EMU was not to use slide fasteners (e.g., "zippers") for entry.

To minimize the technical, cost, and schedule challenges, NASA requested that the proposals be based on the use of existing/certified technology where possible and a minimal EMU operating pressure increase from 3.7 psi (25.5 kPa) to 4.0 psi (27.6 kPa). NASA additionally specified the use of the Apollo/Skylab helmet and neckring due to an existing residual in-life inventory and the use of flat pattern joint mobility elements to minimize cost. Since the spacesuit system was to be based on existing technology, NASA elected not to fund the creation of demonstration spacesuit systems for the competition.

The AlliedSignal/Aerotherm/DCC team offered two proposals. The primary proposal met all RFP requirements except the front-to-back dimension. The second proposal was for a spacesuit assembly (SSA)/extended mobility concept

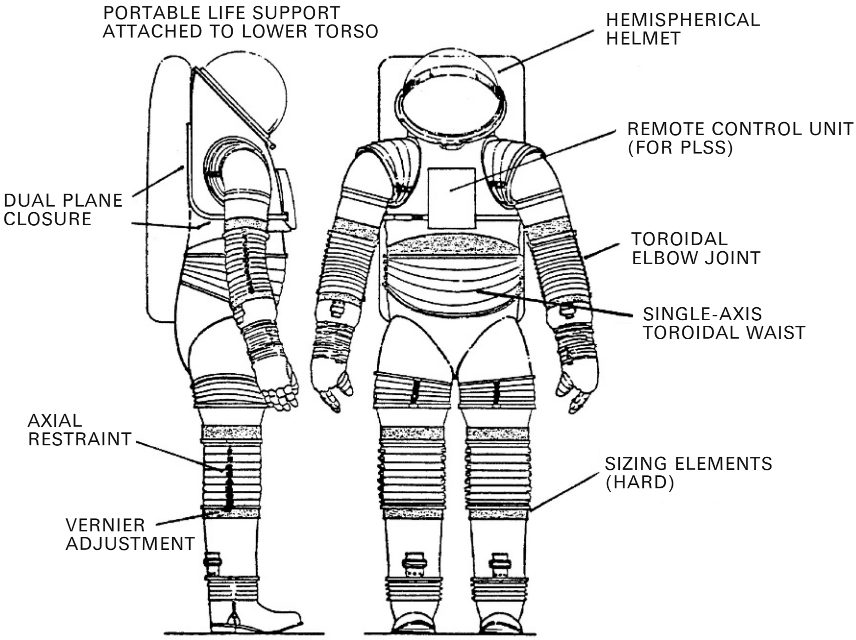


Figure 10.1.6. Aerotherm suit system concept from 1976 AlliedSignal proposal (courtesy G. L. Harris/W. Elkins).

(EMC). The SSA/EMC was to be an 8 psi (55 kPa) system using AiResearch/NASA-ARC mobility systems including a new Ames/Aerotherm glove system featuring a dual-axis wrist joint (Figure 10.1.6). This proposal concept pointed to NASA-ARC's recent developments as technology demonstrators.

HS/ILC offered one proposal, which met all of NASA's requirements. While NASA did not require or fund any accompanying proof-of-concept prototypes, HS/ILC elected to submit technology prototypes. One prototype was a pressure suit designated the SX-1 for Shuttle Experimental #1. The SX-1 pressure suit (Figure 10.1.7) was a significant step forward from the configuration of the Apollo and Skylab EMUs. The Apollo/Skylab program suits utilized steel cables for axial restraints. The reliability/durability problems of the cable swaging process were compelling reasons for moving away from the cabling axial restraint system. The cable/swage interface had proven to be the weak point of the non-redundant cable restraint system. Additionally, the integrated steel cables and corded/taped bellows of the Apollo joint system were extremely labor and skill intensive. The SX-1 featured a Kevlar flat pattern restraint system that had no cable restraints. The advanced Apollo prototypes (Chapter 7) used mobility systems with metallic elements. These approaches carried weight and cost penalties over the flat pattern fabric restraints. The SX-1 demonstrated a mobile and more cost-effective restraint system.

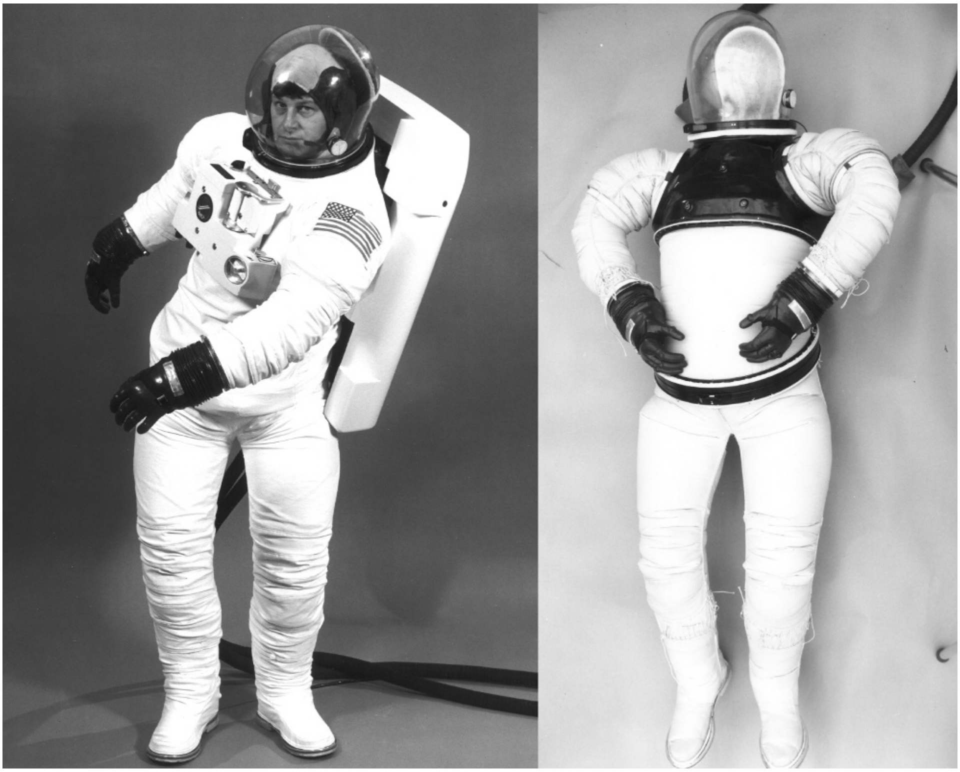


Figure 10.1.7. SX-1 waist bearing and mobility systems (courtesy Hamilton Sundstrand).

The SX-1 design included bearings to the scye (shoulder) and waist for mobility improvement. It also featured a generous waist joint (Figure 10.1.7). Except for permitting an easy walking stride as the Apollo suit's "walking brief" had done, the SX-1 offered greater mobility with less effort than the Apollo program suits, even though it had a slightly higher operating pressure.

The SX-1 design also included longer life materials. For Apollo, the neoprene/natural rubber blend limited life to three years. The "softgoods" of the Shuttle EMU were to have a six-year life.

While the Apollo suit thermal/micrometeoroid garment (TMG) was built on the experience of Gemini and underwent limited development during Apollo, the lifespan of the Apollo TMG was limited. The nested TMG layers also proved to be extremely labor intensive and thus expensive to produce. Therefore, ILC developed a new TMG design for the Shuttle program. The outer layer of the Shuttle TMG was a new material called Ortho Fabric, which was a weave of Gore-tex/Teflon with Nomex, incorporating a Kevlar ripstop. Under the Ortho Fabric were four or five (varies with location) layers of nylon-reinforced, aluminized Mylar. These layers were similar to the thermal layers of the Apollo TMG except that the Dacron scrim was replaced by a nylon reinforcement weave bonded to the inner side of each layer of Mylar in the Shuttle TMG; also, the Mylar was not perforated in the new TMG. The perforations were found to be unnecessary as there was sufficient leakage through the seams to eliminate the chance of damage during pressure equalization. The Shuttle TMG also provided sufficient protection for the orbital EVA environment while decreasing bulk, reducing construction time/cost, and dramatically improving service life.

The hard upper torso (HUT) was the centerpiece of the SX-1 design. The HUT was part of both the life support system and the pressure suit, as life support gases and fluids flowed between the primary life support system (PLSS) in the back and the display and control module (DCM) in the front through passages built into the shell. This eliminated the external hoses used in Apollo. The elimination of external hoses had been a personal goal of CSD's James V. Correale ever since he had seen the falls taken by astronauts on the lunar surface. Deletion of these hoses also improved mobility, precluded catching on protruding objects, and reduced hazards to the life support system. The HS/ILC proposal specified that two sizes of HUT would adequately allow the crew population to reach controls and perform activities. The HUT probably represented the first effective HS/ILC collaboration, with ILC contributing technical input and evaluation support to the HS design and manufacture of the aluminum structure. ILC assembled the HS-provided aluminum main structure and the A-L–supplied helmet and waist disconnects with the ILC-designed and fabricated mockup cover garment.

To simplify the donning of the HUT and the lower torso assembly, ILC and A-L jointly developed a return ventilation system that was integrated into the cooling garment to form a liquid-cooling and ventilation garment (LCVG, Figure 10.1.8). ILC created the intricate softgoods systems while A-L designed and produced a highly compact connector that provided the mate/demate of the liquid-cooling and return ventilation systems in one simple connection.

The SX-1 prototype included a volumetric mockup of an accompanying preliminary "backpack" life support system design. This preliminary design was accompanied by two HS life support technology demonstrators. One demonstrated a single motor fan/water pump/water removal system that combined three functions and two motors from the Apollo PLSS into one highly compact package. The other demonstrator was a water recovery system, which recycled humidity (water) from the ventilation loop to supply evaporative cooling water for the sublimator. This approach essentially combined the Apollo PLSS's three water storage systems into one resulting in significant volume and weight savings. These prototypes combined to demonstrate the ability to meet the Shuttle EMU's front-to-back envelope requirement. Past experience also indicated an ability to meet the requirement. HS had designed an EVA spacesuit for the USAF's Manned Orbiting Laboratory in 1968–1969 that had also met NASA's Shuttle front-to-back requirement. This had been accomplished by repackaging Apollo PLSS components (see Section 8.4). For the proposal submittal, HS additionally supplied a full-scale volumetric mockup of the Shuttle Orbiter's decks and hatches. The SX-1 demonstrated the ability to pass through any hatch in the Shuttle.

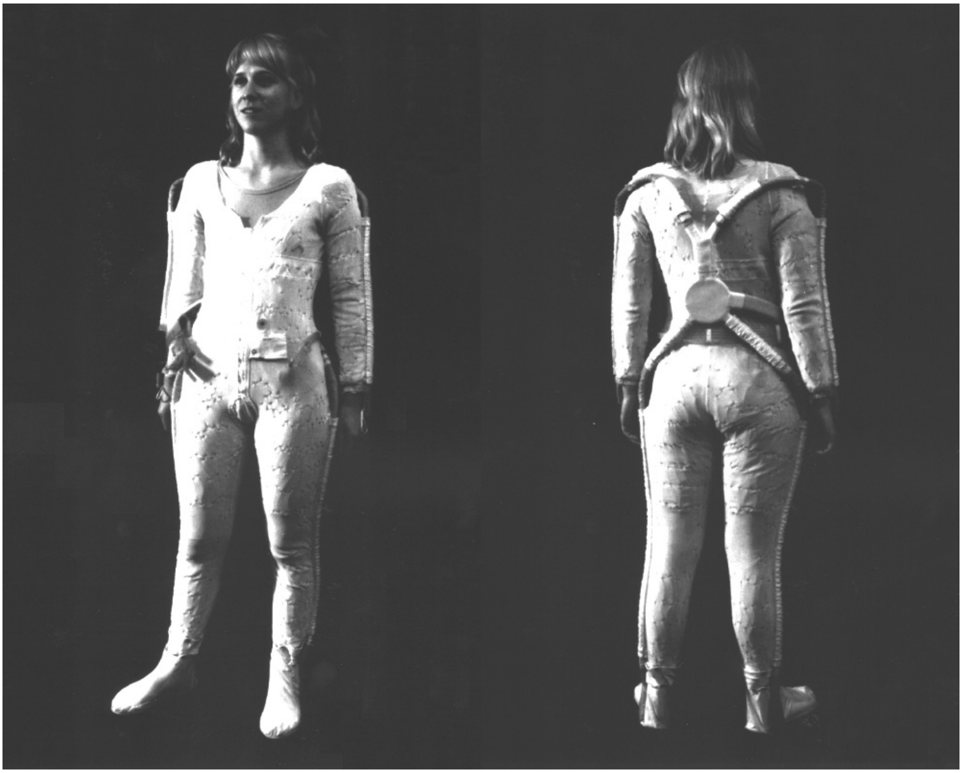


Figure 10.1.8. The liquid-cooling ventilation garment (LCVG) (courtesy Hamilton Sundstrand).

The competition was held in February 1976. The HS/ILC/A-L team won and the contract was formally awarded to HS in January 1977.

Changes in requirements and further EMU development (1977–1983)

The EMU design that supported the first EVA in 1983 was substantially different from the design that was directed for implementation in 1977. Beyond the planned design of a new pressure glove and the completion of the life support systems (LSS) design, the extensive testing that followed the program's start revealed many new needs and desires.

Manned testing revealed that the Kevlar fibers used in the bladder and restraint systems quickly abraded and could not meet the required operational life. Polyester and nylon were then considered for restraint webbing material, and polyester was found to have better properties. When tested, polyester restraint webbing proved to be lighter and stronger than the steel cables, while offering a substantially increased cycle life. In 1978, NASA added a requirement that the Shuttle EMU would incorporate a backup "secondary" restraint to the pressure garment. The use of webbing rather than cables made the design of the secondary restraint system easier. Dacron proved to be the best restraint layer material. The Shuttle suit's pressure bladder layer was revised to a polyether polyurethane-coated nylon material assembled by use of heat-sealed seams. This method of assembly was much less skill sensitive than the previous method, leading to better quality control and lower cost. It also allowed some areas to be "beefed up" for extra abrasion protection.

The next changes were related to improving don/doff (getting into and out of the suit). As a result of astronaut corps evaluations in 1977–1978, the HUT was changed from an aluminum to a fiberglass shell with a "hinged" two-point shoulder system later called the "pivoted" HUT design (Figure 10.1.9, left). The pivoting feature allowed the shoulder bearings to tip in at the top during donning and float with arm motions for a very conformal fit. Pivoted HUTs would be built in five sizes although only four would see flight service due to implementation costs. An accompanying change was the movement of the entry closure from the waist bearing at the hips to a separate elliptical closure attached to the bottom of the HUT. The pressure suit had lace-in fabric sizing elements for low-mass, low-cost sizing adjustment (Figure 10.1.9, right).

Figure 10.1.9. Pivoted HUT and baseline pressure suit (courtesy Hamilton Sundstrand).

Figure 10.1.10. Baseline EMU demonstration (courtesy Hamilton Sundstrand).

NASA's 1977–1979 evaluations of SX-1–based EMU prototypes also resulted in revisions to the display and control module (DCM) and extravehicular visor assembly (EVVA). The DCM (Figure 10.1.10) gained an optional capability for manual activation of the backup life support system, a display light intensity control, and separate volume controls for the primary and backup radios. The Shuttle program started with a Skylab configuration visor assembly. The EVVA was revised to have the center shades activated by levers on the sides and for the protective visor to be permanently secured in the down position to preclude users from forgetting and damaging expensive pressure helmets (Figure 10.1.10).

In parallel with the manned suit evaluations, the completion of the life support design progressed. This system consisted of three modules: the DCM, the primary

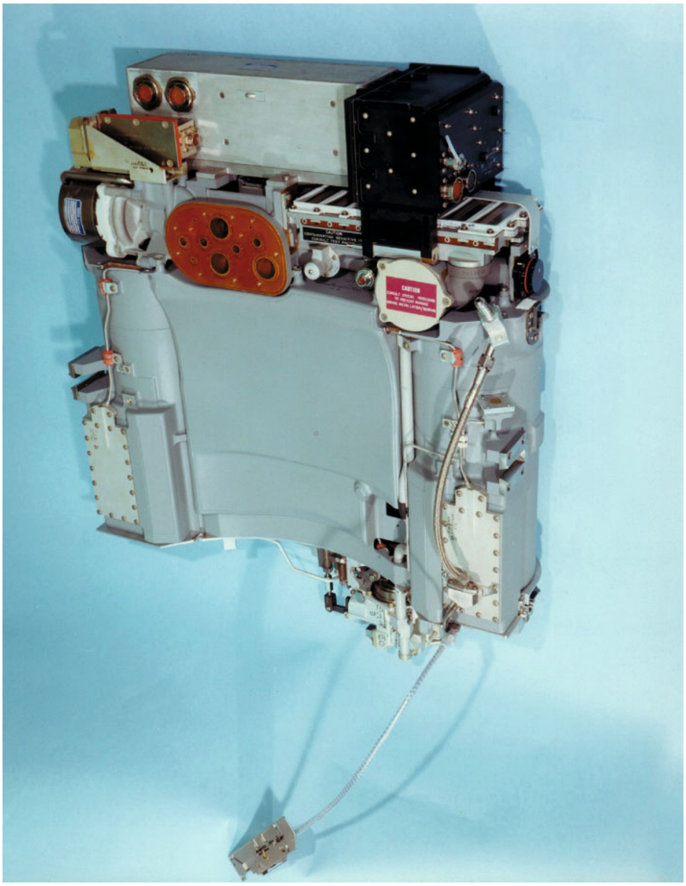


Figure 10.1.11. Primary life support system (PLSS) (courtesy Hamilton Sundstrand).

life support system (PLSS), and the secondary oxygen package (SOP). Additional features added to the PLSS (Figures 10.1.11 and 10.1.12) design included changes to the "sublimator" to lower cost and to facilitate field processing. The sublimator permits the spacesuit system to reject heat to space by the direct transformation of ice to vapor, called sublimation. The changes to the sublimator involved selecting a lower cost material for the porous plates through which sublimation takes place, and making them easily removable for cleaning by ground servicing personnel. In contrast, Apollo PLSS sublimator porous plates were welded in place, which meant that they could not be cleaned and would slowly degrade over time. One important assumption made was that the sublimator capacity would have to accommodate a heat load resulting from a full Sun condition while an EVA crewmember was in the payload bay for an extended period. This condition was remarkably similar to an EVA crewmember on the lunar surface in a crater under full Sun conditions. This assumption essentially biased the design of the system to accom-

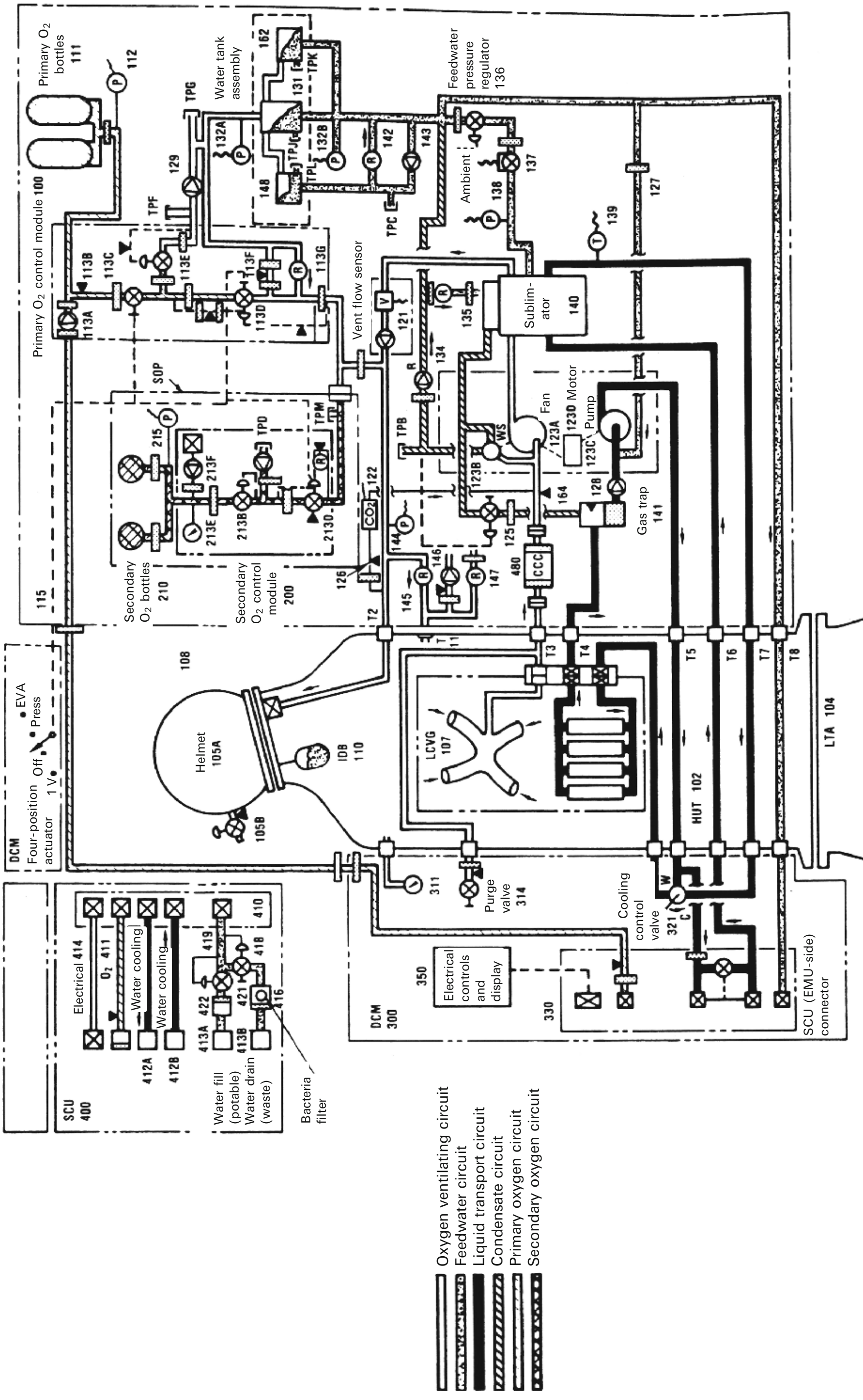


Figure 10.1.12. 1983 Space Shuttle PLSS schematic (courtesy Hamilton Sundstrand).

modating the "hot" case, a decision that sat easily with those who had seen the results of insufficient cooling during the Gemini program. However, later Shuttle missions and the cooler ISS thermal environment ultimately resulted in the need to provide a means of decreasing the cooling, as discussed in the life support system enhancements in Section 10.3.

For the Shuttle, NASA understood the need for a new EMU glove design due to the age and cycle limitations of Apollo glove materials. Also, manufacturing the Apollo wrist joint and pressure glove was extremely labor and skill intensive. The goals of the Shuttle glove development program were to produce a reusable glove within a system of standardized sizing, while retaining or enhancing the mobility of the A7LB glove. The first Shuttle glove designed by ILC was the 1000 series. This glove featured a one-piece urethane bladder, a separate polyester restraint layer, and a nominally attached but removable TMG overglove. The pressure glove incorporated a gimbaled wrist joint (Figure 10.1.13, left) for improved, multidirectional movement and reinforced, thimble-shaped, fine polyester mesh (later replaced by Kevlar) fingertip caps for improved pressure glove tactility. At this point, the 1000 series glove retained the Apollo-style aluminum glove disconnect and softgoods attachment method.

Figure 10.1.13. Original and production 1000 series glove (courtesy Hamilton Sundstrand).

On the Apollo/Skylab series glove TMGs, the finger and hand areas were covered with Chromel-R, which was a metallic cloth that had a very poor cycle life and was very expensive ($1,500/yd circa 1966). Beta cloth, which was used in the gauntlet area of the overglove, was a very fragile fiberglass fabric. The Shuttle TMG incorporated Kevlar reinforcement in the RTV fingertips and used silicone-coated Kevlar on the palm and the fingers for greater durability. Three layers of aluminized Mylar interspaced with three layers of Nomex felt provided insulation. Teflon fabric was added as an outer layer on the back of the hand and on the wrist gauntlet for longer life and resistance to abrasion. Additionally, 1000 series glove TMGs had other improvements. The length of the gauntlets was extended to cover a greater portion of the forearm for increased thermal protection and, although the 1000 series TMGs still featured the ILC-invented RTV fingertip caps like the earlier Apollo gloves, the Shuttle units were smaller to aid in tactility. The glove TMGs were designed for velcro attachment of an optional overmitten that provided the capability to support extreme cold or abrasive environments.

In 1979, the PLSS/DCM/SOP were all designed and the certification process was underway when the results of manned testing and detailed review of program planning forced a reconsideration of the planned 4.0 psi (27.6 kPa) operating pressure. Mission planners were anxious to reduce the 4 hours of pre-breathing pure oxygen before being able to decompress 4.0 psi to go EVA. The solution was instituting a reduction of cabin pressure from the normal 14.7 psia (1 atm) to 10.2 psia (70.4 kPa) 24 hours before an EVA and an increase in the EMU operating pressure to 4.3 psi (30 kPa). The EMU pressure had to be raised by this small amount to assure an acceptably low risk of DCS. The cabin pressure couldn't be reduced any further than 10.2 psia (70.4 kPa) due to flammability concerns arising from the reduction of nitrogen, and assuring that no less than about 3.08 psi (21.2 kPa) of oxygen was available for breathing. Review of the PLSS design indicated that an increase to 4.3 psi (30 kPa) could be achieved without redesign of any major components. However, the pressure suit components required yet another redesign for structural capabilities. Most noticeable of these was a substantial increase in structure in the glove disconnect/wrist bearing and in the wrist gimbals (Figure 10.1.13, right). The glove-side disconnect was changed from aluminum to a corrosion-resistant steel. The new disconnect featured a flange clamp which facilitated glove bladder and restraint assembly replacements.

The SOP had been designed with a high-pressure shutoff valve, followed by an expansion chamber, and ultimately by a two-stage pressure regulator. All operating elements were contained in an aluminum module. In April 1980, while an unmanned EMU was being prepared for a manned certification test, an ignition occurred in the SOP pressure control module when the SOP was activated. Although the resulting fire lasted only seconds, a technician bending over the supine EMU was severely burned and the EMU was virtually destroyed. While the exact cause of the fire could not be proven, one of the significant findings of the investigation was that—once ignited from contamination, particle impact, or other source—the combustion of aluminum was self-sustaining at the SOP storage pressure levels of approximately 5,880 psi (400 atm). The corrective actions implemented included deletion of the high-pressure shutoff valve and expansion chamber (the first stage of the regulator then doubled as a shutoff valve) and redesign of the SOP pressure control module housing using a combustion-resistant metal and the creation of a NASA specification for high-pressure oxygen to require the use of combustion-resistant metals in high-pressure oxygen systems.

Evaluation and processing experience additionally pointed out areas of corrosion or durability concerns. Many more aluminum components were replaced with corrosion-resistant steels. While this made for a robust system, it caused the baseline EMU to have an Earthly weight of 375 lb (170 kg), as opposed to the original weight of the 1978 4.0 psi (27.6 kPa) EMU design which was 312 lb (141.5 kg).

There were also changes due to evaluation experience that refined the requirements that determined the ultimate configuration of the EMU. An example was elimination of noise level. In the creation of the EMU, it was thought that less sound in the suit was better and no discernible sound was ideal. Many considered the suits of the 1960s "noisy" with their hoses and complicated ventilation paths. In response, the Shuttle EMU noise requirements were very stringent. EMU production items initially had difficulty meeting the noise level requirement, causing the introduction of a retrofit muffler in the ventilation system. Subsequent crewmember experience found the extreme quiet a distraction, perhaps out of an instinctive concern that the life support system was not functioning. The crew preferred the faint sound of the ventilation fan running in the background, providing an audible confirmation that all was right in their very small world. Consequently, the mufflers were removed from the EMU system.

The aforementioned revisions produced the "baseline" configuration that went into widespread training in 1980 and started EVA service in 1983.

Manned maneuvering unit development

Astronaut maneuvering capability on the Shuttle was not a baseline requirement. Indeed, it was largely through the efforts of Charles E. Whitsett Jr. that the Shuttle MMU was made a reality. He assembled a small group, called the Maneuvering Unit Working Group to determine whether or not there was rationale for providing astronaut-independent maneuvering capability on the Shuttle. Astronaut Bruce McCandless II, Ed Whitsett, Lou Ramon (now of Boeing), and NASA Crew and Thermal Systems Division's Joe McMann were the primary members, with support from EMU and other disciplines. The Maneuvering Unit Working Group was not an official body. It met after hours and at odd times. McCandless and Whitsett set about defining a role in satellite capture that was to make the MMU a program asset.

Development of the manned maneuvering unit (MMU) had two facets. One was designing the EMU to operate in conjunction with the MMU. The other was the parallel activity to create the MMU itself. Defining the attachment interface was a joint EMU/MMU activity. The primary life support system (PLSS) was designed to contain the EMU-side MMU attachment brackets. The EMU design envelope and the physiology of the range of user sizes established the remainder of the interfaces. Martin Marietta was the prime contractor for the MMU. The MMU was a self-contained, one-crewmember propulsion system developed to permit manual satellite retrieval and facilitate in-space servicing and construction. MMU features (#Figures 10.1.14 and 10.1.15#) included an inertial guidance system, a fixed thruster system, ability to recharge gaseous nitrogen (GN2) during EVA and all systems being fully redundant designed for fail-safe operation. The 24-thruster system provided 6 degrees of freedom control. The guidance system allowed automatic attitude hold (stopping spinning) at the push of a button, and the MMU permitted EVA access to all external Shuttle locations in case of emergency.

The first MMU was flown by Astronaut Bruce McCandless on July 2, 1984, during STS-41B (Figure 10.2.6). The other missions that utilized the MMU were STS-41C and STS-51A. These missions, also in 1984, demonstrated many capacities, including a capture device for satellite retrieval (Figure 10.2.7). The MMU was an excellent flyer, but its size and mass (327.1 lb, 148.4 kg) not only limited the activity of the crewmember flying it but also represented a volume and launch load penalty. The MMU was not flown after STS-51A and was officially retired from service in 1994. The introduction of the Simplified Aid For Extravehicular Rescue (SAFER, see Section 10.3.1) provided the next generation of maneuvering capability systems.

EVA lights and helmet TV camera

Lockheed Aerospace developed the EVA lights and helmet TV camera under contract to NASA as options to the EMU. EVA lights, which are most commonly called helmet lights, are an incandescent lamp and battery system that mounts on the extravehicular visor assembly to provide the EVA crewmember light when needed. The EVA light assembly weighs up to 6.5 lb (2.9 kg) and can provide seven hours of illumination for work in fully shaded applications. While EVA lights started service as optional EVA equipment, they have proven so useful as to become a standard part of the EMU. For the enhanced EMU, NASA funded Lockheed for an improved version of this EVA tool.

While useful and potentially necessary for some applications, the helmet television (TV) camera has truly been an option. Coupled with the capacity of the manned maneuvering unit (MMU), the helmet camera was seen as a way for the ground crew, along with the astronaut in orbit, to be able to inspect any location on the Shuttle. While the MMU never reached routine flight service, the helmet TV camera has remained optional EVA support equipment. With an Earthly weight of 13.5 lb (6.1 kg), the camera is not carried on all flights.

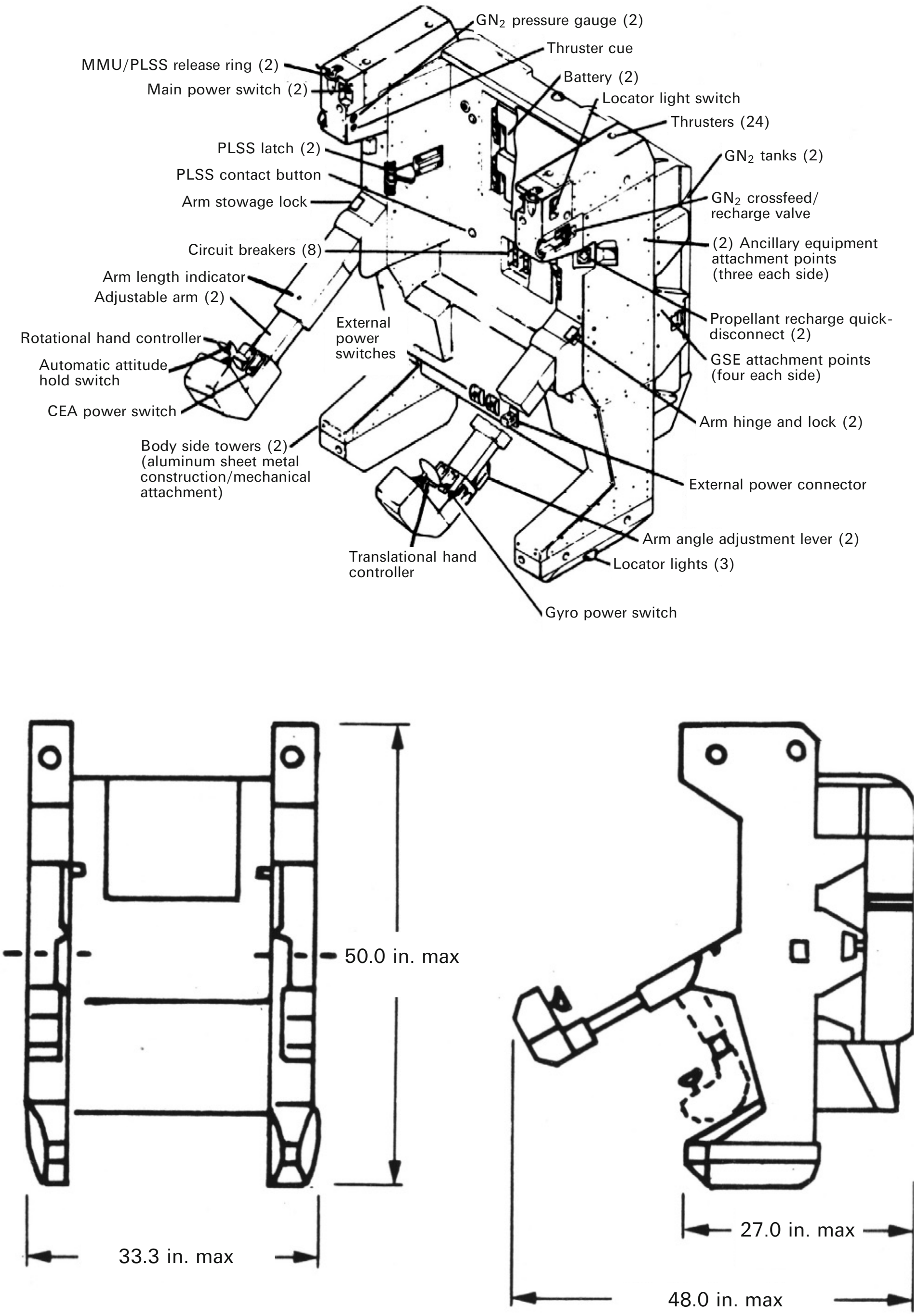


Figure 10.1.14. Features and dimensions of the manned maneuvering unit (MMU) (courtesy NASA).

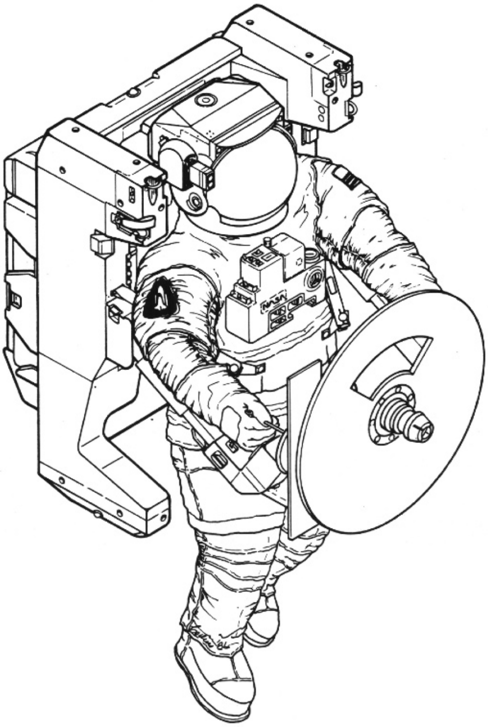
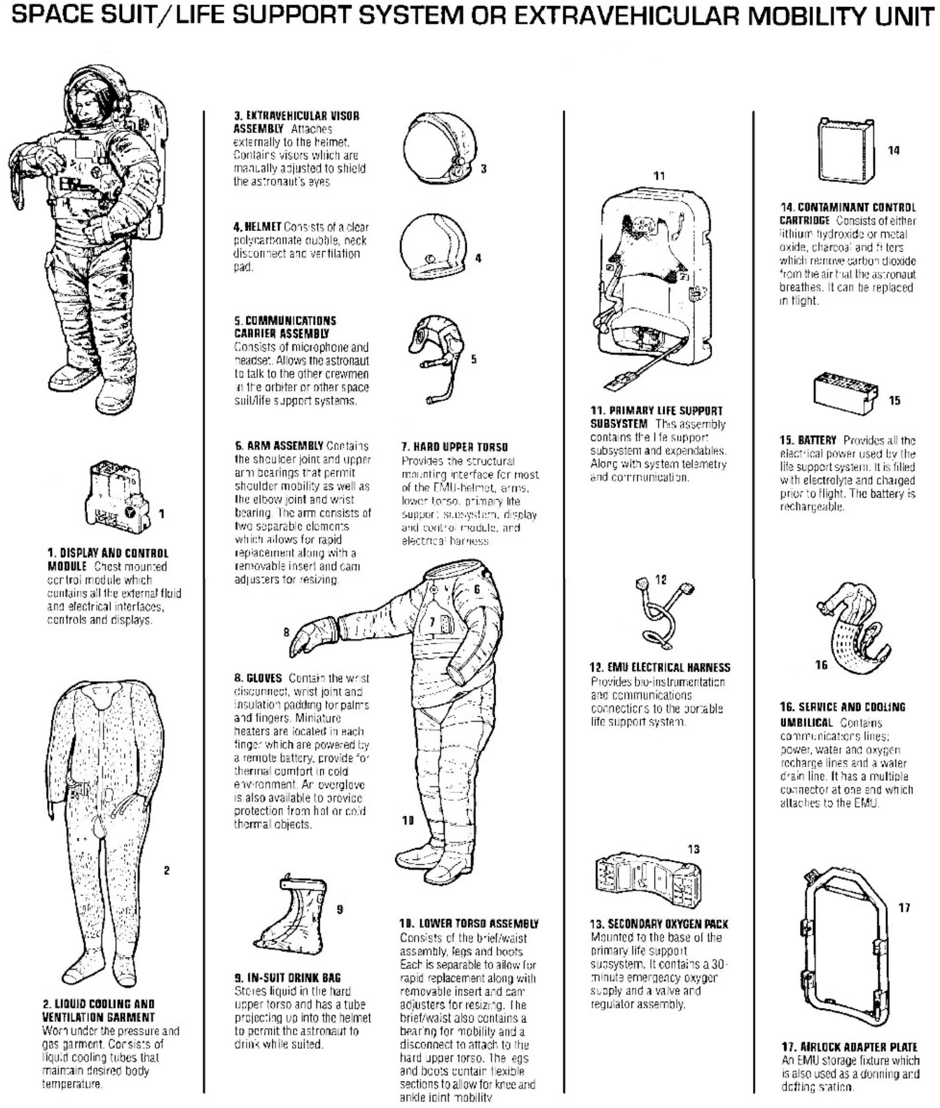


Figure 10.1.15. MMU with satellite attachment devise (courtesy NASA).

10.2 SHUTTLE EMU: BASELINE CONFIGURATION (1979–2002)

The ‘‘baseline’’ configuration of the Shuttle extravehicular mobility unit (EMU) was optimized for relatively short, up to 10-day missions that allowed sizing and servicing activities to be performed on the ground maximizing orbital time for astronauts to perform tasks. Also, short mission times before return to Earth tended to favor non-regenerable technologies.

The EMU differs from previous U.S. program spacesuit systems in a couple of significant ways. First, the Shuttle EMU (both baseline and enhanced) consists of modules called contract end items (CEIs) (Figures 10.2.1 and 10.2.2) that are mixed and matched to support flight needs. The creation and technical support of the EMU CEIs is a highly interrelated contractor team activity. As the prime contractor to NASA for the EMU, HS created the system level requirements with inputs from NASA, ILC, A-L, and other organizations. The EMU was then designed to meet those requirements. HS is also the life support system (LSS) integrator/provider. For the Shuttle, the pressure suit or pressure garment assembly was retitled the spacesuit assembly (SSA). ILC is the integrator of the SSA and—being the SSA integrator—has many roles. ILC is the designer of the mobility systems and manufacturer of the fabric portions of the EMU called softgoods. ILC also performs final assembly,



SPACE SUIT/LIFE SUPPORT SYSTEM OR EXTRAVEHICULAR MOBILITY UNIT

1. DISPLAY AND CONTROL MODULE Chest mounted control module which contains all the external fluid and electrical interfaces, controls and displays.

2. LIQUID COOLING AND VENTILATION GARMENT Worn under the pressure and gas garment. Consists of liquid cooling tubes that maintain desired body temperature.

3. EXTRAVEHICULAR VISOR ASSEMBLY Attaches externally to the helmet. Contains visors which are manually adjusted to shield the astronaut's eyes.

4. HELMET Consists of a clear polycarbonate bubble, neck disconnect and ventilation pad.

5. COMMUNICATIONS CARRIER ASSEMBLY Consists of microphone and headset. Allows the astronaut to talk to the other crewmen in the orbiter or other space suit/life support systems.

6. ARM ASSEMBLY Contains the shoulder joint and upper arm bearings that permit shoulder mobility as well as the elbow joint and wrist bearing. The arm consists of two separable elements which allows for rapid replacement along with a removable insert and cam adjusters for resizing.

7. HARD UPPER TORSO Provides the structural mounting interface for most of the EMU-helmet, arms, lower torso, primary life support subsystem, display and control module, and electrical harness.

8. GLOVES Contain the wrist disconnect, wrist joint and insulation padding for palms and fingers. Miniature heaters are located in each finger which are powered by a remote battery, provide for thermal comfort in cold environment. An overglove is also available to provide protection from hot or cold thermal objects.

9. IN-SUIT DRINK BAG Stores liquid in the hard upper torso and has a tube projecting up into the helmet to permit the astronaut to drink while suited.

10. LOWER TORSO ASSEMBLY Consists of the brief/waist assembly, legs and boots. Each is separable to allow for rapid replacement along with removable insert and cam adjusters for resizing. The brief/waist also contains a bearing for mobility and a disconnect to attach to the hard upper torso. The legs and boots contain flexible sections to allow for knee and ankle joint mobility.

11. PRIMARY LIFE SUPPORT SUBSYSTEM This assembly contains the life support subsystem and expendables. Along with system telemetry and communication.

12. EMU ELECTRICAL HARNESS Provides bio-instrumentation and communications connections to the portable life support system.

13. SECONDARY OXYGEN PACK Mounted to the base of the primary life support subsystem. It contains a 30-minute emergency oxygen supply and a valve and regulator assembly.

14. CONTAMINANT CONTROL CARTRIDGE Consists of either lithium hydroxide or metal oxide, charcoal and filters which remove carbon dioxide from the air that the astronaut breathes. It can be replaced in flight.

15. BATTERY Provides all the electrical power used by the life support system. It is filled with electrolyte and charged prior to flight. The battery is rechargeable.

16. SERVICE AND COOLING UMBILICAL Contains communications lines; power, water and oxygen recharge lines and a water drain line. It has a multiple connector at one end which attaches to the EMU.

17. AIRLOCK ADAPTER PLATE An EMU storage fixture which is also used as a donning and doffing station.

Figure 10.2.1. EMU modules information (courtesy Hamilton Sundstrand).

delivery, and systems level engineering support of all SSA CEIs. A-L provides the EMU pressure-sealed bearings, disconnect assemblies, and helmet/visor assembly to ILC and is also a contractor to HS on various EMU life support components. A-L has the distinction of having been the bearing and disconnect provider for every NASA spacesuit system since Mercury. NASA is also an EMU CEI provider. From the outset of the Shuttle, NASA elected to control the communications and biomedical systems, tools, and ancillary items such as helmet lights

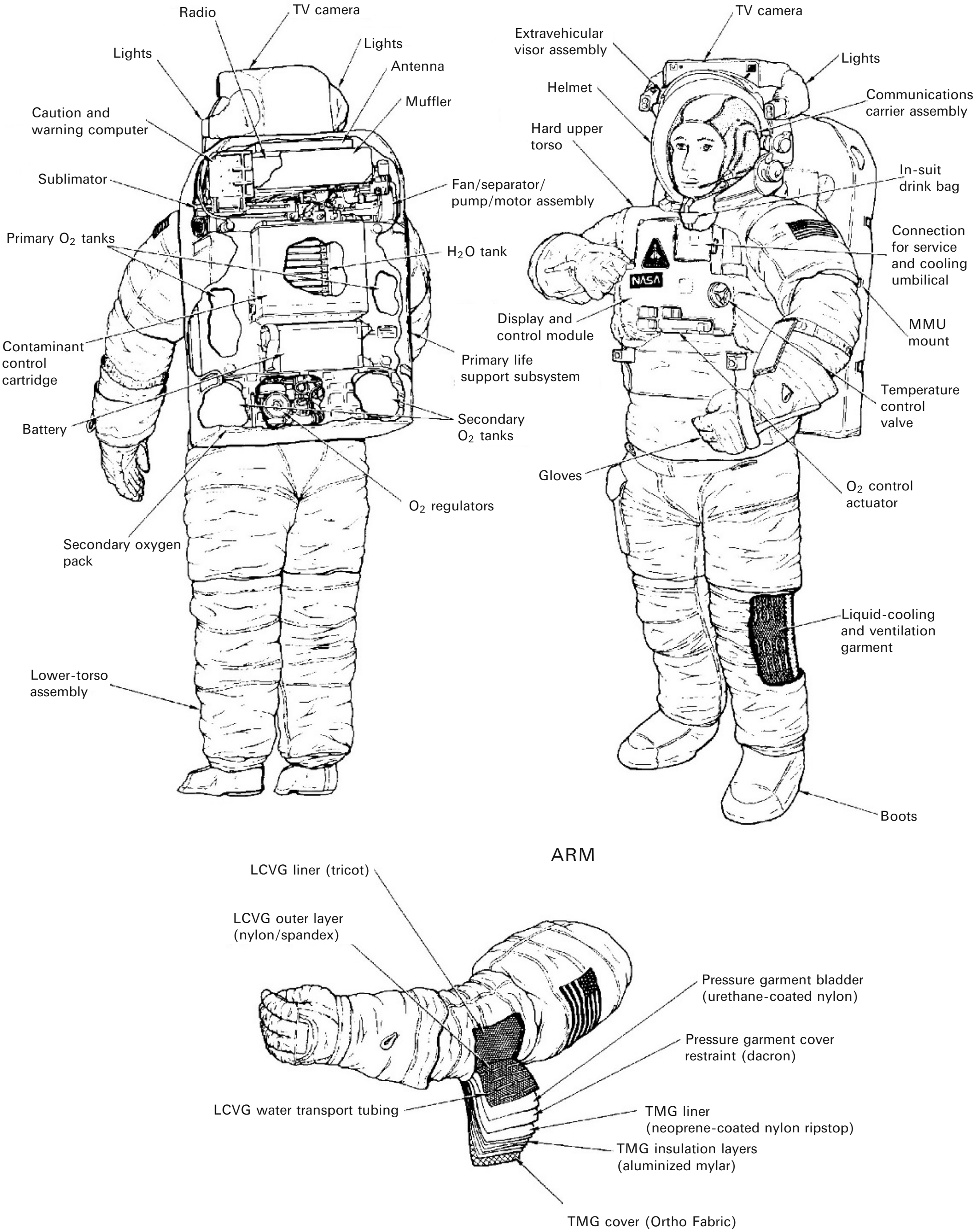


Figure 10.2.2. Shuttle EMU explanation diagram (courtesy Hamilton Sundstrand).

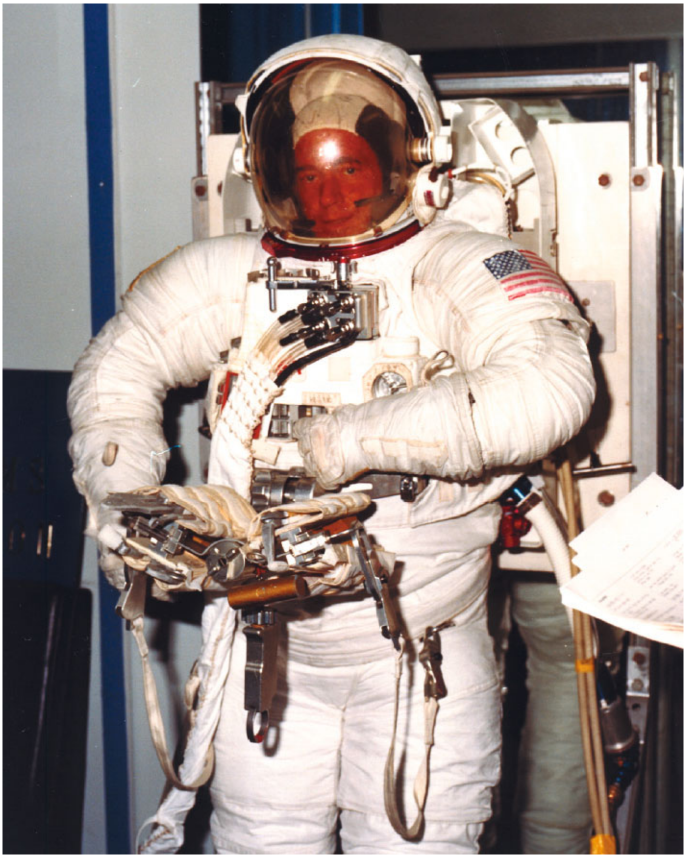


Figure 10.2.3. Shuttle EMU with mini-workstation and service and cooling umbilical (courtesy Hamilton Sundstrand).

through oversight and separate contracting. This included an integrated tool carrier/workbench named the mini-workstation (Figure 10.2.3).

EMU CEIs have lifespans and some also have refurbishment cycles, which provide opportunities to make changes at minimum cost. Because NASA has taken advantage of this to make improvements, the Shuttle EMU has been a slowly evolving system. The designation "baseline" refers to the Shuttle EMU configurations that existed before 1990, and were slowly phased out by 2002. During the life of the baseline EMU, incremental improvements were made to improve serviceability. In 1990, the decision was made to evolve the EMU further via improvement/enhancements to meet the needs of the then Space Station *Freedom* (now the International Space Station). This resulted in the "enhanced EMU" (addressed in Section 10.3).

The baseline EMU evolved incrementally into the enhanced configuration with flight experiments in 1994 and "enhanced" production CEIs starting training use in

1996. The baseline configuration saw a long and distinguished service, setting many spacesuit records of accomplishment before being upgraded to the completely "enhanced" configuration that reached flight and EVA service in 1998 (Section 10.3). The last baseline CEIs phased out of flight service in 2002 but continue to see training use in Houston, Connecticut, Japan, and Russia. More detailed discussions of baseline EMU are provided in the following topics (also see Appendix A):

- Life support system contract end items
- Spacesuit assembly contract end items
- Support and ancillary items
- Incremental improvements to the Shuttle EMU before 1990
- Baseline flight service
- Baseline EMU summary.

Life support system contract end items

The best-known EMU LSS CEIs are the Item 100 primary life support systems (PLSS), the Item 200 secondary oxygen package (SOP), and the Item 300 display and control module (DCM). The PLSS (Figures 10.1.11, 10.2.1 ref. #11, and 10.2.2) provides suit pressurization, humidity control, thermal control, and gaseous environmental control for the EMU. The PLSS includes oxygen bottles, water storage tanks, a sublimator (space-cooling system), a fan/separator/pump/motor assembly, a contaminant control cartridge, various regulators, valves and sensors, interfacing wiring harnesses, communications, and the microprocessor caution and warning system module. The expendables, stored in the PLSS before EVA, include 1.2 lb (0.5 kg) of oxygen pressurized to 900 psi (61 atm) in the primary bottles, and 10 lb (4.5 kg) of water for cooling stored in three tanks with bladders and lithium hydroxide in the contaminant control cartridge. A small amount of activated charcoal for odor control is also contained in this cartridge.

The SOP (Figures 10.2.1 ref. #13 and 10.2.2) is designed to activate automatically if the PLSS malfunctions or if the pressure suit assembly experiences leakage beyond PLSS makeup capacity. Automatic SOP activation causes the EMU crew warning system to alert the crewmember and mission support personnel. The EMU also has provisions to allow the crewmember to manually activate the SOP in a purge mode for additional redundancy. The SOP provides 30 minutes of emergency life support by storing 2.6 lb (1.2 kg) of oxygen at 6,000 psi (408 atm).

The DCM (Figures 10.2.1 ref. #1 and 10.2.2) attaches directly to the front of the hard upper torso. The DCM contains all of the EMU's mechanical and electrical operating controls and a liquid crystal display that is easily seen by an astronaut wearing the EMU and helmet. The DCM interacts with the caution and warning system in the PLSS. This system contains a software program enabling the astronaut to cycle the display through a series of system checks, thereby determining the condition of a variety of components. The DCM also attaches to the PLSS for needed interfaces to support the aforementioned functions.

Although the PLSS oxygen, battery, and cooling water are rechargeable while on orbit, the carbon dioxide (CO_2) and contamination removal system—known as the Item 480 contaminant control cartridge (CCC)—was not regenerable during missions in the 1980s and 1990s. The CCC (Figure 10.2.1 ref. #14) removes odors, particulates, and carbon dioxide by beds of activated charcoal and lithium hydroxide. While the CCC is not regenerable during a mission, CCC cartridges are reusable as the CCC beds can be replaced on the ground.

Less obvious LSS CEIs are the Item 400 service and cooling umbilical (SCU) and Item 470 airlock adapter plate (AAP). The SCU (Figure 10.2.1 ref. #16) and AAP (Figure 10.2.1 ref. #17) combine to form the EMU's recharging station, and the AAP doubles as a donning stand to help astronauts get in and out of the EMU in the zero gravity of space. The SCU is a 12 ft umbilical that contains power, oxygen, water resupply, cooling water circulation lines, and communications lines. It allows the astronaut to check out the EMU before going EVA and provides oxygen for purging the suit without using PLSS expendables. The SCU also recharges the EMU expendable supply of water, oxygen, and battery power after each spacewalk. The AAP is a mounting fixture for EMU stowage during launch, entry, and in orbit. The AAP also provides the storage attachment for the SCU when the SCU is not in use.

HS also makes the Item 602 hard torso shell (HTS). The name HTS is misleading as it is a complex assembly and the main structural component of the hard upper torso (HUT). The HUT/HTS is functionally part of both the LSS and spacesuit assembly (SSA). As part of the LSS, life support gas and fluids flow between the PLSS and the DCM through passages in the HTS shell. As part of the SSA, the HTS also provides the pressure retention for the upper torso and is the center structure to which all the other EMU components attach. In this interesting interrelationship, HS acts as ILC's subcontractor furnishing the HTS for HUT manufacture. ILC is, in turn, HS's subcontractor providing the completed HUT.

The baseline Shuttle HTS featured pivoted arm apertures. The pivoting feature allowed the shoulder bearings to tip in at the top during donning and float up and down with arm motions. Fabric bellows provided pressure retention. The pivoted HTS included the arm aperture metallic components. Both NASA-JSC and HS had been concerned about the critical failure modes inherent in the pivots-plus-bellows design. In 1990, NASA-Ames brought a Shuttle EMU–compatible hard upper torso to JSC in order to demonstrate an advanced arm and shoulder. This test item had no pivots or bellows, but had specially canted scye openings, into which either current Shuttle EMU arms or the advanced arm could be inserted for evaluation. The advanced arm and shoulder combination would not accommodate Shuttle requirements, but NASA-JSC and HS soon realized that this approach could eliminate the need for pivots and bellows. Evaluation units were built and successfully demonstrated fit and function. Consequently, this approach—called the planar HUT because of the planes of the canted openings—was implemented across the program, substantially decreasing the number of EMU critical failure modes.

Spacesuit assembly contract end items

The ILC Dover subsidiary of ILC Industries Incorporated is the spacesuit assembly (SSA) integrator for the EMU. As integrator, ILC is responsible to HS (and thus to NASA) for all aspects of SSA contract end items (CEI). ILC is also the EMU softgoods (i.e., fabric assemblies) designer and manufacturer. SSA manufacture typically starts with the creation of the "hard" components—usually metallic details (supplied by A-L and others)—which arrive at ILC. In parallel, ILC creates the very specialized softgoods needed to complete the SSA items. Then ILC performs final assembly, acceptance testing, and delivery of the SSA components for EMU. These components (Figures 10.2.1 and 10.2.2) are Item 101 communications carrier assembly, Item 102 hard upper torso, Item 103 arm assemblies, Item 104 lower torso assembly, Item 105 helmet assembly, Item 106 glove assemblies, Item 107 liquid-cooling and ventilation garment, Item 108 extravehicular visor assembly, and Item 109 in-suit drinking bag.

To support a sizing requirement spanning 5th percentile female astronauts to 95th percentile male astronauts, the baseline era SSA was ultimately designed with one size of the helmet and extravehicular visor assembly (EVVA), five sizes of the hard upper torso (HUT), four sizes of the scye (shoulder) bearing, six sizes of upper-arm assemblies, four sizes of arm bearing, nine sizes of lower-arm assemblies, one size of glove disconnect, nine standard sizes of glove assemblies, five sizes of lower-torso assembly (LTA) body seal closure (BSC), six sizes of waist assembly, four sizes of waist bearing, and two boot sizes with six sizes of slip-in sizing inserts. The extra-small size SSA components and many of the anthropomorphic "fringe size" subelements were never implemented for flight. Through mixing and matching, the inventoried SSA components were able to accommodate the sizing needs of the astronauts selected to be EVA specialists. The only area of potential customization was gloves due to the importance placed on adequate hand function in EVA work.

ILC creates the softgoods portion of the Item 101 communications carrier assembly (CCA, Figure 10.2.1 ref. #5). This "Snoopy cap" ensures that the headset microphone, earcups, and associated cables remain secure and comfortably positioned during EVA. NASA contracts the remaining elements of the headset assembly.

The Item 102 hard upper torso (HUT, Figure 10.2.1 ref. #7) provides the interface for the primary life support system (PLSS), display and controls module (DCM), helmet, arms, lower-torso assembly (LTA), and the EMU electrical harness. Development and production of the HUT was and is a team effort. Air-Lock (A-L) provides ILC with the HUT-side helmet disconnect, the HUT-side body seal closure, the multiple water connector (MWC), and water line vent tube assembly (WLVTA) clamps and fittings. The MWC/WLVTA provides the connection between the HUT and the liquid-cooling and ventilation garment. HS provides the fiberglass main structure—the Item 602 HTS. ILC manufactures the softgoods such as the thermal/micrometeoroid garments (TMG), the shoulder harness system, and flexible vent components for the WLVTA, plus a variety of smaller yet key items. ILC assembles the HUT, performs acceptance testing, and provides delivery.

The Item 103 arm assembly (Figure 10.2.1 ref. #6) consists of the upper-arm restraint and bladder assembly, the lower-arm restraint and bladder assembly, the scye (shoulder) and arm bearings, the wrist disconnect, and the thermal/micrometeoroid garment (TMG). The bearings and disconnect are produced by A-L. The overall design, the remainder of the assemblies, and the CEI deliveries are all ILC products. For the baseline EMU, the arm assemblies featured lace-in restraint layer fabric-sizing elements. The bladder layer was designed to accommodate the longest option–sizing element. This provided a very simple, lightweight, and less expensive sizing system.

The Item 104 lower-torso assembly (LTA, Figure 10.2.1 ref. #10) consists of the waist, brief, leg, and boot assemblies and contains a waist bearing that permits torso rotation and mobility joints at the hip, knees, and ankles. Like the arm assemblies, the baseline LTA was of joint ILC/A-L manufacture and used a fabric-sizing element system.

The Item 105 helmet assembly (Figure 10.2.1 ref. #4) consists of a clear polycarbonate bubble, neck disconnect, ventilation pad, and combination purge valve. The helmet provides visibility, pressure retention, impact protection, and emergency purge capability for a crewmember using the SSA in an EVA configuration. The helmet was originally developed and furnished by A-L for the Apollo program. A-L has continued this support to ILC for the Shuttle EMU program.

The Item 106 glove assemblies (Figure 10.2.1 ref. #8) are the active interface between the crewmember and the work being performed. Shuttle EMU gloves provide an effective degree of hand mobility along with a protective barrier against the natural environment and workplace hazards. The first Shuttle glove design was the 1000 series, which served until 1983. Because this CEI is so critical to effective human performance in space, EMU gloves would see three additional design iterations during the baseline era.

The Item 107 liquid-cooling and ventilation garment (LCVG, Figure 10.2.1 ref. #2) assembly is a form-fitting, stretchable undergarment that provides cooling and return ventilation from the pressure suit to the PLSS. The LCVG consists of a liner assembly, the restraint assembly, the vent plenum assembly, and the multiple water connector (MWC). The liner assembly is made of a lightweight nylon tricot material and aids in both donning and doffing while providing a comfort layer between the tubing and the crewmember's skin. The restraint assembly is made from a nylon spandex mesh, which supports the weave-through flexible water line tubing and holds the tubing firmly against the crewmember's body. The vent plenum assembly is a flexible vent system returning ventilation gas from the arms and legs. The MWC is the make-and-break connector for the cooling and vent systems.

The Item 108 extravehicular visor assembly (EVVA, Figure 10.2.1 ref. #3) is a heat and light–attenuating device (via the visors and eyeshades) that attaches to and covers the helmet. It provides micrometeoroid protection and protects the helmet from accidental impact damage. The outer sunvisor has a high reflective and emittance thermal optical coating that protects against excessive solar radiation from entering the helmet and onto the facial surface and eyes. The inner protective visor has a low-emittance thermal optical coating that prevents excessive heat loss outwards as well as icing and fogging on the helmet interior visual surface area when facing towards the environment of deep space. The EVVA contains the shell, TMG, center and side eyeshades, sunvisor, and protective visor. With the exception of the EVVA's TMG (thermal/micrometeoroid garment or outer softgoods cover)—which is provided by ILC—the EVVA is manufactured by A-L.

The Item 109 in-suit drinking bag (Figure 10.2.1 ref. #9) was a sealed bag assembly that stored water in the hard upper torso and consisted of a bladder, inlet valve, outlet valve, drink tube, and velcro attachments. It was attached to the front interior of the HUT and served to supply water to the crewmember during EVA. During the baseline era, the in-suit drinking bag was available only in a 21-ounce size. In the mid-1990s, an optional 32-ounce capacity in-suit drinking bag was introduced. The disposable in-suit drink bag replaced the in-suit drinking bag in the late 1990s.

Support and ancillary items

For the Shuttle EMU, NASA elected to retain top-level management and control of the communications system and tools. This prime contractor role effectively was a continuation of an Apollo EMU responsibility. During the baseline era, the Shuttle EMU radio had the formal title of the Item 163 extravehicular communicator (EVC). The EVC contained primary and backup systems to ensure a continuous link between the astronaut out in space and the rest of the world. The EVC transmitted not only voice communications but also real time life support and astronaut biomedical data. NASA's supplier for both the baseline and enhanced era versions of the EMU radio has been Lockheed Aerospace. To support the more challenging communication needs of the ISS, the space-to-space EMU radio (SSER) replaced the EVC.

Another key element of the communications system is the Item 101 communications carrier assembly (CCA, Figure 10.2.1 ref. #5). The CCA includes the headset microphones, earcups, associated cables, and a fabric cap to ensure that the CCA remains secure and comfortably positioned during EVA. ILC creates the softgoods portion of the CCA. NASA contracts the creation of the headset assembly and integration of the headset into the softgoods to complete the CCA. The current CCA was originally designed for Apollo by David Clark Company and has seen only minor changes through the decades.

Beyond the helmet lights and helmet TV camera (discussed in Section 10.1.5), NASA managed a variety of tools and tool systems during the baseline era. These included the mini-workstation, tethers, the wrist mirror, the cuff checklist, the Valsalva device, and the Fresnel lens. The mini-workstation (Figure 10.2.3) is a foldout toolkit platform that mounts to the front of the EMU and allows easy access to required tools during an EVA. Tethers are strap-like devices used to ensure that the EMU remains attached to the Orbiter and tools attached to the EMU to preclude the possibility that crewmembers or tools could float away. Tethers can also provide an EVA crewmember with a stable position from which to perform work. The wrist mirror permits astronauts to view areas outside the direct line of vision such as the controls on the front of the DCM. The cuff checklist is a short-form checklist of EVA procedures and EMU display codes that attaches to the wrist for crewmember reference during an EVA. The Valsalva device is an item that is positioned inside the helmet to aid the crewmember to adjust delta pressures on the inner ear while decompressing or recompressing. Basically, the device is an appliance that permits the crewmember to close off nasal passages. The Fresnel lens is an optionally available lens that can be mounted to the lower front inside of the helmet to improve close-up DCM visibility for crewmembers with glasses.

Incremental improvements to the Shuttle EMU before 1990

In parallel to the zero-prebreathe suit and Space Station *Freedom* advanced EMU next-generation equipment of the 1980s, the EMU underwent a mild evolution. This was facilitated in part by the modular architecture of the Shuttle EMU allowing subsystem upgrades at scheduled replacement or servicing increments. These upgrades were invisible to the system as a whole.

Gloves were the area of greatest evolution. The lack of adjustability in the 1000 series glove system resulted in the need for custom gloves for many EVA crewmembers. Also, the 1000 series had a life limitation of 42 pressurized hours. To alleviate these conditions, NASA funded the development of the 2000 series in 1983. The 2000 series enhanced sizing adjustability by introducing finger length adjustability and a two-position palm bar system. This design attempted to improve dexterity and tactility by the use of lighter, more flexible nylon/polyester pressure glove restraint assembly materials. Also, the 2000 series introduced a reformulation of bladder material for increased bladder life. Before the 2000 series reached flight service, training usage illustrated areas for potential improvement, including a three-position palm bar adjustment system. The incorporation of these improvements resulted in the 3000 series, which reached flight service in 1984.

The 3000 series used the same wrist disconnects and wrist gimbal rings as the previous 1000 and 2000 series. To minimize costs, existing gloves were cannibalized to provide disconnects and gimbals for 3000 series units. Extra bladder material was provided in the thumb area to increase mobility, and the finger length adjustment approach was also improved. During the service life of the 3000 series, the glove featured evolutionary improvements in the bladder, restraint, TMG, and mitten assemblies. Bladder life was dramatically increased from the previous 42 manned, pressurized hours to 461 manned, pressurized hours. The TMGs specifically gained a more durable/serviceable silicone palm and palm-side finger covering in 1985. In-flight use of the 3000 series gloves was first conducted during STS-61B, and results were less than favorable. One of the EVA astronauts suffered thumb numbness for some time after the flight, apparently due to added bladder easement. Other crewmembers complained of pain in the finger crotches, due to pressure points caused by the new finger length adjustment system.

While the 3000 series glove achieved the goal of longer pressurized life (to 461 hours), the problems associated with hard contact with the hands of some crewmembers resulted in a further refinement starting in 1986. This was embodied in the

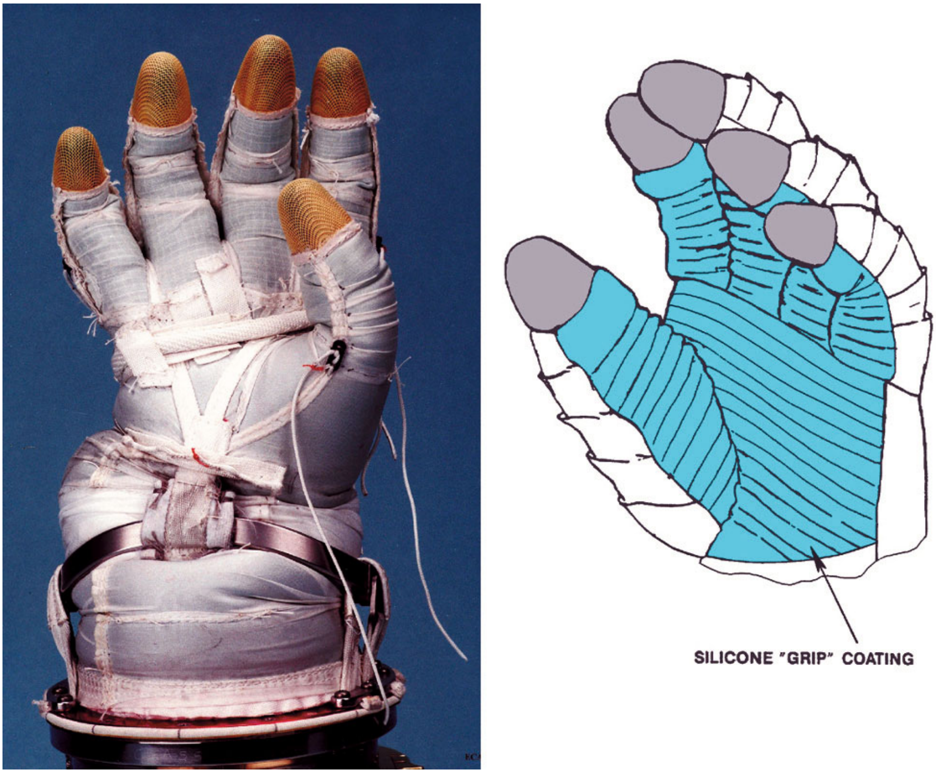


Figure 10.2.4. Shuttle EMU 4000 series pressure glove (courtesy Hamilton Sundstrand).

4000 series gloves (Figure 10.2.4), which not only adjusted patterning to alleviate pressure points but also reduced bladder bunching and added another palm bar adjustment location for improved fit and mobility. With the introduction of the 4000 series glove, the 3000 series was removed from service principally through attrition, and the metallic "hard" parts from the 3000 series were recycled into the 4000 series to minimize expense. Many 3000 series gloves saw training service into the late 1990s. The 4000 series glove has the distinction of being the longest used model of EVA glove in the history of U.S. space exploration, seeing service until 2001.

Gloves were not the only area of improvement. During the 1980s, the display and control module (DCM) received changes to reduce ground-handling and information-processing times. A redesign of the DCM created two separable halves: the Item 350 electronics assembly and the Item 385 oxygen/water manifold assembly. The electronics were extensively redesigned to reduce the number of printed circuit boards from six to two. In redesigning the electronics, current limiters for the solenoid valves were packaged into two hybrid microcircuits per DCM. The DCM display was also improved for readability in bright sunlight by changing the light-emitting diode configuration to a liquid crystal display. Field processing and manufacturability were greatly enhanced by these changes to the DCM.

During the 1980s, the primary life support system (PLSS) saw changes to improve operational life. Problems with chemicals inherent in the neoprene water tank bladders caused premature degradation of sublimator performance. After a brief and unsuccessful experimentation with an ion exchange bed to try to extract the offending chemical (abietic acid), HS selected Fluorel to replace neoprene as the water tank bladder material, which increased sublimator life. The main PLSS structural element also doubles as the water storage tank. Since every bit of space is important, the structure contains three irregularly shaped water storage areas, which are poor pressure vessels. A pressurization error in field servicing resulted in a cracked water tank structure; so stiffening elements were added to all existing structures. One result of the redesign was to change the interior water tank coating material to improve corrosion resistance that allowed an increase in the structure's useful life from 15 years to 40 years. In a separate effort to eliminate potential corrosion and provide longer life, many elements that had direct contact with the PLSS water loop were revised from coated aluminum to corrosion-resistant steel assemblies.

Baseline flight service

The Shuttle baseline extravehicular mobility unit (EMU) configuration went into flight service on April 12, 1981. The Shuttle EMU's planned debut on STS-5 was disappointing. With one EMU, the PLSS fan operated at below specification speed. The suit circuit regulator in the other EMU failed to attain the proper pressure level. The fan anomaly was caused by water-based corrosion of Hall effect speed sensors located in the motor that powered the ventilation fan, water circulation, and the centrifugal water separator. The regulator problem was traced to the omission of thread-locking inserts in the regulator adjustment mechanism. It is surmised that the regulator adjustment "backed off" as a result of launch vibration. Both conditions were rectified for STS-6.

Story Musgrave and Donald Peterson performed the first Shuttle extravehicular activity (EVA) on April 6, 1983 during mission STS-6. The two exited the airlock and translated to the aft end of the cargo bay without difficulty (Figure 10.2.5). Looking out at the expanse of universe outside the cargo bay, Musgrave joked "this is a little deeper pool than I'm used to working in." All would not go this easily. In practicing manual contingency closure of the 60 ft. (18.2 m) long payload bay doors, the winch bound up during rewind. At one point, cutting the winch cable was considered. However, with patience and persistence, the cable was freed and the activity completed. Other than Musgrave reporting that his fingers had become cold during a simulation activity and greater-than-anticipated oxygen usage by Peterson, the remainder of the 4-hour 10-minute EVA was uneventful. During post-EVA debriefings, Musgrave reported that the sublimator can produce rather large ice chips and that after the EVA his hands were "soaking wet".

Figure 10.2.5. STS-6, the first Shuttle EVA (courtesy NASA).

The mix and match sizing accommodations of the Shuttle EMU opened up human space exploration to female astronauts starting with STS-41G. The first to "go EVA" was Kathy Sullivan on October 11, 1984. Nine more have followed for a current total of 27 EVAs and 187.6 hours working in the vacuum of space.

Another early Shuttle EMU milestone was the use of the manned maneuvering unit (MMU). Use of the MMU provided the ability to transform an EMU into a free-flying one-person spacecraft. The first person to venture out into the void of space without attachment to a spacecraft was STS-41B's Bruce McCandless on February 7, 1984 (Figure 10.2.6). He was followed by Robert Stewart. Each astronaut equipped with an MMU took a turn practicing for the Solar Maximum Mission (Solar Max) satellite retrieval that was planned for the next flight (STS-41C). McCandless quipped, "It may have been one small step for Neil but it's a heck of a big leap for me."

McCandless made three "trips". The first was 150 ft. (45 m) away from *Challenger*. The second flight reached a distance of 315 ft. (96 m). The last sortie reached a distance of approximately 325 ft. (99 m) before returning. Then Stewart attached the trunnion pin attachment device (Figure 10.1.15)—which would be used to snare Solar Max—and McCandless practiced approach and attachment with a mockup of the Solar Max in the payload bay. Other than the MMU nitrogen

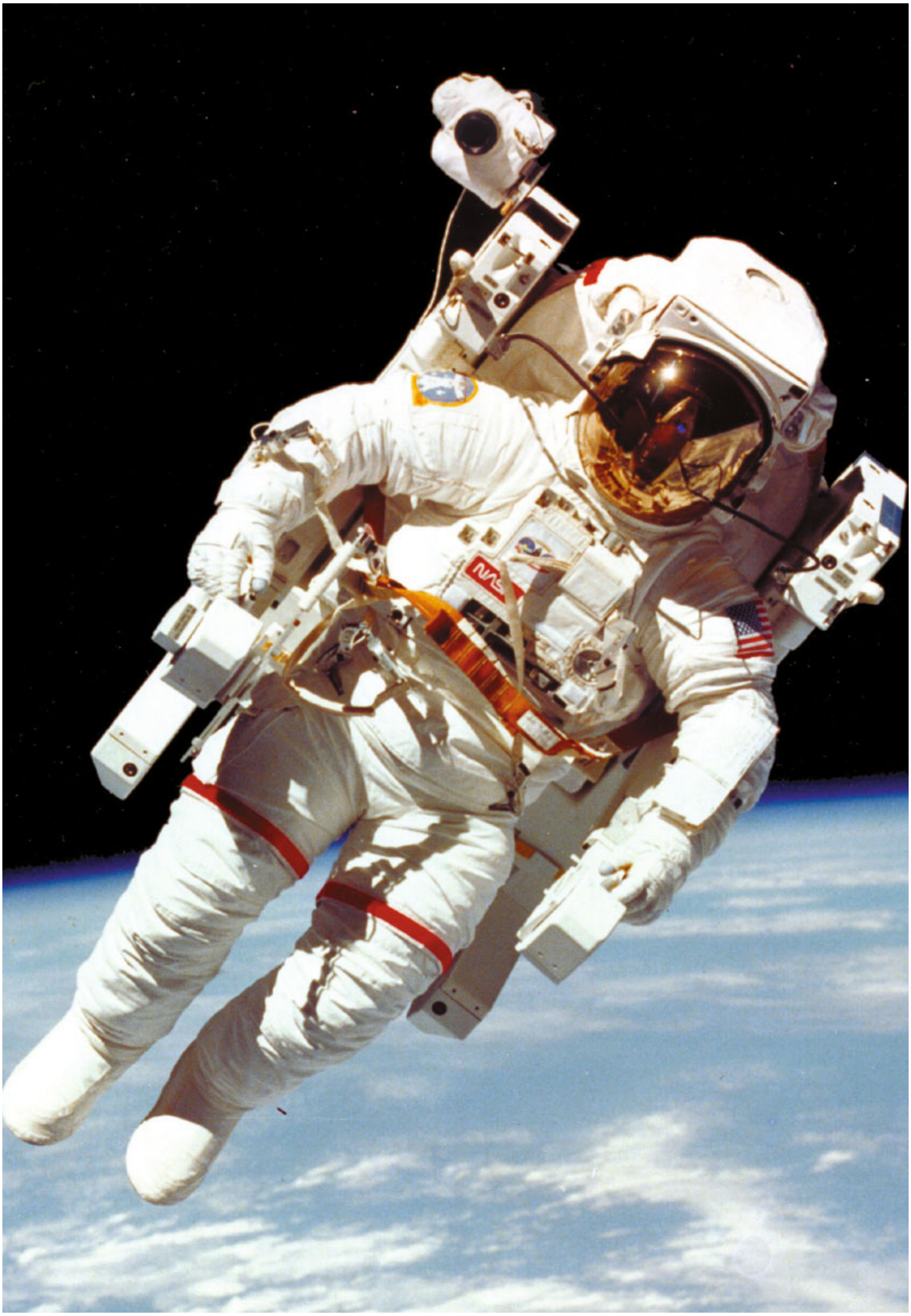


Figure 10.2.6. First manned maneuvering unit flight on February 7, 1984 (courtesy NASA).

propellant use being higher than in simulations and McCandless reporting that one scenario produced a "shudder" and he was chilled when he traveled out away from the payload bay, McCandless' travels were as expected.

Stewart then got his opportunity to fly an MMU. This would last some 65 minutes taking Stewart up to 306 ft. (93 m) from the Shuttle with no problems.

McCandless gained another first during this EVA with his testing of work position simulations in foot restraints at the end of the remote maneuvering system (RMS) manipulating arm. The arm proved more stable for EVA work than expected. These "dress rehearsals" set the stage for STS-41C that would follow.

STS-41C was in orbit and in position on April 8, 1984 when Astronaut George Nelson donned the MMU and ventured out into space to attempt docking with Solar Max. James van Hoften was Nelson's supporting partner on this EVA. Three times Nelson attempted and failed. Each time his efforts would add to the slow spin of Solar Max, which complicated the effort. In a last attempt, he manually grabbed one of the satellite's solar arrays. This reversed the spin but put the satellite into a tumble. At this point, the MMU was low on fuel precluding further attempts that day. Later, the inability to dock would be traced to the Solar Max having an obstructing grommet that did not appear on its blueprints.

Fortunately, NASA's Goddard Space Flight Center, which operated Solar Max, was able to stabilize the satellite making another attempt possible. On April 10, 1984, the crew of STS-41C was able to capture Solar Max with the RMS on the first try and successfully placed the satellite in its servicing cradle in the payload bay. Later that day, EMU-clad Astronauts Van Hoften and Nelson went EVA to successfully replace the satellite's 500 lb (227 kg) attitude control and main electronics box. After that, the RMS moved the satellite back into free orbit for return to service. However, that was not the last MMU satellite retrieval mission.

On November 12, 1984, Joseph Allen performed an MMU EVA from the Shuttle *Discovery* on mission STS-51A. Allen piloted the MMU to a successful first-time docking with the 1,222 lb (555 kg) Palapa 8-2 satellite (Figure 10.2.7). Without difficulty, the MMU's automatic attitude hold feature stopped the satellite's spin. Allen's EVA partner, Dale Gardner, was in foot restraints on the end of the RMS. Allen maneuvered the satellite to Gardner, but Gardner was unable to attach the 8 ft. (2.44 m) A-frame device that was intended to be used to place the Palapa in *Discovery*'s payload bay. After many attempts, Gardner was finally permitted to perform a manual capture of the satellite. RMS operator Anna Fisher then guided the satellite into its servicing location in the payload bay with Gardner acting as the capture device. Other than some abrasion to Gardner's gloves, there were no other ill effects from this operation. The investigation into why the A-frame was unable to perform the capture later found a Palapa waveguide extension—which did not appear in the satellite's blueprints—had blocked the capture. The satellite was then serviced and reorbited for continued use.

However, on reflection, mission STS-51I in August 1985 potentially put the EMU into a new load-bearing regime. EVA crewmember James "Ox" van Hoften managed to stop the slow spin of the LEASAT satellite (U.S. Navy Leased Satellite Program) by repeatedly grasping and releasing a bar on the satellite, while he was

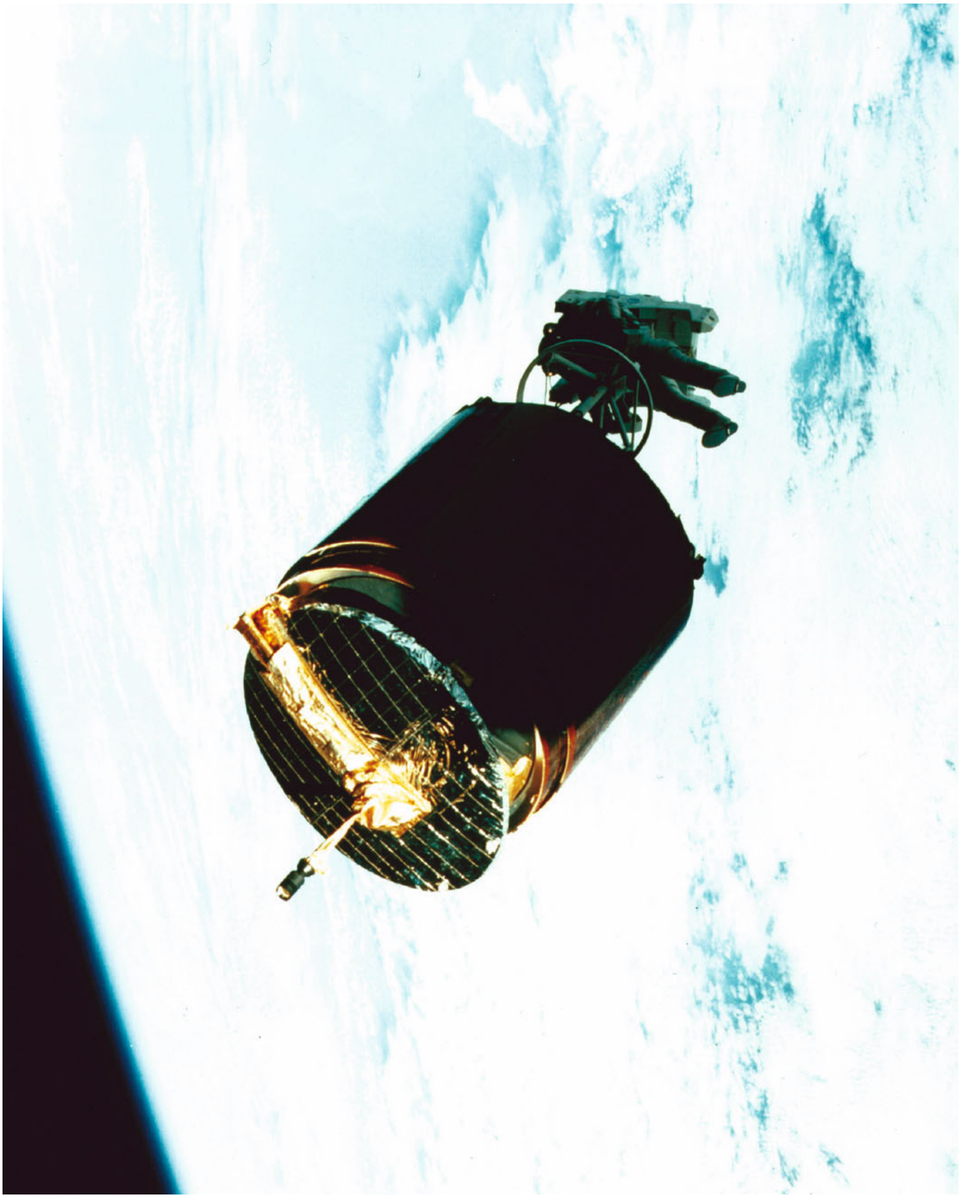


Figure 10.2.7. MMU being used by Astronaut Joseph Allen for satellite retrieval (courtesy NASA).

captured in foot restraints. Commenting that he "felt it down to his toes" when the mass of the satellite stretched his body, he caused the EVA community to begin revisiting both human-induced loads as well as loads caused by satellites with the EMU acting as the link in the moving system. This highlighted a difference of experience within the community. Man-load testing was conducted during Apollo. The data from the testing indicated man-loads substantially below then current Shuttle EMU requirements. However, other sources of data indicated potentially higher possible loads. Lingering doubts resulted in the performance of instrumented testing of man-load and manned satellite-type loads in Shuttle EMUs. The load levels observed in the testing were generally equivalent to or in some cases higher than the then current requirements. The design load values were consequently revised upward. The resulting suit component capacity improvements would appear in the enhanced EMU configuration. Mission results also revealed that the crewmembers were too cold during EVA, even after going to minimum cooling. One crewman shut off the water supply to aid in maintaining body heat, but encountered helmet fogging due to moisture buildup. Astronaut van Hoften got a surprise at the conclusion of the last EVA, when his high CO_2 warning came on, and for the first and only time the purge valve was opened. Later it was revealed that his CCC had not been replaced after the first EVA and had seen upwards of 10 hours of use, illustrating the amount of margin in the design.

Another historic human capture of a satellite came with STS-49 in May 1992. The Intelsat VI satellite became stranded in low-Earth orbit in March 1990 due to a boost system malfunction. Without a boost to its proper orbit, not only did the satellite not serve its intended purpose, but it would also lose altitude and burn up in entry to the Earth's atmosphere. STS-49 was to attach a 23,000 lb (10,455 kg) solid-fueled apogee kick motor to boost the satellite to its proper place in geosynchronous orbit. On the first EVA of the mission Pierre Thuot and Richard Hieb were to attach a capture device and secure the 17 ft. × 12 ft. (5.2 m × 3.2 m) Intelsat satellite in the Shuttle's cargo bay to allow installation of the kick motor. The capture device, which worked perfectly in Earthly simulations, proved unable to function in space due to the dynamics of the multiaxis environment in orbit. Three attempts were made. Each attempt resulted in a worsening wobble of the satellite, and the wobble was judged to be too pronounced to attempt a fourth try.

The next day, Thuot and Hieb again went EVA. This time greater care was taken in positioning Thuot and less force was applied on the capture bar. Thuot attempted five more times to attach the capture bar. The bar refused to latch and the satellite began wobbling worse with each attempt until the EVA was terminated. Thuot later would comment that satellite handling "was much more dynamic than our training had led us to believe."

The next EVA was performed on May 13, two days later. This EVA marked the first and only time three humans ventured out together from a space vehicle. This time Thomas Akers joined Thuot and Hieb. Since the Orbiter was equipped to recharge only two EMUs at a time, to minimize the consumption of expendables before going out, the three astronauts "buddy-shared" the recharging umbilicals. The three erected secure working positions with available foot restraints/tethers and together manually captured Intelsat IV (Figure 10.2.8). They then manually attached the capture bar to the satellite, which allowed positioning of the satellite into its servicing location. This EVA also set another world record: as it lasted 8 hours and 29 minutes, it broke the Apollo 17 record of 1972. During this third EVA, the apogee

Figure 10.2.8. STS-49 EVA, Akers, Thuot, and Hieb manually retrieve Intelsat (courtesy NASA).

kick motor was installed, and on May 15 Intelsat VI began its long-delayed voyage to geosynchronous orbit and service. The fourth and final EVA of the mission was carried out by astronauts Kathy Thornton and Tom Akers. During this exercise, they carried out the Assembly of Station by EVA Methods (ASEM) experiment to demonstrate and verify maintenance and assembly capabilities for the then Space Station *Freedom*. The ASEM spacewalk program was cut from two days to one because of the Intelsat activities. Astronaut Thornton was allowed to conduct the EVA with a malfunctioning DCM display, relying on ground monitoring of data and good communications capability.

Unquestionably the most famous satellite rescue mission of the Shuttle program was STS-61 and the Hubble Space Telescope repair. Hubble was launched in 1990 on STS-31. Once operational, the images were found to be out of focus. This would be traced back to the incorrect grinding of a mirror a decade before the telescope was launched. Fortunately, the telescope had been concepted to be routinely serviced and upgraded for improved exploration by the Shuttle. Servicing accesses into the telescope's interior had been designed around the Shuttle's EMU and RMS. Thus, these events transformed the first servicing mission into a repair and servicing effort with the world's attention focused on the repair.

Launched on December 2, 1993, STS-61 was a highly ambitious mission that had as primary goals the replacement of a host of items: the solar arrays, rate-sensing units 2 and 3, the wide-field/planetary camera, magnetic sensing system (MSS) magnetometer 1, the electronics control unit, solar array drive electronics 1, and the Goddard high-speed photometer with a corrective optics space telescope axial replacement. The corrective optics constituted the repair portion of the mission. Additionally, if time permitted, the mission was to install a power supply redundancy kit, a 386 co-processor for the primary computer, and replace magnetic sensing system 2, the rate-sensing unit's fuse plugs, and electronics control unit 1. This was all to be accomplished in just five EVAs in eleven days. With five EVAs, this set a record for the most EVAs on a space mission.

To maximize the chances for success on this mission, the selected crew were all veterans in the roles that they would perform. The astronauts supporting EVAs 1, 3, and 5 were Story Musgrave and Jeffrey Hoffman. EVAs 2 and 4 were supported by Kathy Thornton and Thomas Akers. Claude Nicollier was the RMS operator who had performed the initial capture of the Hubble, supported moving astronauts around in foot restraints to perform servicing functions, and carried out the handling of replacement items for all five EVAs from inside the Shuttle. Nicollier, a European Space Agency astronaut, gained the nickname "the magician" for his precision of movement and his ability to anticipate the need to move the EVA crewmember before the crewmember asked for an adjustment in position.

On the first EVA (Figures 10.2.9 and 10.2.10), an impromptu revision of the approach saved precious EVA time. Musgrave, being shorter than Hoffman, was able to slip under Hubble's sunshade to reach the rate-sensing units. This avoided the removal of the sunshade, which saved approximately an hour of EVA time. Through most of the EVA, Musgrave and Hoffman were ahead of the timeline. The first and only challenge of the EVA came when the astronauts went to close the rate-sensing unit compartment door. The door had deformed as a result of exposure to extreme heat and cold cycles during Hubble's first three years in space. The astronauts ultimately overcame the door's reluctance by means of a double team effort with Musgrave pushing on the bottom and Hoffman, in foot restraints positioned on the RMS, applying pressure on the top.

The second EVA of the mission started with Kathy Thornton's radio being unable to receive transmissions from either *Endeavour* or the ground. As Akers was able to relay communications to Thornton, this was not deemed a constraint and the astronauts were permitted to go EVA. About 3 hours and 15 minutes into the EVA Thornton's radio regained full communications; however, incoming communications would be lost again near the end of the EVA. Other than the radio inconvenience, the EVA went better than expected.

EVAs 3, 4, and 5 all progressed exceptionally well except for the inconvenience of Thornton's continuing communications problems on EVA 4. The mission

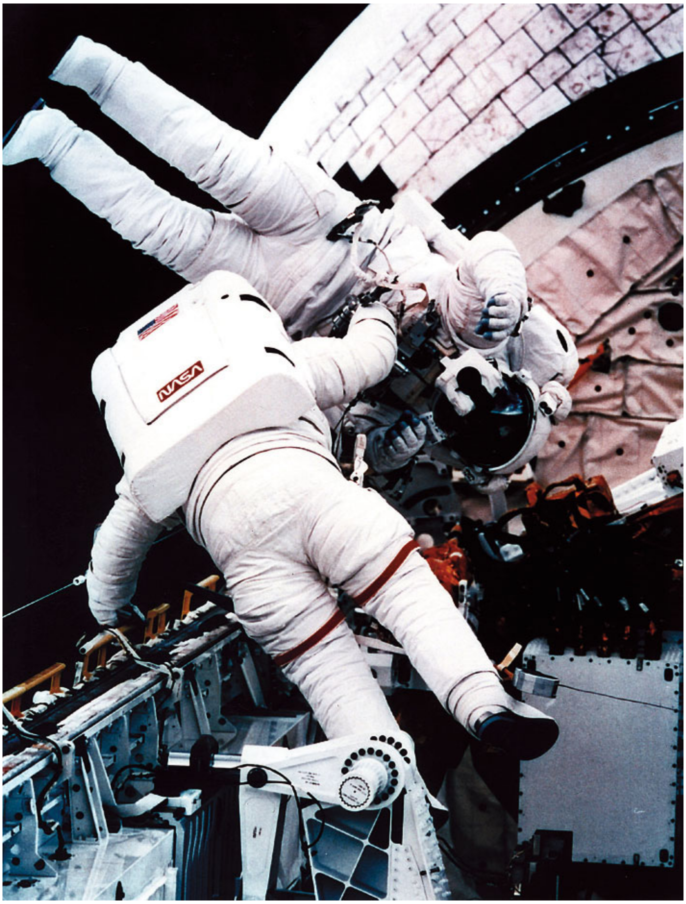


Figure 10.2.9. Astronauts Hoffman and Musgrave going out to work (courtesy NASA).

completed all its primary and secondary goals. At the end of EVA 5, the telescope was given the command to deploy its solar arrays. Difficulties were experienced forcing Musgrave and Hoffman to aid in the deployment. With astronaut assistance, each array was unrolled in 5 minutes completing the mission's activities. Partial communication problems on this EVA resulted in no biomedical data for most of the EVA. The completion of EVA 5 (the 65th of the Shuttle program) set another record. The mission's total EVA time of 35 hours and 28 minutes was the longest in a single mission.

The next day, Nicollier used the RMS to maneuver the telescope out of *Endeavour*'s payload bay and positioned the telescope so that the telescope's batteries could charge. Ground control commanded the telescope to deploy its high-gain antenna booms and open its lens aperture door. With everything appearing operational, Nicollier then released the telescope. Covey and Bowersox

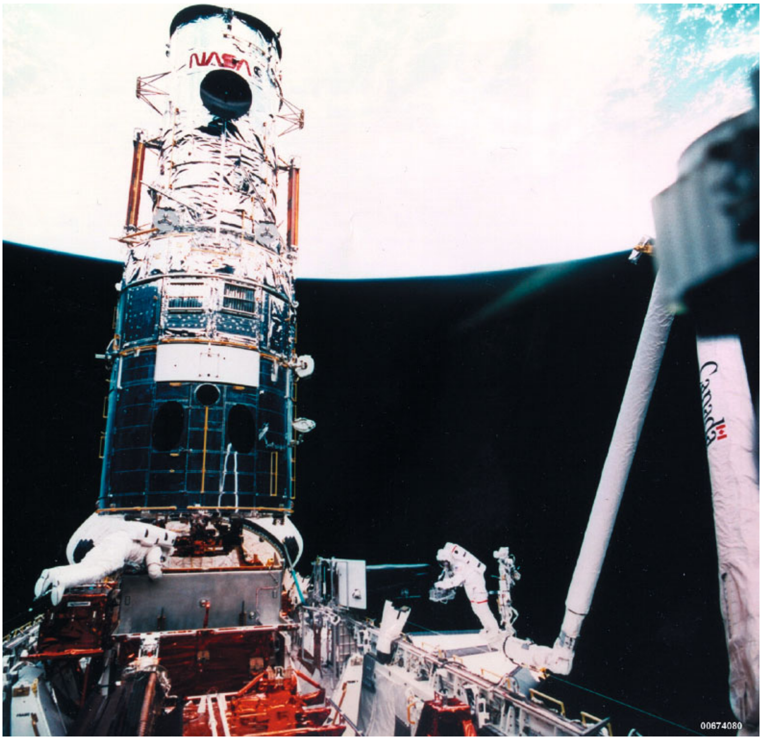


Figure 10.2.10. STS-61, the first Hubble-servicing mission (courtesy NASA).

moved *Endeavour* away, taking care not to strike the HST with plumes from the Orbiter's steering jets. Before returning, the crew performed spacesuit evaluations in the mid-deck and stowed the RMS. *Endeavour* landed in Florida on December 13. The HST began capturing the mysteries of the universe from the optically corrected, rejuvenated, and improved telescope.

Starting with STS-64 in September 1994, the baseline configuration of the Shuttle EMU became a flight testbed for modules of the enhanced or Space Station configuration. The first enhanced EMU module was the Simplified Aid For EVA Rescue (SAFER, for details see Section 10.3.1). In September 1995, STS-69 would test an early configuration of a heated glove, designed to allow the handling of cold objects in space without the use of bulky and clumsy thermal overmittens (see Section 10.3.2).

In January 1996, an enhanced EMU passive heating system called "LCVG bypass" (LCVG = liquid-cooling and ventilation garment) was tested on STS-72. This on-orbit testing was coupled with evaluation of a later generation of the heated glove. The combination proved highly effective for keeping astronauts comfortable in extremely cold situations.

As part of the dress rehearsals in preparation for International Space Station (ISS), seven U.S. astronauts served tours on the *Mir* space station and the Shuttle performed nine dockings with the station. On the third Shuttle visit to *Mir*, STS-76, baseline EMUs were used on the first U.S. EVA off a foreign space station. In this EVA, Rich Clifford and Linda Godwin placed a *Mir* environmental effects payload (MEEP) to collect data on the orbital conditions that would be encountered on the ISS. This stemmed from the relative locations of the Russian launch center at Baikonur Cosmodrome and the U.S. launch point at Kennedy Space Center, which is closer to the equator. It is easier to launch larger payloads into orbit by gaining benefit from the Earth's rotation, but making use of this effect places spacecraft into an orbit closer to the equator and does not overfly Baikonur. Launching from Baikonur, Russian spacecraft are forced into an orbit that runs farther north and south. Since the U.S. was capable of launching into a Russian-type orbit, but the Russians could not launch into orbits typical of U.S. activities, a Russian-type orbit was selected for ISS. This was a new environment for the U.S. in terms of orbital debris and solar effects on materials, thus creating the need for MEEP. For placement of the MEEP on the exterior of *Mir*, the EMUs were equipped with larger tether hooks to be compatible with the *Mir* handrails and tested foot restraints that could be used by both U.S. and Russian spacesuits. The MEEP would return to Earth for evaluation in September 1997 on Shuttle flight STS-86 (discussed later).

On STS-82, the second Hubble servicing mission, baseline EMUs were again used to demonstrate the Shuttle's ability to service the world's most valuable telescope. Two EVA teams would perform 33.2 hours of trouble-free EVA to leave the telescope in a better and more powerful condition than when they arrived in February 1997.

In September 1997, mission STS-86 brought the seventh Shuttle visit to *Mir*. Baseline EMUs were used to retrieve the MEEP from its resting place on the exterior of *Mir*. This EVA, performed by Scott Parazynski and Vladimir Titov on October 1, 1997, marked the first astronaut/cosmonaut EVA team working in U.S. spacesuits and the second such team to go EVA. The first U.S./Russian EVA was performed outside *Mir* by Cosmonaut Vasili Tsibliyev and Astronaut Jerry Linenger on April 29, 1997 in Russian Orlan M spacesuits (Figure 11.1.5.2).

December 1998 brought EVAs that were historic in many ways. Leading up to this, the first element of the International Space Station (ISS) was launched into orbit by a Russian Proton rocket in November 1998. This element was the functional cargo block named Zarya (Zarya means "sunrise" in English.) Zarya weighed 42,600 lb (19,363 kg) on Earth and was designed to provide the station's initial propulsion and power. The second ISS module launch was Node 1 named Unity. Unity was launched into space on December 4, 1998 aboard the Space Shuttle *Endeavour*. This was Shuttle mission STS-88. Unity would be the connecting passageway to living and work areas of the ISS. Unity is 22 feet long and 15 feet in diameter containing six hatches to serve as docking ports for the other modules. The 7-day STS-88 mission was to be highlighted by the mating of the U.S. built Unity station element to the Russian Zarya. This required three EVAs that had historical significance as well.

The STS-88 flight marked the first EVA use of the enhanced EMU (discussed in Section 10.3). On each of the three EVAs, only one of the two EMUs would be the

Figure 10.2.11. STS-88 baseline (foreground) and enhanced EMUs assembling the ISS (courtesy NASA).

enhanced configuration (Figure 10.2.11). This mission was also historic in that it carried out the initial ISS assembly (Figure 10.2.12). This mixing of EMU configurations would be common during the phase-out of the baseline EMU as the configuration was a crew preference option and also because the enhanced configuration was not offered in all the optional sizes that had been available in baseline. Where the baseline EMU had four sizes of hard upper torso (HUT) and a large sizing variety of supporting modules (contract end items or CEIs), the enhanced configuration was originally implemented with only two sizes of HUT and limited sizing options in the other CEIs. This was to limit development and inventory costs for the new configuration. The Russian EVA suit system, as a point of reference, has one size of HUT with one configuration of arms and a lower torso that has built-in (on-orbit) sizing ability. The three STS-88 EVAs made station assembly look routine and effortless.

Figure 10.2.12. First step in assembling the ISS completed (courtesy NASA).

An extra-large baseline EMU was used, in conjunction with three enhanced EMUs, to perform the STS-103 servicing of the Hubble Space Telescope. This would permit Hubble to perform into the 21st century with greater searching capacity than ever before. While they tended to be relegated to missions without planned EVAs, baseline EMUs would perform EVAs in five more missions. The last flight and EVA of the baseline configuration came on STS-110 in April of 2002. On this mission, the large baseline SSA was the preference of a veteran astronaut. Thus, with the completion of the 78th Shuttle EVA (116th U.S. EVA), the baseline EMU ended flight service.

Baseline EMU summary

From 1983 to 2002, the baseline EMU supported 56 EVAs (17 in conjunction with an enhanced EMU) for a total of 594.1 man-hours outside a spacecraft. Through the years, many post-EVA crew debriefings drew remarks that the (baseline) EMU was "invisible" during their EVA in that the crewmember was unaware of the EMU. The EMU was simply there doing its job without inconvenience or obstruction. Part of this perception could be that the crewmembers had trained so extensively in the EMU that functioning in the suit was a normal part of their existence; however, the fact that crewmembers frequently went EVA for 7, 8, or more hours every other day without ill effects or exhaustion speaks well for the performance of the baseline EMU. While the baseline EMU did not have all the qualities and capacities that everyone in the EVA community desired, the above is a positive reflection on how well the suit system performed.

Food and water accommodations were improved over Apollo/Skylab, but were not perfect. In-suit drink bags and internally mounted food bars removed the safety hazard of a pass-through but, in the early years of the Shuttle, the food bar frequently crumbled leaving floating crumbs inside the suit. While later formulations rectified that condition, food bars continued to be messy and on occasions malfunctioned. The in-suit drink bag has had a checkered history of leaks and inability to satisfactorily dispense water, and has evolved to a disposable model that seems to have solved most of the problems.

Although the flight version of Shuttle EMUs has been upgraded to the enhanced version, the training baseline configuration is still in service. Also, four baseline-training EMUs were modified to feel and function like enhanced units. Of these, two have been retained at JSC and two were sent to Russia in the late 1990s to support cosmonaut training. In a training capacity, the baseline configuration logged over 32,000 man-hours of pressurized time and continues to accumulate training hours of service.

10.3 THE ENHANCED EMU FOR THE INTERNATIONAL SPACE STATION (1990–PRESENT)

The International Space Station (ISS) posed significant extravehicular challenges. The number of spacewalks necessary for ISS construction would be greater than the previous spacewalks conducted in all the world's space programs combined. This spike in EVA activity was so pronounced when seen on graphs that it would come to be known as the "wall of EVA". The financial constraints to proceeding with the U.S. portion of the ISS were formidable, especially while attempting to continue NASA advances in aviation and other space arenas. Due to these constraints, NASA elected in 1990 to implement evolutionary improvements (enhancements) to the Shuttle extravehicular mobility unit (EMU), rather than develop an all new advanced EMU (see Section 11.1.3).

The baseline configuration was designed around the Shuttle's relatively short mission spans, which provided ground-processing opportunities for resizing the spacesuit assembly (SSA), performing checkout of critical system components, and replacement of the carbon dioxide removal material (lithium hydroxide) and odor-removing activated charcoal in the contamination control cartridges (CCCs).

Given the number of planned extravehicular activities (EVAs), the storage volume and weight penalty associated with carrying fresh CCCs up to the ISS and returning spent cartridges was prohibitive. Also, to avoid placing complete space EMUs in orbit, the major modules needed to be replaceable by station crews to minimize the on-orbit inventory. This replacement capability is denoted as ORU for on-orbit replacement units.

While the enhanced EMU for joint ISS/Shuttle activities shows only subtle external changes, almost every subassembly of the EMU was revised and improved. Beyond ORU ability and the previously discussed helmet lights and helmet TV camera (discussed in Section 10.1.5), there was a new radio system named the space-to-space EMU radio (SSER) to address the reception challenges imposed by the ISS, and new systems were added such as the Simplified Aid for EVA Rescue (SAFER), the spacesuit assembly power harness, and the rechargeable EVA battery assembly (REBA). These are discussed in the topics that follow. The Shuttle EMU also gained a more safe and robust SSA with easy on-orbit resizing, an active glove-heating system, and more nimble/better fitting gloves. An additional topic elaborates on the enhanced EMU's passive heating system and its on-orbit regenerable CO_2 removal system, longer life battery, and a variety of lesser life support improvements.

Another facet of the enhanced EMU era was an organizational change. Previously, facets of NASA-JSC coordinated the separate contracts for EMU CEI manufacture/technical support, EVA communications/tools, crew training, and field processing of EVA hardware. In 2002, NASA started a process to merge these activities under one contract to improve efficiency and provide a single point of contact for management accountability. This culminated in September 2004 with NASA-JSC selecting Hamilton Sundstrand (HS) to be the prime contractor of all EVA activities such as spacesuit, all related tools and crew aids, training support, and on-site engineering. Under this new One EVA contract, HS, ILC Dover, Oceaneering Space Systems, United Space Alliance and Boeing will continue to support their roles but within a set of common goals with shared responsibility.

By supporting the ISS, the Shuttle EMU also gained more international usage. Japan purchased an EMU to support training and NASA permanently deployed two neutral buoyancy–type EMUs to Russia. Russian cosmonauts frequently became one of the EVA pair supporting ISS maintenance and assembly. Details of these efforts and the relatively short but already accomplished service record (discussed later and in Appendix A) indicates extensive use of the enhanced EMU as it supports NASA's EVA needs at the beginning of the 21st century.

System level enhancements

The first EMU enhancement to reach flight service was the Simplified Aid For EVA Rescue (SAFER). Progressing into the space station program, there was a need to have an EVA crewmember be able to return to ISS if tether restraint was lost and "float-away" occurred. Although the same predicament could be anticipated for the Shuttle, the Orbiter's ability to maneuver provides the capability for pursuit and rescue of a stranded crewmember. ISS, on the other hand, has no such capability, hence the need for a backup rescue system.

Although there had been many ideas for providing a stranded EVA crewmember with a personal rescue device ranging from Ed White's HHMU to a version of the MMU, a trio of Lockheed employees came up with the idea that ultimately became the Simplified Aid For EVA Rescue, or SAFER. In 1987, former astronaut Joe Kerwin had joined Lockheed as manager of the Extravehicular Systems project, providing hardware for Space Station *Freedom*. In 1988, Kerwin along with Charles H. Simonds and Gregory T. Christian, came up with the idea for a small, crew-worn jetpack and theirs was the concept chosen for SAFER.

SAFER is a very compact 2 ft.^{3} (57 L) when stowed and has a launch weight of only 65 lb (29.5 kg). SAFER has twin thruster towers that unfold to provide 24 fixed position thrusters at locations bracketing the suited crewmember's center of gravity for efficient attitude control and translation capability (Figure 10.3.1). SAFER made use of existing EMU attachment points precluding the need to redesign any EMU components to support SAFER implementation. SAFER's avionics system provides six degrees of freedom control with an automatic attitude hold feature that will stop a spinning and out-of-control astronaut at the push of a button. This system provides a 12 ft/s (3.6 m/s) delta velocity and permits nitrogen recharging and battery replacement during EVA. While NASA chose to design and manufacture SAFER, it used various contractors on key elements of the project. SAFER had the distinction of being the first EMU-related Space Station system to be flown.

The first SAFER flight was mission STS-64 on September 16, 1994 (Figure 10.3.2). In the words of astronaut Mark Lee, the first crewman to fly the SAFER, "It works like a champ." Control was judged to be very precise, and Lee said that he could turn "square" corners. Astronaut Carl Meade also flew the SAFER on this flight with excellent results, remarking that it flew better than the simulations.

While SAFER was originally designed to interface to the U.S. EMU, NASA and the Russian Space Agency (RSA) agreed in late 1995 that—in order to meet ISS safety requirements for all EVA hardware (U.S. or Russian)—a "Russian SAFER" was needed for the Orlan EVA system. A joint venture ensued that culminated in the development of a Russian SAFER in 2002 (discussed in Section 11.1.5).

The incorporation of on-orbit replacement units (ORUs) was a key feature of the Space Station *Freedom* advanced EMU that was canceled in 1990 in favor of using the Shuttle EMU with improvements (i.e., enhancements). ORU was an enhancement that was not initially funded for the operational EMU program. By 1992, the disadvantages of using the Shuttle EMU as-was configuration were becoming generally recognized. In 1992–1993, a study was conducted on ways to

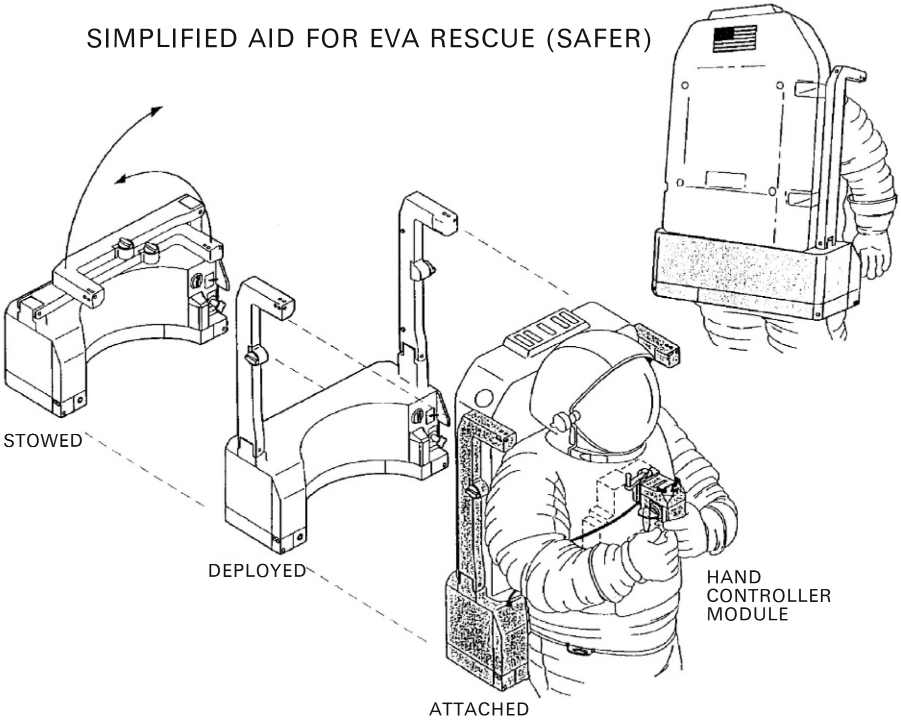


Figure 10.3.1. The Simplified Aid For EVA Rescue (SAFER) concept (courtesy NASA).

meet Space Station EMU-provisioning needs. The report noted that a malfunction of a primary life support system (PLSS), secondary oxygen package (SOP), display control module (DCM), hard upper torso (HUT), or arm could remove an entire EMU from service. This would multiply the number of spares required on the Space Station to support EVA.

The report concluded that the Shuttle EMU needed ORU capacity to meet the wall of EVA imposed by ISS construction and maintenance tasks. Life expirations of baseline configuration HUTs facilitated the implementation of this ORU system. The "pivoted" HUT of the baseline EMU was designed in 1978 for a 6-year useful life. To maximize use of existing hardware, the pivoted HUT was progressively life-extended by analysis, inspection, and testing in 1986, 1991, 1992, and 1994 to 8, 11, 12 and 14 years, respectively, before material limitations ended the extensions. In parallel with the life extensions, the development of a less expensive and more robust HUT was proceeding as part of the HS/ILC Corporation (ILC)/Air-Lock Corporation (A-L) EMU team. The redesign of the HUT greatly simplified the ORU interface process as it provided the volume needed for bolt-on adapters to the PLSS and DCM to be designed into the HUT along with the HUT-side ORU features. After evaluation of many concepts and HUT materials, a longer life ORU HUT with fixed ("planar") arm apertures was selected.

Figure 10.3.2. SAFER for enhanced EMU (courtesy NASA).

The "planar HUT" went through a prototyping and evaluation process resulting in an ORU system with redundant safety features and "trailer hitch" lower PLSS mounts for simplified change-out. The "trailer hitch" in this design consists of a mushroom-shaped PLSS-side mount that is captured by a slotted pocket on the back of the HUT. This allows the HUT to drop into place at the bottom and align for simplified attachment at the top.

Many factors made development of ORU a formidable task. The orbital change-out would have to be performed without specialized tools and fixtures that are common to field processing. PLSS to DCM cables and harnesses that are routed outside the HUT and under the TMGs provided additional complications. ORU implementation (Figure 10.3.3) was coordinated as part of the many parallel enhancement developments. Production training versions of the planar HUT and PLSS/DCM retrofit system were delivered in March 1996. The first Class I (flight-type) certification units were delivered on October 1996. The first

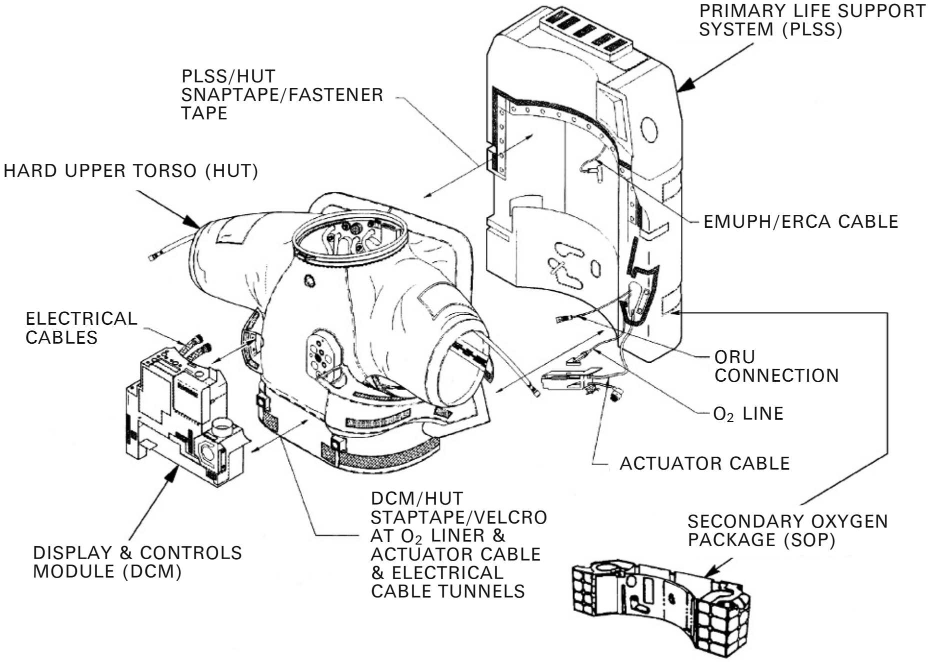


Figure 10.3.3. On-orbit replaceable unit (ORU) concept (courtesy Hamilton Sundstrand).

Class I flight HUT and retrofit kit followed in December of that year. Planar HUTs and ORU kits entered flight service with mission STS-88 in December 1998 (Figure 10.2.11).

NASA also elected to design the spacesuit assembly power harness and rechargeable EVA battery assembly (REBA). The EMU internal battery had no power to spare for the glove heaters, so support of the heated glove (heated glove TMGs) required a power cable and a battery location somewhere on the "body" of the EMU and provided the initial need for the spacesuit assembly power harness. As helmet lights and the helmet TV camera had separate battery systems and both were being redesigned, NASA chose to power all three remotely from the NASA-designed REBA (Figure 10.3.4). The REBA is located on the bottom/back of the PLSS/SOP above the SAFER (Figure 10.3.15) and was designed to fit in a TMG pouch originally created to house the never implemented ion exchange bed discussed previously.

In the enhanced era, EMU operations would not be limited to the U.S. To support Russian training and U.S./Russian technical discussions, NASA deployed two of the semi-enhanced EMUs to the Gagarin Cosmonaut Training Center near Moscow. "Semi-enhanced" denotes that the EMUs were baseline units that were modified and partially upgraded to feel and work like enhanced versions.

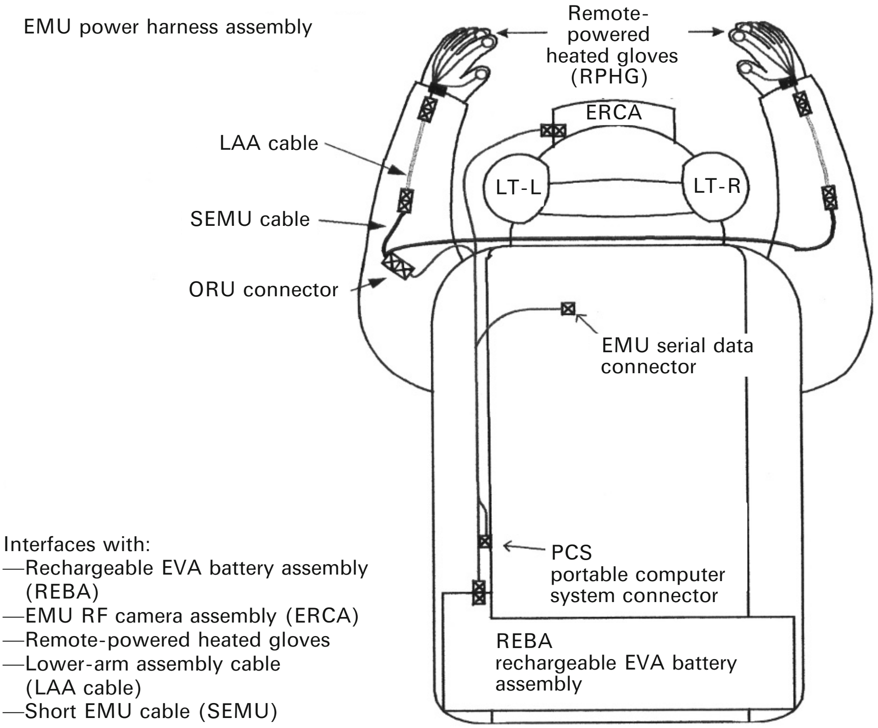
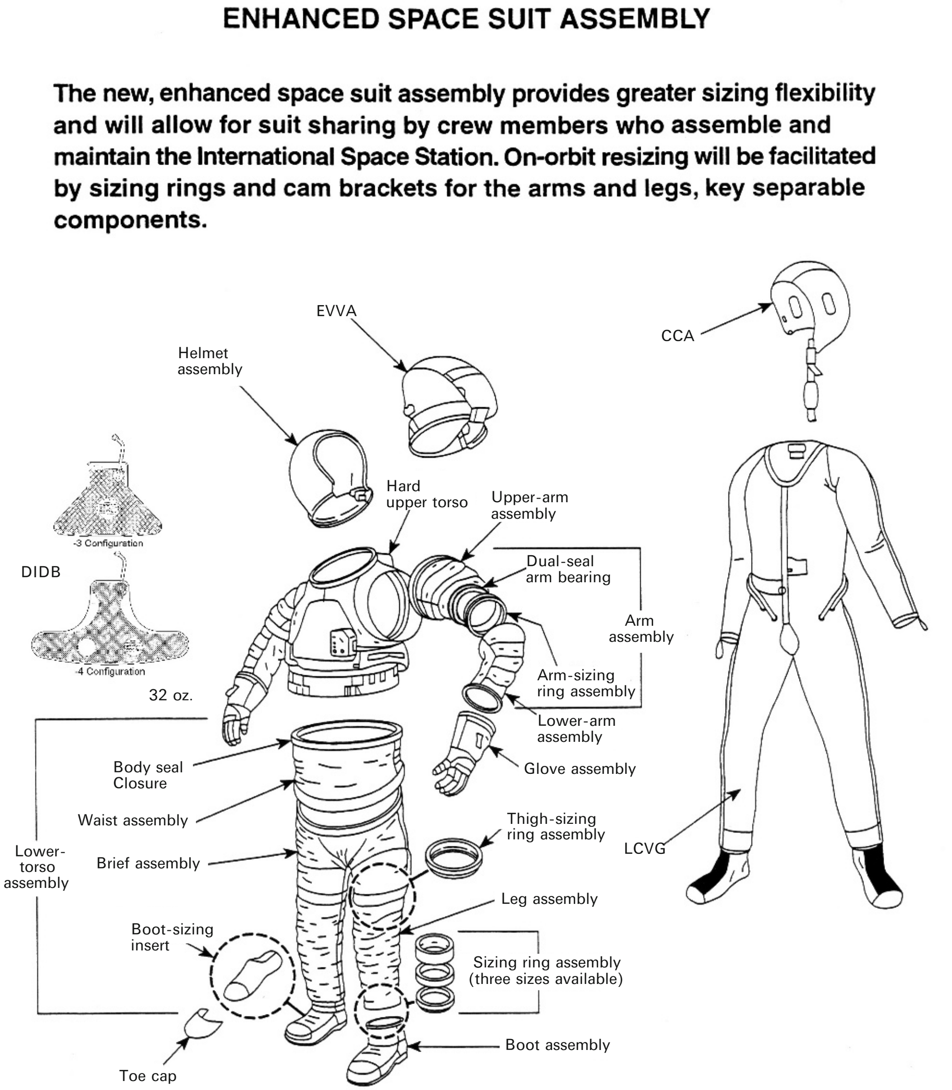


Figure 10.3.4. EMU power harness and REBA diagram (courtesy Hamilton Sundstrand).

Pressure suit enhancements

Spacesuit assembly (SSA) enhancement design and development (Figure 10.3.5) were conducted under the HS/ILC/A-L EMU contract. For the enhanced SSA, the glove thermal/micrometeoroid garment (TMG or outer glove), the pressure glove (the inner glove in the glove assembly), the arms, lower torso assembly (LTA), hard upper torso (HUT, previously discussed), and in-suit drink bag were all redesigned to better support the ISS.

The glove TMG evolved into a "low-torque" configuration with electric heating as an alternate option. From 1979 to 1994, the method of controlling object handling in extreme cold was the use of thermal overmittens that could be installed over the glove TMGs during an EVA. In space, without physical contact with another object, all heat gain or loss is through radiation. However, holding an object provides a direct conductive path for heat loss, not unlike holding an ice cube. In direct sunlight, the exposed areas of objects absorb energy and expand. In shade, objects cool and contract. To maintain dimensional control, orbital satellite maintenance and International Space Station (ISS) assembly procedures have increasingly been performed in shade or during the "night-side" of orbits where temperatures can reach −140°F (−95.5°C). Performing assembly operations with bulky overmittens would have been an impediment. In recognition of this, ILC internally funded the



ENHANCED SPACE SUIT ASSEMBLY

The new, enhanced space suit assembly provides greater sizing flexibility and will allow for suit sharing by crew members who assemble and maintain the International Space Station. On-orbit resizing will be facilitated by sizing rings and cam brackets for the arms and legs, key separable components.

Figure 10.3.5. Enhanced EMU/SSA diagram (courtesy Hamilton Sundstrand).

development of a heated glove prototype during the summer of 1994. This prototype featured heating elements attached to the fingertips (in the area of the fingernail) of the glove's thermal/micrometeoroid garment (TMG) with a switch and battery pack located on the exterior of the TMG at the back of the hand. This permitted crewmembers to turn the heating elements on and off manually. The low-torque TMG element in this design revised the palm area to reduce bulk and effort when grasping tools or working controls.

Figure 10.3.6. Heated glove TMG and Phase VI pressure glove (courtesy, left and right, NASA and G. L. Harris, respectively).

A proof-of-concept glove was further developed and tested under NASA funding in 1994–1995. This detailed test object utilized off-the-shelf components to reduce development costs. The test glove successfully completed chamber runs at NASA-JSC and performed flawlessly during an evaluation on flight STS-69 in September 1995. The disadvantage of this system was battery pack bulk affecting wrist mobility. Thus, the glove-mounted batteries were eliminated in favor of a (suit location) spacesuit assembly power harness (Figure 10.3.6, left). However, this was not the only glove enhancement.

In 1989, there was an attempt to bring developments from the Space Station *Freedom* advanced (SSF) EMU glove (Figure 11.1.3.5) into the Shuttle EMU program as the 5000 series glove. Development of the 5000 series included a low-torque pressure glove thumb and TMG over glove. The goals of the 5000 series were to be optionally upgradable to higher operating pressure glove systems and improve EVA crewmember performance.

The 5000 series glove was flown and evaluated by one of the EVA crewmembers on Shuttle mission STS-37 in April 1991 as a detailed test objective under limited certification. The in-flight evaluation was disappointing, in that the fingers on the left glove were too tight, causing some numbness, which lasted for a period after EVA.

There was also some bladder bunching, which aggravated the problem. Another glove problem occurred with the other EVA crewmember's 4000 series right glove. It was discovered after EVA that the right-hand glove's palm bar—which can be bent to reduce ''ballooning'' of the palm area, and also provides a fold in the bladder and restraint for grasping—had become misformed to create a protrusion that actually wore through the restraint and bladder layers and into the crewmember's hand. Corrective measures included protective stitching to prevent penetration.

While the 5000 series did not reach flight service, hybrid 4000/5000 series options were discussed. One by-product of the 5000 series that came to fruition was the optional use of the more flexible and tactile low-torque glove TMG with the 4000 series pressure glove. This was first flown in May 1992 on STS-49 and later became a crewmember option for all 4000 series flight gloves. Gloves utilizing this hybrid configuration were designated 4750. STS-49 astronaut Kathy Thornton, who wore gloves with the 4750 TMG, commented after the flight that she was pleased with the modification and that her hands did not get tired.

After the EMU program had elected not to implement the 5000 series glove, ILC continued internally funded development of the system in the belief that it was needed to facilitate ISS assembly. The glove that would ultimately result from this continuation would be named the ''Phase VI'' as the configuration represented the sixth phase in a continuing glove development.

The Phase VI glove differed principally from the 4000 and 5000 series in that it was the first EVA glove to be developed completely using computer-aided design. This results in a faster development cycle, higher accuracy, and lower cost. As part of this effort, ILC developed a laser scanning process that provides a three-dimensional database of a crewmember's hands, which can quickly and inexpensively produce molds for conformal fit. The 3D model can easily be adjusted to obtain optimum fit. Conformal fit provides minimum volume, thus reduced effort to perform work. The Phase VI utilizes pleated, lightweight polyester restraint fabric. The fingers and thumb mobility joints are designed as all fabric assemblies to decrease torque and increase fingertip tactility. A one-piece urethane bladder design exhibits less wrinkling than preceding designs when integrated into the glove, thus significantly improving fit and performance. Additional features include a lower torque wrist bearing and an enhanced rolling convolute wrist joint using a Russian Orlan-style two-gimbal ring system. This provides reduced effort in use and has improved producibility through reduced wrist complexity of design as compared with the 5000 series wrist. The Phase VI pressure glove (Figure 10.3.6, right) also utilizes a revised attachment method for rapid change out of the TMG on orbit.

The first flight of the Phase VI glove was STS-88 (December 1998) under a single-mission certification to permit evaluation. Phase VI entered fully certified flight service with STS-99 (February 2000). Under the Phase VI implementation, EVA crewmembers named for flight are fitchecked in ''close fit'' gloves that have been customized for other crewmembers. Some excellent fits have been achieved, thus eliminating the need to create a custom glove for many.

Enhancements to the LTA and arm assemblies started with three goals. The first and principal goal was to enhance on-ground and in-orbit sizing changes. This was

Figure 10.3.7. Comparison of enhanced (left) and baseline (right) SSAs (courtesy Hamilton Sundstrand).

to be accomplished by removable sizing rings and adjustable brackets on the waist (Figure 10.3.7, left). The second goal was to further reduce operating torque. This was to be accomplished by reducing the bearing torque and modifying the softgoods with Spectra webbing and improved patterning. The third goal was to increase bearing pressure seal potential safety/reliability by moving from single-seal bearing designs to dual-seal systems. This provided backup rotating bearing seals throughout the SSA to perform the function were a primary seal ever to fail.

The original enhanced SSA plan was to create four sizes of hard upper torso (HUT) and lower-torso assembly (LTA) body seal closure (BSC), as had been implemented in the baseline EMU. However, this came at a period when NASA was actively working with the Russian Space Agency. The Russians have but one on-orbit adjustable base size of EVA suit system. The Russian approach is to select potential EVA cosmonauts on the basis of their ability to work effectively in the provided EVA suit. This and Space Station budgetary constraints led to a revision in sizing philosophy and EVA crewmember selection. By 1994, NASA had elected to proceed with two base sizes of HUT utilizing one LTA BSC size to minimize LTA subelements. The two remaining sizes of HUT were dimensionally adjusted to support a broader anthropomorphic range that additionally supported some users who would have otherwise been eliminated by size. However, this did not resolve sizing issues entirely.

The physical advantages of extra-large crewmembers in station assembly tasks caused the baseline extra-large size EMU to see ever greater service in the late 1990s. NASA elected to implement a compromise extra-large enhanced-style HUT that utilized the same arm and LTA as the medium and large enhanced HUT. The first enhanced SSA extra-large HUT entered flight training in 2000. A small-size enhanced SSA was reconsidered and development was briefly funded. The unique pressure suit constraints imposed by subjects with shorter arms and torsos was resulting in specialized sizes and mobility elements. Also, station-related systems had been designed during the two-HUT-size period around longer arm reach. These factors combined with funding limitations resulted in termination of the "small EMU" before it reached completion of development and certification.

Also in 1993–1994, redesign of seal materials and bladder construction were added to the enhancement process. The lives of polyester/polyurethane pressure seals in disconnects and bearings were successfully increased from 3 years to 8 years by a chemical enhancement process. Arm and LTA bladders were extended from 6 years to 8 years with the exception of the waist assembly of the LTA. This area is limited to 6 years due to cemented reinforcement flanges and tapes.

The benefit of the modular EMU system is that SSA enhancements could be and were rotated into service as replacements for expired flight items and as flight opportunities for processing and on-orbit practice became available. The first flight of EMUs featuring enhanced arms and LTAs was STS-79 in September 1996. The first on-orbit use of the resizing capability came in February 1997 with STS-82.

For the enhanced EMU, the in-suit drink bag was transformed into the disposable in-suit drink bag. This started with an ILC analysis of the cost of ground processing of the in-suit drinking bag. The study indicated that it was less expensive for NASA to throw away a disposable in-suit drink bag than to ground-refurbish an in-suit drinking bag. To maximize storage before use, to support the long-duration ISS missions, and to maximize the use of training disposable in-suit drink bags, these were designed to be filled and potentially refilled on orbit. The disposable in-suit drink bag entered flight service in October 2000 aboard STS-92.

Life support enhancements

The first life support system (LSS) enhancement to reach flight was the passive suit-heating technique named the "LCVG by-pass". From the beginning of EVA in the 1960s, spacesuit insulation of aluminized Mylar effectively provided protection from the extreme temperatures of space and the Moon (+257°F to −130°F). This traditionally left a problem with the removal of metabolic heat from the suit. As mentioned in "Changes in requirements and further EMU development (1977–1983)" (see p. 282), the EMU cooling system had been designed to accommodate hot case conditions, more than cold situations. Starting in the 1990s, there had been an EVA trend to conduct servicing and repair activities in cold environments. This coupled with the colder ISS environment made keeping the crewmember comfortably warm an issue. The solution was deliberate retention of body and electrical component heat. The LCVG by-pass had been a provision of the Skylab cooling system approach, which let coolant by-pass the suit. However, adapting this to the Shuttle EMU was a challenge.

To conserve volume and simplify systems, the Shuttle EMU had originally been designed so that the astronaut and electronics were cooled in the same cooling loop. While the astronaut cooling was adjustable by means of the temperature control valve (TCV) on the front of the DCM, there was always a minimal flow through the entire system to provide minimal electronics cooling. This made cold situations slightly colder for the astronaut. The LCVG by-pass solution was to retrofit EMUs with TCVs that allowed 100% shutoff of the astronaut LCVG cooling flow and the installation of a thin adapter plate between the PLSS and HUT. The adapter plate featured a by-pass port that allowed cooling water flow to EMU electronics when the TCV was turned to full off. The TCV change and adapter plate installation were both easy, screw-on, field retrofits. The retrofit allowed the suit to capture and retain the crewmember's body heat as a passive heat sink.

The LCVG by-pass flew on STS-69 (September 1995) and STS-72 (January 1996) for systems tests. The results were so positive that the LCVG by-pass became flight-mandatory (under limited certification) with STS-85 in July 1997. Full 15-year life certification was conducted in parallel and completed in February 1998.

The next LSS enhancement to reach flight was the increased capacity battery. The initial baseline era Shuttle EMU silver oxide/zinc battery was designed and certified for a 90-day activated life. Through the acquisition of data over the years, this had been expanded to a 170-day operational life and six charge cycles. However, even this increase in life would not support ISS needs. The solution was the increased capacity battery (ICB), which also used the proven silver oxide/zinc technology. The ICB was designed and certified for 32 charge cycles, a 425-day operational life once activated, and a 15-year dry shelf life. The challenge of the new and larger battery was that it must fit into the PLSS without redesign of other PLSS components or cause interference with the walls of the airlock when stowed or in recharge/donning. Increased launch loads added to the technical challenges of the ICB container and system. The challenges were met and the ICB for the ISS saw its first flight on STS-100 in April 2001.

Yet another LSS enhancement was the metal oxide "METOX" regenerable CO_2 removal system. In November 1995, ISS mission projections indicated that 70 baseline EMU, ground-refurbishable (but not in–orbit regenerable) LiOH-based contamination control cartridges (CCC) would be required to support ISS assembly. This would impose significant processing costs and flight storage penalties. NASA competed a contract for a regenerable ISS CO_2 removal system. In January 1996, HS won the competition with a proposal for a minimum development system (Figure 10.3.8) using metal oxide (METOX) CO_2 sorbent, which was a

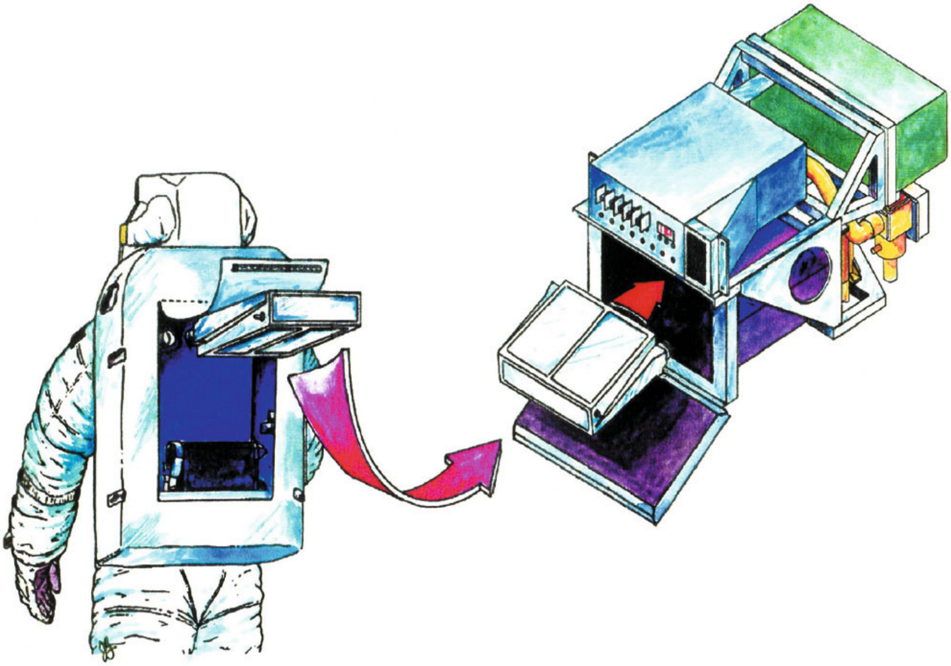


Figure 10.3.8. METOX regenerable CO_2 removal (courtesy Hamilton Sundstrand).

system adaptation of the SSF advanced EMU technology system, the metal oxide regenerative extravehicular system (MORES). This effort principally consisted of creating an EMU-compatible canister and an airlock-compatible regeneration unit.

The regenerable METOX canister was designed to meet the more stringent ISS metabolic profile for CO_2 generation and trace contaminant removal from the ventilation loop during EVA. By design, the canisters could also be used for CO_2 removal in the ISS airlock during unsuited "camp-out" at reduced pressure for denitrogenation. The METOX canisters include a state indicator that provides visual verification as to whether the canister is fully regenerated or used, thus guarding against the reuse of a CO_2 removal canister, as had been the case during STS-51I. The canisters have been certified to remove at least 1.48 lb (0.5 kg) of CO_2 per cycle for a minimum of 55 cycles.

The METOX regenerator was designed for use in the ISS airlock to regenerate up to two METOX canisters at a time. Regeneration of the canisters takes 10 hours to complete. The METOX systems finished flight certifications in May 1998. The first flight of this system was mission STS-101 (ISS assembly mission 7A) in May 2000.

Beyond ORU, LCVG by-pass, ICB, and METOX, there were also upgrades and improvements to the primary life support system (PLSS) such as an infrared (IR) CO_2 sensor, 25 EVA life extensions or upgrades, filter enhancements, an assured EMU availability (AEA) component life extension program, and an enhanced caution and warning system. Infrared CO_2 sensor technology was selected due to its stability and accuracy.

The EMU was originally certified for three EVAs between ground servicing. Preliminary estimates for the ISS indicated that as many as 25 EVAs could be needed from a given set of EMU life support system hardware while on orbit. The ISS's need for an on-orbit capacity for one year or 25 EVAs without any ground service activity was met through life extensions or component upgrades when required. This effort was completed in 1992.

Sizes considered and incorporated

For the baseline EMU, five sizes of hard upper torso (HUT) with an assortment of ancillary spacesuit assembly (SSA) components were designed, but only four sizes of EMU were implemented into flight due to cost considerations. At the start of EMU enhancements, four sizes of EMU were originally planned but, early in the process, NASA directed that two sizes be implemented (medium and large) to reduce implementation costs. Due to a significant portion of the astronaut cadre being extra-large, extra-large HUT sizing was reintroduced before the enhanced EMU reached flight. Astronauts needing a size small to be an EVA mission specialist campaigned for the reintroduction of the size small. In 1999, this was evaluated by NASA. The additional SSA inventory cost and the resulting impact on providing hardware for the greater number of larger people caused size small to be dropped from consideration.

While size small was under consideration, NASA elected to contract Global Effects, Inc. (known for rapid fabrication of spacesuit replicas for the film industry) for a parallel small EMU HUT prototype effort featuring innovative concepts. The president of Global Effects, Chris Gilman, had extensive experience in fitting various types of protective systems to the human body. Gilman in turn solicited the collaboration of Dennis Gilliam. Gilliam is a spacesuit historian and aerospace engineer/manager. NASA ground rules for the project were that only the HUT and helmet were to be redesigned. The redesigned HUT had to interface with existing Shuttle EMU components such as arms, lower torso assembly, PLSS, and DCM. Additionally, the redesigned HUT had to meet a critical front-to-rear dimension, which allowed the suited crewmember to utilize a contingency Shuttle ingress method.

In eight weeks, the Gilman/Gilliam team designed and manufactured a HUT design that utilized a novel configuration of shoulder bearings, which effectively permitted movement of the location of the arm opening in the HUT shell as the astronaut moved his/her arm. This design allowed the HUT to self-adjust to closely fit each crewmember. Additionally, an internal sizing system was added which provided the astronaut the ability to reposition his/her body within the HUT without opening the HUT. Integration of a hemispherical helmet into the HUT eliminated the restricted downward and overhead visibility of the Shuttle/Apollo heritage helmet dome. A unique sunvisor concept allowed full coverage of the hemispherical dome and stowed in a position that still provided unrestricted

Figure 10.3.9. The Gilman & Gilliam small EMU prototype (courtesy Global Effects, North Hollywood, CA).

upward visibility. The sunvisor assembly with protective impact shield was designed to be on-orbit replaceable. Since the HUT size is not a function of pressure, there was no need to develop a pressurizable HUT for evaluation of the redesigned suit. This also permitted low-cost mockups of the soft parts of the suit to be utilized (Figure 10.3.9) since they were not part of the HUT sizing and visibility range evaluation. Although the HUT was not designed to be pressurizable, a ventilation system was incorporated in the design to provide vent air circulation for the comfort of the test subject evaluating the suit. The resulting analog suit system was presented to NASA in January 1999 for evaluation. Although it was favorably received, NASA pursued no further development.

In 1999, the small size enhanced EMU was again dropped from consideration by NASA ending all other developments.

Japan's purchase of a U.S. EMU

Japan is a major participant in the International Space Station (ISS), providing the Japanese Experiment Module. As part of its space program, Japan constructed an entire city dedicated to the manned exploration of space. One facility in this complex is the Weightless Environment Test System (WETS) Facility (Figure 10.3.10) for Japanese neutral buoyancy simulations (Figure 10.3.11). For this, Shuttle EMUs were initially leased or borrowed. Under contract to Kawasaki Heavy Industries (KHI), HS/ILC were responsible for the manufacture/fabrication of Japan's first spacesuit, which was a semi-enhanced training version of the Shuttle EMU. This "semi-enhanced" EMU uses the enhanced era planar HUT but baseline arms and LTA to provide the fit and feel of the enhanced version while balancing budget constraints.

While elements within NASDA (then Japan's space agency) wished to purchase a full second WETS EMU, budget limitations did not make this possible. Instead, NASDA purchased enough EMU CEIs to assemble either a size medium or a size

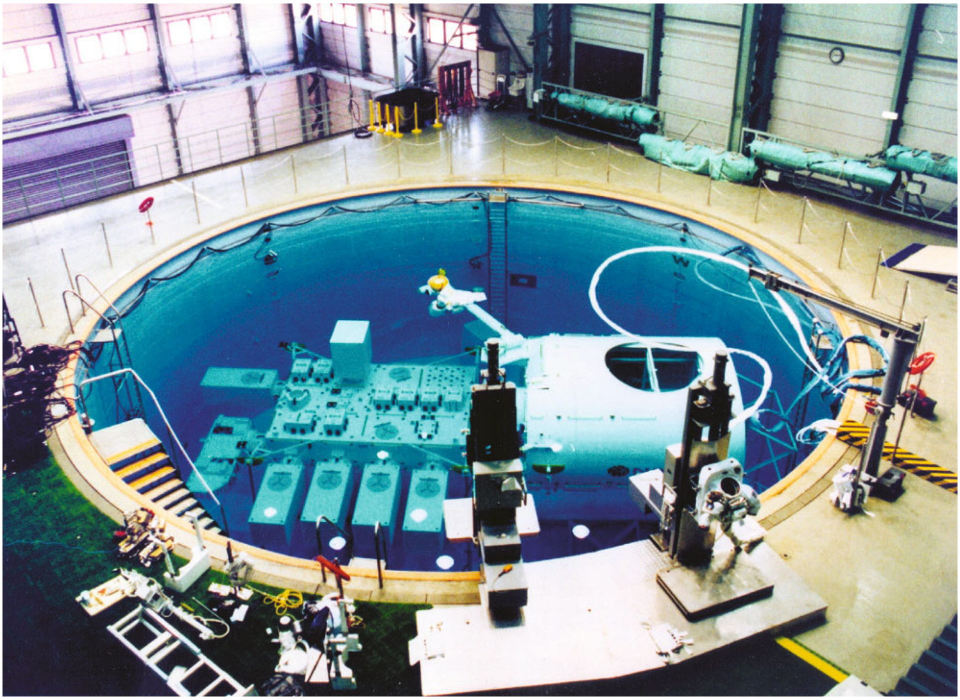


Figure 10.3.10. JAXA Neutral Buoyancy Facility (courtesy Hamilton Sundstrand).

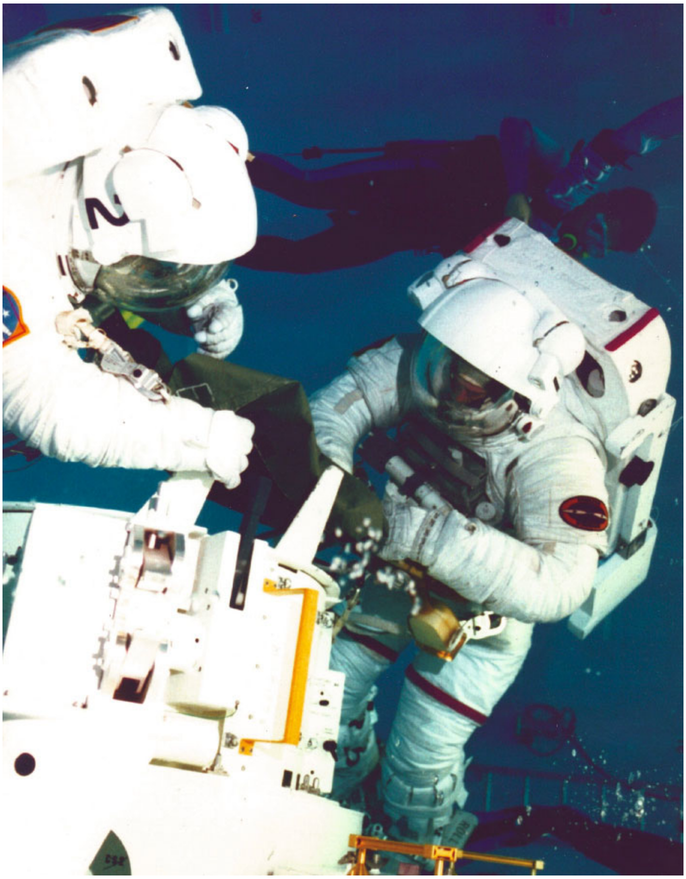


Figure 10.3.11. Training in JAXA's facility (courtesy Hamilton Sundstrand).

large. For a second EMU, the Japanese Space Agency relies on borrowing from NASA or leasing a second EMU from Hamilton Sundstrand. On October 1, 2003, NASDA was redesignated the Japanese Aerospace & Exploration Agency (JAXA).

Enhanced EMU flight experience

The enhanced EMU has already distinguished itself as a key component of ISS assembly. With over a score of ISS flights and three Hubble servicing missions, the enhanced EMU has logged 7,000 man-hours of training and supported over 1,650 EVA man-hours in space. While these EVA missions seem to have become almost routine, there are some that stand out.

The unity module (Node 1) mission was the EVA debut of the fully enhanced EMU (Figure 10.3.12). Known to the ISS program as mission 2A and to the Shuttle

Figure 10.3.12. 1998 enhanced EMU on first ISS assembly mission (courtesy NASA).

program as mission STS-88, this December 1998 effort joined the 22 ft. (6.7 m) long and 15 ft. (4.6 m) diameter Unity to the 41.2 ft. (12.6 m) long and 13.5 ft. (4.1 m) wide Zarya module. Zarya with its two 35 ft. long (10.7 m) and 11 ft. wide (3.4 m) solar arrays was launched from Baikonur in Kazakhstan the month before. This merger was the start of the ISS (Figure 10.3.13).

For the next 3+ years, EVAs were frequently performed using a mixture of baseline and enhanced EMUs. All told, 17 EVAs were carried out with one baseline and one enhanced EMU. This was initially a deliberate exercising of caution coupled with a desire to gain comparative experience with the new systems. However, the baseline configuration continued to see use due to either hardware availability or crewmember preference relating to the greater number of sizing options or familiarity.

Figure 10.3.13. 1999 STS-103 Hubble servicing (courtesy NASA).

ISS assembly was not the only space work that Shuttle EMUs supported during this period. After just one ISS EVA mission to provide equipment and supplies, the next mission was another Hubble servicing activity, STS-103 in December 1999. All three STS-103 EVAs lasted over 8 hours and used a mixed baseline/enhanced pair of EMUs (Figure 10.3.13). Thanks to crewmember training/dedication and hardware performance, this activity took on the appearance of a normal workday elsewhere.

Starting with the year 2000 through February 2002, the EMU supported 11 ISS missions with 23 EVAs. These EVAs made final attachments of major structural members, such as the U.S. laboratory named Destiny, and a great variety of station systems in preparation for and later in support of human habitation of ISS. EMUs additionally supported securing supplies and equipment in temporary storage locations on the exterior of ISS. While this working in space may have begun to seem commonplace, the lack of problems adds testament to the value of Shuttle EMU and EVA systems in general. This period saw the first all enhanced EMU EVA (STS-101 in May 2000) and the raising of the EVA duration bar. This started with a climb of EVA time that culminated in the second Apollo 17 EVA where Cernan and Schmitt logged a world record 7-hour 37-minute exploration sortie. This lasted as the longest duration mark until 1992 when mission difficulties resulted in three astronauts going out to manually retrieve a satellite on STS-49. To accomplish stowage of satellite and tools, the EVA lasted 8 hours and 29 minutes. This was surpassed on ISS mission 5A.1/Shuttle mission STS-102.

On the first EVA of Shuttle mission STS-102/ISS mission 5A.1, newly delivered Expedition 2 crewmembers James Voss and Susan Helms performed an 8-hour 56-minute EVA, which reset the world record (Figure 10.3.14). This beyond-nominal-duration EVA was accompanied by careful ground monitoring of EMU

Figure 10.3.14. 2001 James Voss and Susan Helms (pictured) set new EVA duration record (courtesy NASA).

expendables and EVA crewmember condition. By allowing this extra duration, the astronauts prepared a large pressurized mating adapter (PMA) structure to be moved from the Unity module to make room for a multipurpose logistics module. The multipurpose logistics module is an ISS pressurized cargo vessel. This module would carry equipment to outfit the U.S. laboratory for use. This space version of musical chairs also required Voss and Helms to remove an antenna from the common berthing mechanism to make room for the PMA to be temporarily stowed there while the multipurpose logistics module was connected to the ISS for unloading. This EVA also performed the removal of a lab cradle assembly from the Shuttle's cargo bay and its installation on the side of the U.S. laboratory. The lab cradle assembly mounted on the U.S. laboratory forms the base for a giant robotic arm/crane structure that would be delivered on the next Shuttle mission—STS-100.

STS-100 not only added to the Shuttle/ISS accomplishments but also reflected the good humor that is typical of EVA crewmembers. Windows in spacecraft are typically used for viewing out. However, during an idle moment on STS-100, Scott Parazynski demonstrated that this is not always the case (Figure 10.3.15). Also during this period, the Space Station's joint airlock arrived on STS-104 (ISS 7A) in July 2001.

The joint airlock was designed to support both U.S. and Russian spacesuit systems. This capacity enabled the ISS to continue assembly activities and

Figure 10.3.15. 2001 STS-100 Astronaut Scott Parazynski at window (courtesy NASA).

Figure 10.3.16. 2001 Mike Gernhardt (pictured) and Jim Reilly make first EVA from the ISS (courtesy NASA).

perform routine station maintenance without a Shuttle being present. The obstacles to developing a joint airlock were formidable. The Russian and U.S. EVA suit systems have different shapes, interfaces, and oxygen/water/electrical recharge requirements. To overcome these challenges, NASA drew heavily on the U.S. contractor community and worked in unison with the Russian Space Agency. On July 20, 2001 with the third and last EVA of STS-104, Mike Gernhardt (Figure 10.3.16) and Jim Reilly had the distinction of initiating the first EVA from the ISS as a verification of the joint airlock.

The presence of both Russian and U.S. spacesuits aboard the ISS not only permitted an alternative should one configuration have servicing or technical issues but also one of convenience. As the two suit systems were typically stored in different airlocks, the suit selected was at times a function of where on the ISS an external activity had to be performed. Due to many factors including the regenerability of the enhanced EMU's carbon dioxide removal system, the U.S. suit system

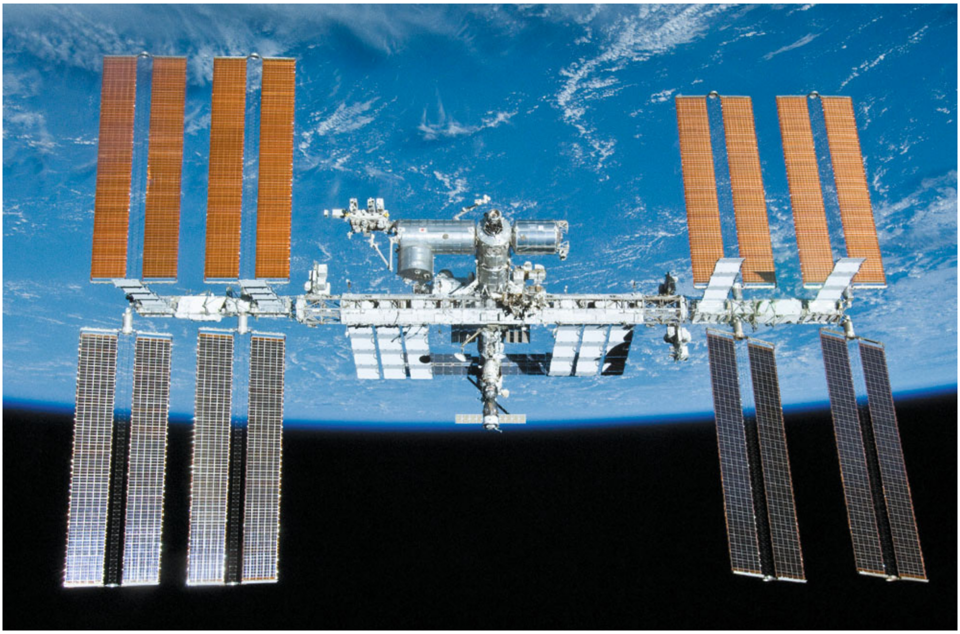


Figure 10.3.17. 2010 STS-132 leaves a completed ISS (courtesy NASA).

would prove to be the most used system that supported the growth of the ISS. Shuttle mission STS-132 in May 2010 delivered an integrated cargo carrier and the Russian-built Mini-Research Module-1 to complete the ISS (Figure 10.3.17), the world's largest space structure (Figure 10.3.17).

Enhanced EMUs have also played a significant role in Hubble-servicing missions. Hubble was the world's first satellite designed to be serviced in space. The servicing missions were part of the Hubble's operating plan from the outset. There were five missions in all. The third, on STS-103 in December of 1999, saw the introduction of the enhanced configuration in Hubble support. Specifically, three of the four astronauts performing the servicing activities used enhanced EMUs. The last two Hubble missions used exclusively enhanced EMUs. Thanks to the servicing ability, the Hubble was upgraded with technologies that were not available when it was originally launched. Designed for an operational life of 15 years based on servicing, Hubble should have passed into history in 2005. Thanks to the last servicing mission in May of 2009, Hubble is expected to continue expanding human understanding of the universe until 2014 or more.

The enhanced version of the Shuttle/Space Station EMU has supported over 44% of the world's extravehicular activity since the beginning of manned spaceflight. After completion of the ISS and Shuttle retirement in 2011, the enhanced EMU is scheduled to continue supporting routine external maintenance aboard the ISS until at least 2020. So, this percentage of enhanced EMU usage in EVA can only grow more significant.

10.4 SHUTTLE EMU SUMMARY

Gemini EVA systems used an intravehicular suit with add-on insulation and a mixture of open and semi-open purge umbilical systems for ventilation, pressurization, cooling, moisture removal, and CO_2 control. Apollo used an entirely different technique, relying on custom-fitted suits made for extravehicular activity and a self-contained backpack with water cooling for life support and environmental control. After only a few uses, the backpacks would be left on the lunar surface. Skylab returned to the umbilical approach, but added Apollo's water-cooling feature and adopted a modified version of an Apollo suit. Thus, a pattern of system design approach based on lessons learned and use of proven equipment was established. Another characteristic of past programs had been their predictable duration and sequence. One ended as the next was being developed. This changed with the Shuttle and ISS EVA equipment programs.

The Shuttle adopted the self-contained backpack approach of Apollo, but chose a mix-and-match suit component approach to accommodate a rich variety of potential crew sizes. The backpack was compactly designed, with multiple reuse over years of service.

When the International Space Station (ISS) became a reality, the previous pattern of selecting mostly new suit and life support system designs was changed. The inherent margin in life support system performance and service life, along with its ability to accommodate technology upgrades—such as the METOX regenerable carbon dioxide (CO_2) canister with minimal impact—meant that the same basic EMU life support system could serve both programs. The modular design of the pressure suit with its rugged design provided the same capability. Shuttle EMUs were used to develop the techniques used to assemble the solar system's largest man-made satellite, the International Space Station (Figure 10.3.17) and was the suit system principally used in that assembly. The five EMU-supported Hubble-servicing missions made years of incredible pictures of the cosmos possible. In 90% of the U.S. and over 61% of the world's spacewalks, the people working in the hostile environment of space wore this type of EMU. Since NASA is planning to keep the Shuttle/Space Station EMU operational to at least 2020, this record of accomplishment is far from over.

11

The quest for future extravehicular activity and planetary exploration

As humans go forth to explore the solar system, what challenges will designers and users of spacesuits be facing? What will be the missions and operating conditions? A spacesuit system design approach is a response to a need. If the mission is in zero gravity and EVA is being initiated from an Earth-like 14.7 psi (1 atm) environment such as that of the International Space Station, weight is less of a constraint. However, a requirement for no oxygen pre-breathe and the ability to communicate information in real time might be essential to a rapid emergency response. Vehicles and bases for lunar, Martian, or other celestial body surface missions will most likely need to have lower habitat pressures than Earth to minimize launch weight and long-term leakage rates. This favors lower operating pressure suits that make lighter weight and greater mobility easier to achieve. Working environments like those encountered on the Moon and Mars will require durable and robust systems that can operate in extremely dusty conditions. On Mars, greater-than-lunar gravity, the presence of windborne dust, and convective heat transfer provides additional challenges to weight, reliability, and function. Missions to asteroids or the moons of Jupiter will also have their unique requirements that will shape suit system requirements. For distant voyages, launch weight and storage volume may be driving considerations. Suit systems to support these requirements are yet to be developed. The early U.S. and Russian space programs used one suit for both launch/entry and extravehicular activity. Both the U.S. and Russian space agencies adopted separate suit systems once launch vehicle development could support the additional weight and volume of two systems. Is it possible to develop one system to effectively do it all?

Then there are the inherent constraints to space programs. A human space program includes a vehicle system or a space station. The budget challenges to such an endeavor are tremendous and a spacesuit system is but one supporting part. Programs have historically financed spacesuit capabilities to the specific minimal needs of the program. The more challenging the requirements, the more

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likely the resulting systems will be more expensive and take longer to implement. Challenging requirements may also result in system complexity, which can adversely affect reliability and durability. These considerations tend to drive a minimalist approach.

Development of a new space suit system or systems is always just one supporting piece in NASA's plans for the future. NASA's plan to retire the Space Shuttle and develop in its place a new vehicle system created a need for a new suit system or systems. In August 2006, this new launch and vehicle system gained the names Aries and Orion, respectively. Like Apollo/Saturn, Orion/Aries was to have Block I and Block II configurations. The Block I Orion capsule was to carry six astronauts atop an Aries I "crew launcher" to provide access to the International Space Station (ISS) by 2014. The Block II Orion capsule part of the system was to include an Orion Service Module, a larger Aries V "cargo launcher", an Earth departure stage "booster" and a Lunar Surface Access Module for missions to the Moon by 2020. NASA had further plans to build on the Block II system for a manned flight to Mars by 2030. All these activities required spacesuits.

In the past, there has been significant cost involved in the launch of a few people into space for a relatively few days. Consequently, every space activity, especially extravehicular activity (EVA), was extensively rehearsed for weeks or months on Earth to maximize the efficiency for the actual time-constrained performance in space. With the ISS, people from many nations are currently living and working in space. With ever increasing frequency, people in space are being asked to respond to challenges without preceding terrestrial practice. In the future, there will be even less opportunity to train for events in advance as humans move to explore and work in environments that we have yet to experience. The ability to convey information and provide tools/supplies will be increasingly more important as responding to the unforeseen becomes even more commonplace.

For the Constellation Spacesuit System (CSSS), NASA elected to assume the lead in creating its vision of an adaptable spacesuit system to support this new era of space exploration. Specifically, NASA chose to be the systems integrator, just as NASA had been in Mercury, Gemini, most of Apollo, and all of Skylab. In 2009, Project Constellation progressed to a successful launch of a launch vehicle first-stage prototype. However, in 2010, the Obama administration elected not to include the constellation program in 2011 funding. While the timetable for the U.S. returning to the Moon and progressing onto Mars has become unclear, the story of spacesuit development and desire for human deep-space exploration continues.

11.1 ZERO-GRAVITY DEVELOPMENTS THAT CONTINUE TO INFLUENCE

Since 1979, many next-generational efforts or cooperative studies have been conducted by many organizations. These efforts principally reflected NASA's then current vision of the next step in manned exploration—specifically, the functional needs of the intended mission use. With the first concepting of the Shuttle extravehicular mobility unit (EMU) in the early 1970s, there was a desire in a large part of the U.S. spacesuit technical community for an 8.0 psi to 8.3 psi (55 kPa to 57 kPa) operating pressure. This was due to U.S. studies indicating that a person could decompress from the expected Shuttle cabin pressure of 14.7 psi (1 atm) to 8.0 psi to 8.3 psi (55 kPa to 57 kPa) rapidly without pre-breathing pure oxygen and still avoid decompression sickness.

However, one of the original functions of the new Space Shuttle was to boost Skylab into higher orbit and then support manned missions to the Space Station. Reaching Skylab before it could enter the Earth's atmosphere and be lost provided a time constraint on new development. This plus the wealth of experience at EVA pressures below 8 psi (55 kPa) and the costs associated with higher pressure development resulted in the Shuttle EMU starting with an operating pressure of 4.0 psi (28 kPa), which later was revised to 4.3 psi (30 kPa).

The early 1980s saw an attempt to retain the developments of the advanced Apollo program and to potentially evolve the Shuttle EMU into a higher pressure system zero pre-breathe suit to allow faster response to possible emergency situations and make more effective use of astronaut time in space. Unlike Apollo's exploration in lunar gravity, this orbital theater of operation had no gravity. This meant that, other than launch weight cost, system mass was less of an issue. Also, working in zero gravity adds much greater complications due to basic physics. For every crewmember movement, there is an equal and opposite force reacting somewhere. Here, the greater mass of a spacesuit system might actually be an asset. As higher operating pressure requires greater structure for containment, the higher pressure suit systems of the 1980s were expected to be of greater mass (more Earth weight) than the Apollo or Shuttle EMUs.

In parallel, NASA's Ames Research Center (ARC) was tasked with developing a prototype pressure suit that embodied what ARC considered the best high-pressure mobility technology. This resulted in the AX-5 suit prototype.

Space Station *Freedom* (SSF), which later became the International Space Station, would provide the impetus and funding to change the design direction to an all new suit system named the "advanced extravehicular mobility unit" (AEMU). The AEMU program developed its own high-pressure suit using what the NASA Johnson Space Center (JSC) had deemed the most applicable mobility technologies. This ultimately resulted in comparative testing of the ARC and JSC pressure suit designs for SSF use. Unfortunately, SSF budget pressures led to the demise of the AEMU before the ARC/JSC test report was written. However, since the AEMU was terminated in favor of more cost-effective "enhancements" to the existing Shuttle EMU, some technical efforts associated with both the AX-5 and AEMU would influence the enhanced EMU.

While torso-related high-pressure suit mobility development essentially terminated in early 1990, improvement of gloves for high-pressure use continued. The hands provide the greatest area of challenge. This is not only because of the small diameters of the fingers merging with the irregular shapes of the palms, but also due to complex hand movements that are generally taken for granted and the great variety of hand shape differences from person to person. One of the reasons for not implementing a slightly higher operating pressure in the Shuttle/Space Station–enhanced EMU was the issue of increased hand fatigue over the period of an 8-hour EVA. For these reasons, NASA has continued high-pressure glove development up to the present.

The 1980s also brought international cooperation. This first started in the form of a Cold War era, peace-minded coalition for Space Station *Freedom*. As the Cold War thawed, the comparable technical communities on both sides established relationships. Their respective governments and space agencies followed, resulting in the International Space Station and some limited next-generational efforts.

The 1990s brought "back to the Moon and Mars" efforts. This brought challenges that are yet to be surmounted. Long-duration missions and performing difficult work in partial gravity environments will make low weight, mobility, and much greater durability key attributes.

The 1990s also provided interesting new entrepreneurial spacesuit-related activities outside the traditional NASA community. While the hardware produced by some of these efforts may not be considered credible space program prototypes by many, they added a new element to the potential mix of the future.

Zero pre-breathe suit (ZPS) efforts (1982–1985)

The early 1980s saw three areas of development relating to improved orbital EVA capability. The ZPS had two portions. The larger ZPS segment focused on 8 psi torso/limb mobility. A smaller subset of organizations was involved with 8-psi glove developments. In parallel, NASA funded development of a long-lead regenerable life support technology. The key element of this effort was a heat rejection system which did not vent water vapor. While these efforts drew on overlapping portions of the U.S. spacesuit community, they are addressed separately due to the nuances associated with the different technology areas.

ZPS mobility system efforts (1982–1984)

Common U.S. spacesuit community interest in a higher pressure EVA suit system culminated in NASA's Johnson Space Center (JSC) and Ames Research Center (ARC) merging resources for the ZPS project in 1982. However, ZPS-related efforts were already underway with ARC's planned build of the AX-4 prototype. The AX-4 effort had progressed to mobility element design by 1981 before being deferred in favor of a joint NASA-JSC and NASA-Ames ZPS effort. The toroidal convolute joints with internal restraints that were designed for the AX-4 prototype would be made and evaluated in the ZPS.

The two centers also brought a variety of supporting organizations including the Georgia Institute of Technology (Georgia Tech), David Clark Company (DCC), Hamilton Standard (HS), ILC Corporation (ILC), Life Support Systems

Incorporated (LSSI), and Suitech Corporation. In this mix of talent were three senior advanced suit engineers from different arenas of the community. Joseph J. "Joe" Kosmo of JSC and Hubert C. "Vic" Vykukal of ARC were both NASA engineers who had spent almost their entire careers from the earliest years of NASA in next-generation suit development. Vic (Figures 7.1.3, 7.2.7, and 11.1.2) retired in 2000 with over 40 years at NASA. Joe (Figure 4.4.1, left-center, right-center, and right) continues to head next-generation suit development activities at JSC. William "Bill" Elkins came from the private sector starting as a suit subject in Litton's early Mark 1 efforts in the 1950s. Bill (Figure 7.2.13) progressed to be a designer at Litton and then at AiResearch before becoming director of Aerotherm's Man Systems Department and then founder of Life Support Systems Incorporated (LSSI).

For ZPS, NASA-JSC had the lead for management of the various fabrication tasks and for systems testing. NASA-ARC supplied the initial design layout for most of the joint concepts and many potential manufacturing technologies. ZPS was to bring various technology elements together to be evaluated on one prototype testbed pressure suit. This effort drew together previously competing elements in the U.S. spacesuit community that held divergent views. One goal shared by many was to evolve the Shuttle EMU into a higher pressure, more advanced suit system. Other development objectives included longer life, lower bending effort joints, increased range of reach, lower effort bearings, improved reproducibility, greater reliability, and faster resizing. A premise of ZPS was that the suit component interfaces had to remain the same as the baseline EMU so that ZPS modules could be introduced incrementally. A ZPS 8.3 psi hard upper torso (HUT) was created by retrofitting a baseline 4.3 psi HUT. This verified the potential for retrofitting existing HUTs to higher pressure training units, thus minimizing future ZPS implementation costs.

Various shoulders, elbows, waists, briefs, and knees plus a single supply of sizing elements, ankles, boots were manufactured by ILC and LSSI for evaluation (Figures 11.1.1 to 11.1.3). HS wrote the specifications, which included safety requirements and performance parameters such as ranges, torques, and pressures. HS also performed cost and technical risk studies for possible follow-on production of a ZPS Shuttle EMU.

ZPS evaluated essentially three approaches to mobility systems. One featured hard, wedge-shaped segments with pressure-sealed bearings. In this concept of Ames AX-1/AX-2 heritage (Figure 7.2.7), wedges rotated in combinations of directions to permit joint movement. The second was the rolling convolute (Figure 11.1.4, top), which was devised by Litton for advanced Apollo development. The third was the toroidal joint (Figure 11.1.4, bottom), which was developed by AiResearch as an alternative to the rolling convolute.

The resulting ZPS effort demonstrated that the Shuttle EMU could be evolved to a higher operating pressure. Some ZPS mobility elements demonstrated lower effort at 8 psi than the Shuttle EMU flat pattern joints at 4.3 psi. However, the decision to develop an entirely new advanced EMU (AEMU) for Space Station *Freedom* relegated ZPS to history in 1985.

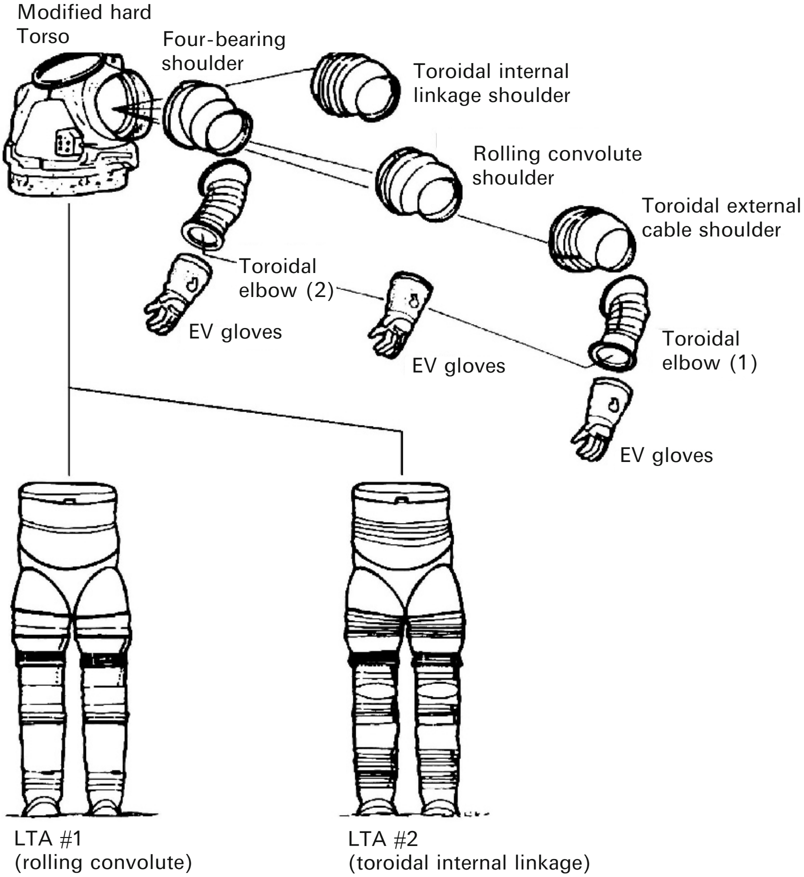

Figure 11.1.1. The ZPS options diagram (courtesy Hamilton Sundstrand).

ZPS-related glove efforts (1982–1984)

In ZPS-related glove efforts, DCC, ILC, LSSI, and Suitech Incorporated were supporting contractors. Additionally, there was an HS/ILC/Black & Decker end-effector (tool potentially replacing a glove) effort in this period.

In the DCC Phases I and II 8 psi glove efforts, DCC utilized Link-net fingers as it allowed the ability to adjust length and because Link-net is generally more conformal and comfortable than other technologies. The 1983 Phase I prototype glove effort demonstrated that the Link-net technology, originally developed in the mid 1950s for DCC's partial pressure suits, could provide effective mobility at 8.3 psi (57 kPa). The Phase I gloves (Figure 11.1.5) also featured a robust palm bar to withstand the higher ZPS operating pressure and a gimbaled near constant volume wrist joint. The modest success of the Phase I gloves led to a Phase II effort.

In Phase II, NASA and DCC explored sliding restraint cord metacarpal joints. The two restraint cord materials evaluated were Teflon fiber cord (brown, almost

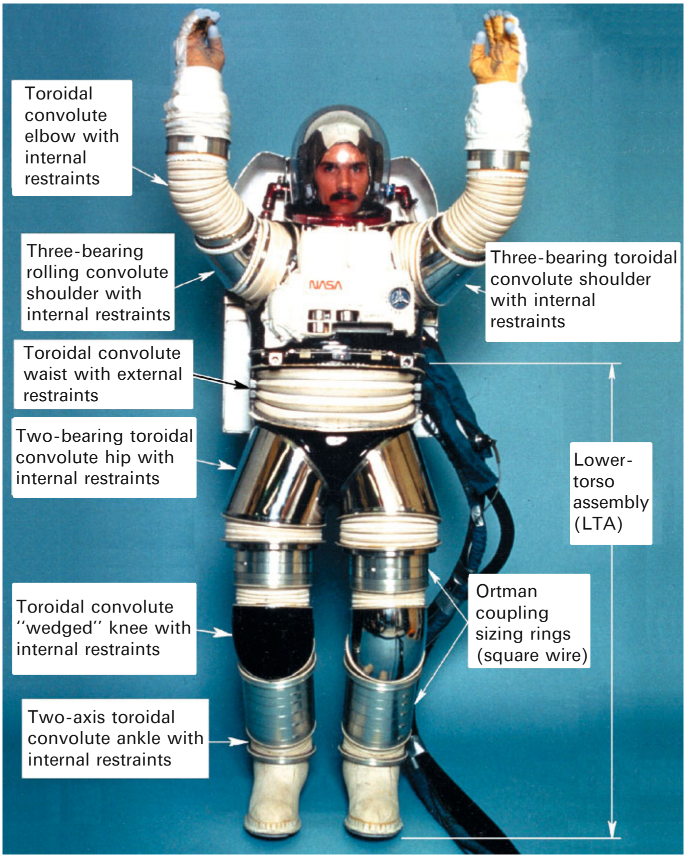

Figure 11.1.2. A typical ZPS test configuration (courtesy Hamilton Sundstrand).

black) and Nomex (natural, essentially white). A revised palm bar configuration was included to aid thumb range of motion. Additionally, the finger caps were revised to improve tactility and durability. The Phase II gloves were manufactured and evaluated in 1983. Another element of the Phase II effort was DCC experimentation with a TMG outer-glove palm and finger section that offered greater flexibility than the then current Shuttle EMU glove TMG.

In parallel to the Phase I and II DCC efforts, ILC produced two ILC 8 psi prototype glove designs. The first was based on glove technology provided by NASA-ARC that was probably influenced by Suitech finger efforts (Figure 11.1.6, left). The second ILC glove system was produced as a follow-on to the overall ZPS-related effort. This glove system was principally based on ILC's 2000 series Shuttle glove but featured a multigimbal wrist joint like ILC's later high-pressure glove efforts.

The third organization to provide ZPS effort gloves was LSSI. The nucleus of LSSI's expertise was former AiResearch/Aerotherm "suit people". The

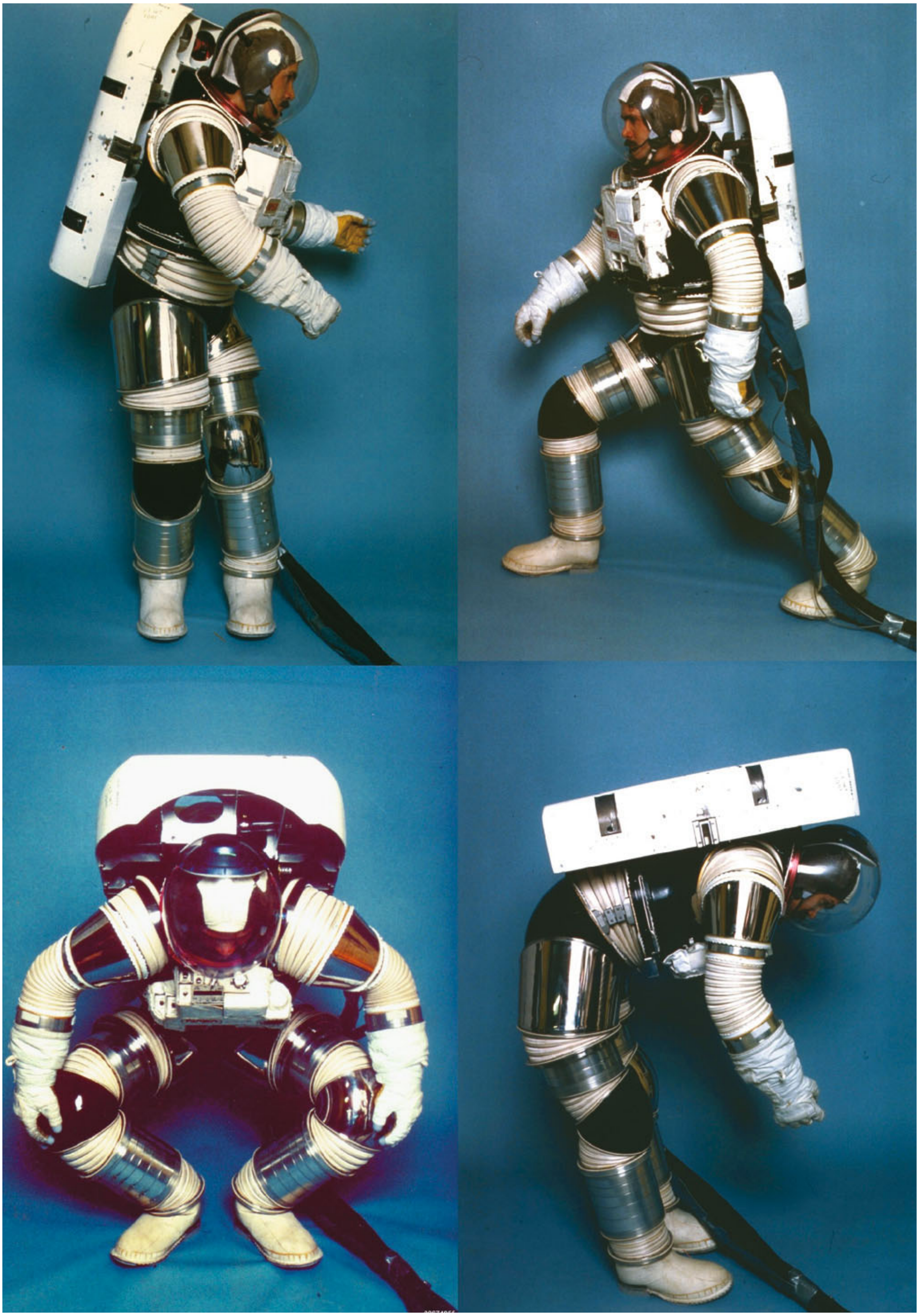

Figure 11.1.3. ZPS bend, rotate, squat, and walking stride (courtesy Hamilton Sundstrand).

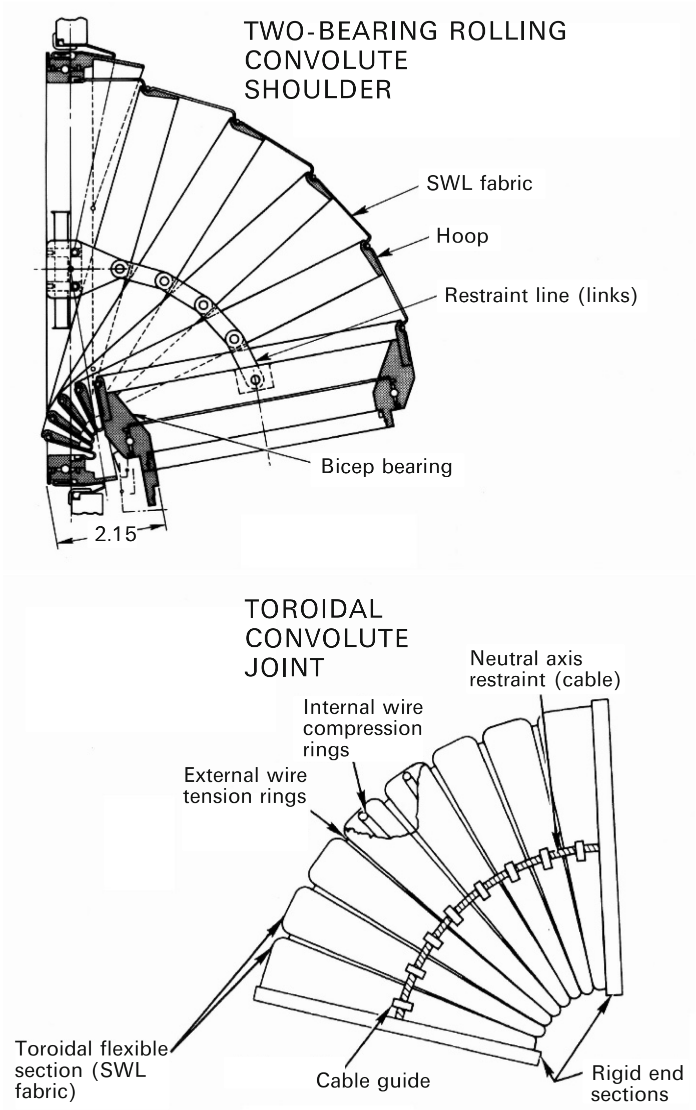

Figure 11.1.4. Rolling and toroidal convolute systems (courtesy Hamilton Sundstrand).

resulting pair of pressure gloves (Figure 11.1.6, right) demonstrated micro-convolute and flexible joint technologies previously proposed in the Aerotherm portion of the 1976 AlliedSignal/Aerotherm/David Clark proposal for the Shuttle EMU.

As originally planned, Suitech was also to provide gloves for ZPS evaluation. Due to budget constraints, Suitech was able to provide only fingers before their portion was reduced and stopped.

Figure 11.1.5. ZPS DCC Phase I gloves (courtesy David Clark Co.).

An interesting non-glove effort was an end-effector effort by an HS, ILC, and Black & Decker contractor team. The power-assisted glove end-effector (PAGE) system explored two approaches. The first was having the tool attach directly to the glove disconnect in place of a pressure glove. This "hand-in-a-can" concept provided unsuited-like activation and control free from pressure glove encumbrance. The bare hand gripped the tool controls in a pressure chamber portion of the tool. The one tool would have changeable end-drives for driving sockets to tighten or remove nuts and bolts, drilling, or saber sawing.

The second approach was having a trigger mechanism built into the pressure glove with external contacts to accommodate a variety of power tools. This approach included exploration of potential hook-and-loop fastener/strap restraint systems so the hand could grasp the tool without sustained effort being required by the astronaut. Evaluation comments ultimately resulted in a third, more conventional concept that interfaced with a conventional EVA glove. The tool had the changeable end-drive attachments of the end-effector-replacing-glove approach but was a separate tool that featured a hand guard that conformed the pressure glove fingers around the grip to allow zero-effort holding of the tool. The only effort required was in the activation mechanism.

Figure 11.1.6. ILC (left) and LSSI (right) gloves with metacarpal joints (courtesy ILC Dover LP and Hamilton Sundstrand, respectively).

Regenerable non-venting thermal sinks (1982–1986)

Placing materials in orbit costs thousands of dollars per pound. Thus, cooling systems that evaporate pounds of water per EVA for cooling spacesuits have significant recurring expense. The costs associated with storing and controlling on-orbit water increases this expense yet further. Also, there are concerns for sensitive experiments—such as those utilizing subcooled infrared sensors—that could be contaminated by water vapor.

During ZPS, Hamilton Standard won a contract for the design and development of a thermoelectric wax radiator for space portable life support systems. This was a regenerable non-venting heat sink and rejection system to support thermal and humidity control within the spacesuit. The prototype system (Figure 11.1.7) fitted over the exterior of the Shuttle EMU primary life support subsystem (PLSS) to make chamber testing possible with the existing Shuttle EMU. Heat from the EMU was stored in paraffin and then radiated to a vacuum chamber replicating space. The prototype had approximately 13.5 ft.^{2} of radiating area. However, this illustrates one

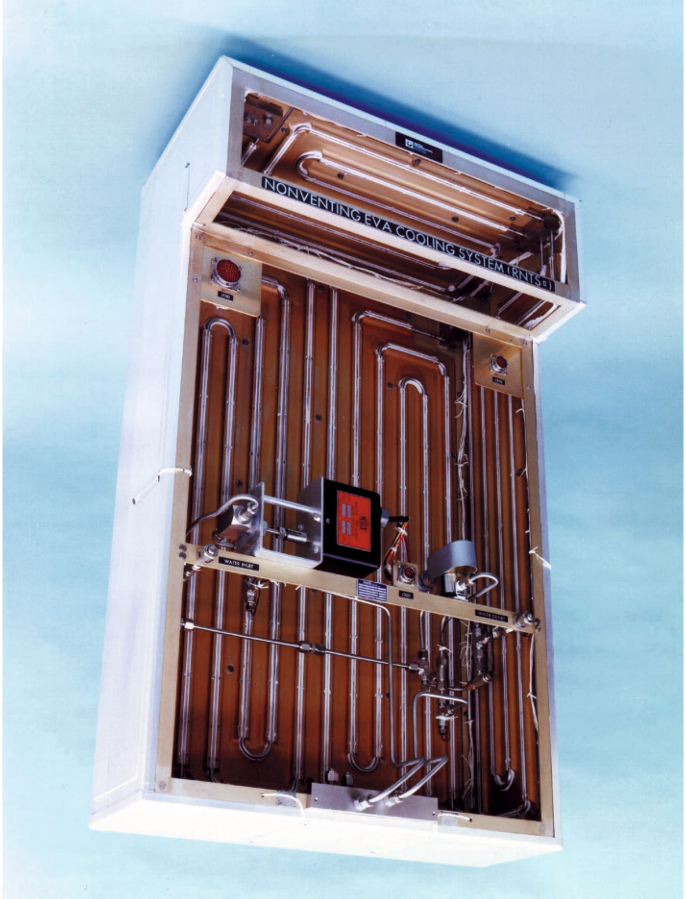

Figure 11.1.7. Regenerable non-venting thermal subsystem (courtesy Hamilton Sundstrand).

problem with the regenerable approaches thus far: their significant increase in overall system volume.

The Ames AX-5 hard suit (1983–1989)

From the 1960s to the late 1990s, NASA tasked their Ames Research Center (ARC) with advanced technology spacesuit development in parallel with the program-specific spacesuit efforts at the Manned Spacecraft Center (later the Johnson Space Center or JSC). In 1982, USAF General James Abrahamson, who was NASA's associate administrator for the space transportation system, directed ARC to create a prototype that embodied what ARC judged to be the most promising high-pressure suit mobility technology. The USAF ultimately contributed

Figure 11.1.8. AX-5 in zero-*g* (neutral buoyancy) demo (courtesy G. L. Harris/NASA-Ames).

approximately a third of the funds required for development. The result was the Ames AX-5.

The AX-5 (Figure 11.1.8) was a Hubert C. "Vic" Vykukal design that was uniquely different from previous spacesuit approaches. The AX-5 was an all hard suit that used spherical joints that featured pressure-sealed bearings using the sphere as the inner race of the bearing to provide low-effort mobility. The suit design provided sized elements in the non-flex areas for quick adjustment between users. Two AX-5 prototypes were built.

While the AX-5 was originally a technical development exercise without a specific program application, the design would be considered for use as the Space Station *Freedom* pressure suit. Although the SSF AEMU program was terminated before a final comparative test report was issued, these NASA efforts played important roles in the enhanced Shuttle EMU. One indirect result of the AX-5 and Mark III suit evaluation was the highly rated AX-5, four-bearing shoulder being integrated into an Ames dimensional equivalent of a Shuttle hard upper torso (HUT) for evaluation. Air-Lock Corporation installed the arm hardware and painted the assembly. The resulting unpressurizable HUT mockup was fitted with a training DCM from JSC. Don, doff, and cross-reach evaluations were performed at Ames and JSC with successful results. While the AX-5 shoulder and elbow did not transition into the enhanced EMU, the Ames mockup showed that pivots were not required if the correct scye-bearing angles were incorporated into the HUT.

The pivots, which were anchored in the multilayer fiberglass shell of the HUT, had long been an area of concern to NASA. Long-term exposure to moisture had been found to weaken the pivot support-to-fiberglass bond, which had the potential to loosen the support and lead to loss of retention with subsequent rupturing of the pressure-sealing bellows of the HUT arm, which would be catastrophic. The discovery that adequate fit over the required sizing range could be attained without the use of pivots started a series of events that led to the enhanced Shuttle EMU's "planar" HUT which has neither pivots nor bellows. It is worthy of note that the resulting planar HUT's scye-bearing angles are within one degree of the Ames mockup.

Ultimately, NASA-Ames donated the two AX-5 suits to the National Air and Space Museum to preserve their technical legacy.

Space Station *Freedom* (SSF) AEMU (1985–1990)

In 1984, President Reagan presented a new space program concept to Congress. This was Space Station *Freedom* (SSF). In 1985, Congress funded SSF's many parallel efforts that included the development of the SSF advanced extravehicular mobility unit (AEMU). NASA set about this task by first developing key technologies desired in AEMU. This created many parallel efforts culminating in an integration contract to implement the resulting suit system as indicated by the subtopic descriptions below:

- AEMU entry architecture study (1985–1987)
- The Mark III pressure suit (1987–1990)
- Pressure glove developments (1985–1987)
- Life support developments (1985–1987)

- Communication improvements (1985–1988)
- Considering Ames AX-5 as the pressure suit for SSF (1988–1990)
- The SSF AEMU implementation contract (1988–1990).

AEMU entry architecture study (1985–1987)

In 1985, NASA wished to determine the conceptual direction for a higher pressure (8.3 psi, or 57 kPa), zero pre-breathe advanced pressure suit development effort and to build a complete prototype. NASA submitted a request for proposals. ILC's proposal won. In this proposal, Hamilton Standard (HS) was ILC's subcontractor for the hard upper torso portion of the system. One objective of this effort was to determine the optimum entry concept. The other was to determine the basic suit concept. The competing suit concepts at the time were the all hard suit (such as the AX-5), a hard/soft hybrid (like the Shuttle EMU), or a soft suit (like the Shuttle launch entry suit and the Mercury through Skylab suits).

The project started with a NASA-JSC review of all known entry concepts. After evaluation, two concepts emerged. These two concepts were the dual plane (Figure 11.1.9, top) and the rear entry (Figure 11.1.9, bottom). HS developed and built a 1.0 psi (7 kPa) hard upper torso (HUT) of each concept in fiberglass. The HUTs were designed to interface with NASA's already existing zero pre-breathe suit components. These were subsequently used in zero-*g* evaluations (Figure 11.1.10). This resulted in NASA selecting the rear-entry HUT, which was the same concept used by the Russian Orlan suit and the Ames AX-5.

The Mark III pressure suit (1987–1990)

In 1987, NASA and ILC were ready to progress with the manufacture of a second complete ZPS pressure suit prototype. The extensive studies and evaluations of potential architectures during 1985–1987 may have been retroactively credited as Mark II even though no Mark II suit was ever built. The advanced pressure suit prototype that followed was the Mark III (Figure 11.1.11).

Evaluation feedback from the architecture studies was then incorporated into a second rear-entry hard upper torso (HUT) design that was created by HS in milled aluminum for material property reasons. For the shoulder design, NASA elected to have ILC fabricate a derivation of Litton's advanced extravehicular suit rolling convolute shoulder. For the lower arm, NASA/ILC chose to use a flat pattern system similar to the Shuttle EMU. In the waist, NASA-JSC decided to forego a waist bearing—as had been used in the Shuttle EMU—as it was hoped that the three-bearing (on each side) brief would provide sufficient rotational mobility. The waist did, however, have a rolling convolute joint to facilitate fore–aft bending. Below the brief on each leg was a short rolling convolute joint to allow the legs to spread or come together with greater ease. The remainder of the legs utilized Shuttle EMU-like flat pattern elements. The ankles also used flat pattern joints.

The Mark III was modular in that the sections were separable via "Ortman wire" connections similar to those used on the ZPS and earlier Ames advanced

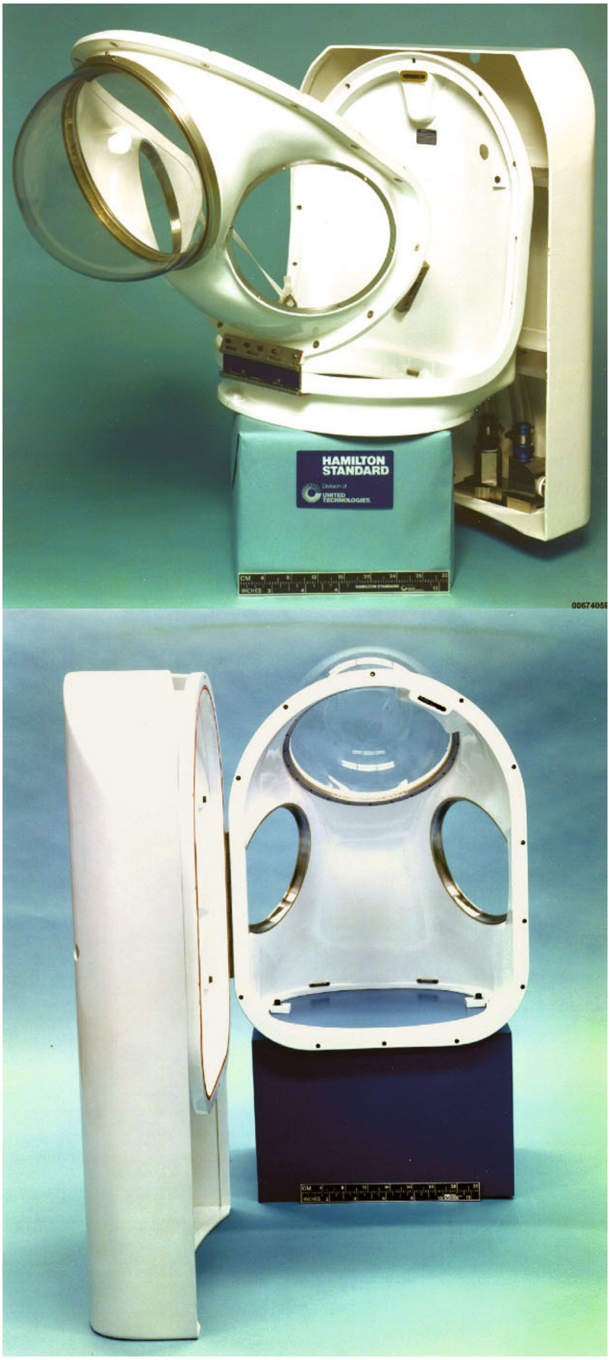

Figure 11.1.9. Dual-plane and rear-entry development HUTs (courtesy Hamilton Sundstrand).

Figure 11.1.10. Mark II in comparative entry testing (courtesy G. L. Harris).

suits. Beyond arm and leg modules of various sizes, additional sizing ability was provided by incremental spacer rings in the arms and two in two locations in the legs. These elements attached via Ortman wire connectors as well. A Mark III joint failure under pressure caused by erroneous use of an undersized wire cast doubt on the reliability of the Ortman wire approach due to the potential for human error and undersizing due to wear.

In 1989, NASA funded Air-Lock Corporation (A-L) to explore manufacturing HUTs in cast aluminum to reduce cost and speed up production. As a deliverable from this study, A-L produced a cast aluminum Mark III HUT. Four years later, NASA funded A-L to explore a sandwiched graphite composite manufacturing method, which produced yet another HUT for the Mark III. In the early to mid 1990s, the Mark III evolved into the hybrid or “H” suit (discussed in Section 11.1.7).

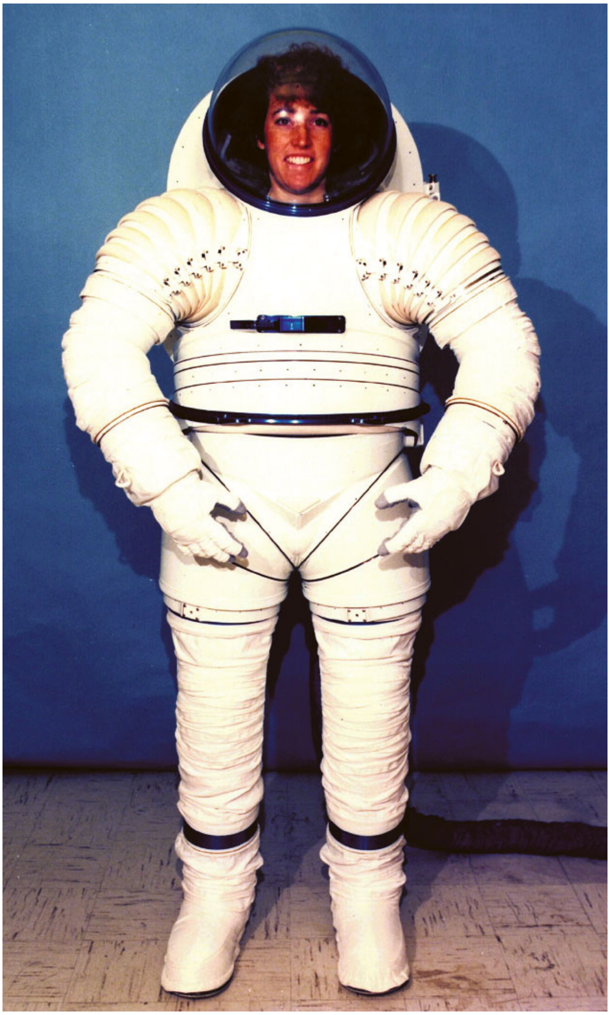

Figure 11.1.11. Mark III pressure suit (courtesy NASA).

Pressure glove developments (1985–1987)

One of the conclusions from the zero pre-breathe suit efforts was that pressure glove development was a pacing technology for 8 psi (55 kPa) suit systems. Thus, NASA continued glove development utilizing the David Clark Company (DCC) and ILC. In 1985, NASA funded the DCC Phase III glove development effort. Phase III consisted of one pair of gloves (Figure 11.1.12, left) that featured a robust, pivoted (or hinged) metacarpal joint/palm bar system. This additionally featured a lower abrasion wrist joint. For this effort, DCC continued the exploration of Teflon Link-net fingers. The DCC Phase III also featured a potentially less expensive, low-torque, higher tactility glove TMG (Figure 11.1.12, right).

Figure 11.1.12. DCC 1985 Phase IIIA glove and TMG (courtesy David Clark Co.).

In 1987, NASA also funded ILC for a Mark III pressure glove. This 8.3 psi (57 kPa) glove continued the development of a multigimbaled, rolling convolute wrist joint (Figure 11.1.13). The restraint layer of the glove incorporated simpler flat pattern fingertips as compared with the Shuttle EMU Kevlar mesh–reinforced finger caps. An interesting feature of this glove was a multidirectional thumb joint using a Link-net style sliding mesh technology. While the Mark III did not make production as NASA elected not to implement the Space Station *Freedom* AEMU for budgetary reasons, a derivation of this glove effort continued in the Shuttle EMU program as the 5000 series glove of the enhanced EMU effort.

Life support developments (1985–1990)

Beyond a continuation of regenerable non-venting thermal subsystem technology, NASA also funded an extensive thermal control aystem study to meet the SSF AEMU's criteria of low operational costs, minimum maintenance, minimum in-flight servicing, minimum ground servicing, and long life.

Hamilton Standard (HS) won the two-year effort that started in 1985. This task developed and fabricated a prototype to allow the comparative evaluation of

Figure 11.1.13. ILC's Mark III, 8.3 psi glove (courtesy Hamilton Sundstrand).

candidate thermal control technologies for the then planned SSF AEMU primary life support system (PLSS). This included the study, selection, and design of candidate heat rejection, water management, humidity control, and water transport subsystems for evaluation. Humidity control system exploration included many options which were interdependent on the selected CO_2 removal system, heat sink system, and humidity removal technology (desiccant bed or condenser/separator).

This was followed by the fabrication and testing of each subsystem and possible technology combinations. Subsystem elements of the thermal control aystem effort or parallel SSF AEMU-related R&D efforts included approaches such as regenerable heat sinks, a combination humidity and carbon dioxide control system using a solid amine sorbent, and an automatic cooling control. The regenerable heat sinks included thermal wax plus an ice-to-water test system that permitted evaluation of a variety of phase/change slurry materials such as water/salt. The results permitted NASA to select the technologies intended for the SSF AEMU contract that followed.

For SSF, non-regenerable on-orbit CO_2 removal cartridges like that used on Apollo or Shuttle EMUs would have been weight and volume prohibitive for launch and unacceptable for Space Station stowage. In 1987, HS won the on-orbit regenerable CO_2 removal system development contract with its metal oxide regenerable extravehicular system (MORES) concept. This effort designed, fabricated, and tested a full scale reactor and canister system. This prototype system met its performance goals and was planned to become an element of the SSF AEMU contract. When the SSF AEMU was terminated in 1990, this system would be the one element to continue receiving NASA funding to completion. The version which eventually saw flight use in the ISS was called the "metal oxide (METOX) system".

Communication improvements (1985–1988)

Vital elements of a spacesuit system extend beyond a pressure enclosure and life support. Communications and controls are essential not only for effective work performance but also for astronaut safety. In recognition of this, the SSF AEMU was to be a giant step forward from past EVA systems. This included the ability to see visual information displayed in real time as the astronaut worked without interruption. Also, as part of concepting for the SSF AEMU, NASA wanted to eliminate the front-mounted displays and control module as was used on the Shuttle EMU. The long-lead portion of this challenge was the development of an alternative display method. NASA submitted requests for proposals in 1986. The Hamilton Standard (HS) helmet-mounted display (HMD) proposal won.

The HMD concept (Figure 11.1.14, left) was to provide a virtual see-through image. For this effort, HS's space organization teamed up with its Flight Systems Department. Many potential configurations and technologies were evaluated. The end-result was an HMD that employed a liquid crystal display (LCD). The LCD is a low-power image-generating device capable of displaying various forms of information via tiny picture elements (pixels). In the course of development, two full scale mockup units were created. The first was concepted in 1986 around the Shuttle EMU helmet geometry. A second mockup was later developed to accommodate the dimensions of the Mark III pressure visor. The technology demonstrator unit (Figure 11.1.14, right) was delivered to NASA for evaluation. This featured three levels of see-through transparency to facilitate evaluations.

Consideration of the Ames AX-5 as the pressure suit for SSF

For SSF AEMU, NASA's Johnson Space Center (JSC) had been developing the Mark III as the pressure suit. In 1988, NASA-ARC and NASA-JSC mutually proposed a competitive evaluation between the Ames AX-5 all hard suit (discussed in Section 11.1.2) and the JSC Mark III. In 1989, the Mark III and AX-5 (Figure 11.1.15) were extensively evaluated in comparative manned testing at JSC. The SSF AEMU program was canceled before conclusions were reached.

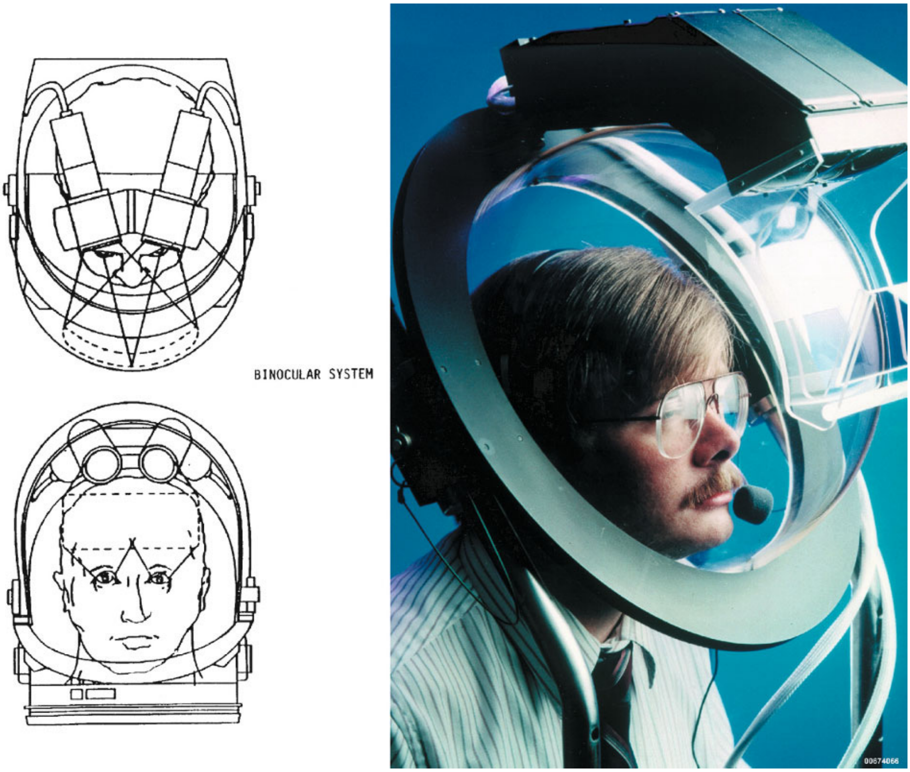

Figure 11.1.14. HMD concept and demonstrator (courtesy Hamilton Sundstrand).

However, the eventual reports found the two pressure suits comparable, with the AX-5 shoulder having potential advantages.

The SSF advanced EMU (AEMU) implementation contract (1988–1990)

For Space Station *Freedom* (SSF), Lockheed Aerospace was NASA's prime contractor. In 1988, Lockheed competed a subcontract for AEMU development and integration. The Hamilton Standard/ILC Industries (ILC)/Air-Lock Corporation team won. The team members' roles and responsibilities were organized like those of the Shuttle EMU program. For use in the SSF AEMU (Figure 11.1.16), NASA selected the regenerable non-venting thermal sink (thermal wax), automatic cooling control, metal oxide regenerative CO_2 removal system and the helmet-mounted display from preceding technology developments.

The challenge of this effort was to complete, develop, certify, and deliver a fully regenerable (no launched expendables), 8.3 psi (57 kPa) (no pre-breathe required) EVA suit system that met NASA's volume constraints. This suit system was to feature no external system controls, which required developing an interactive voice recognition system. One problem with this approach was the need to incorporate a

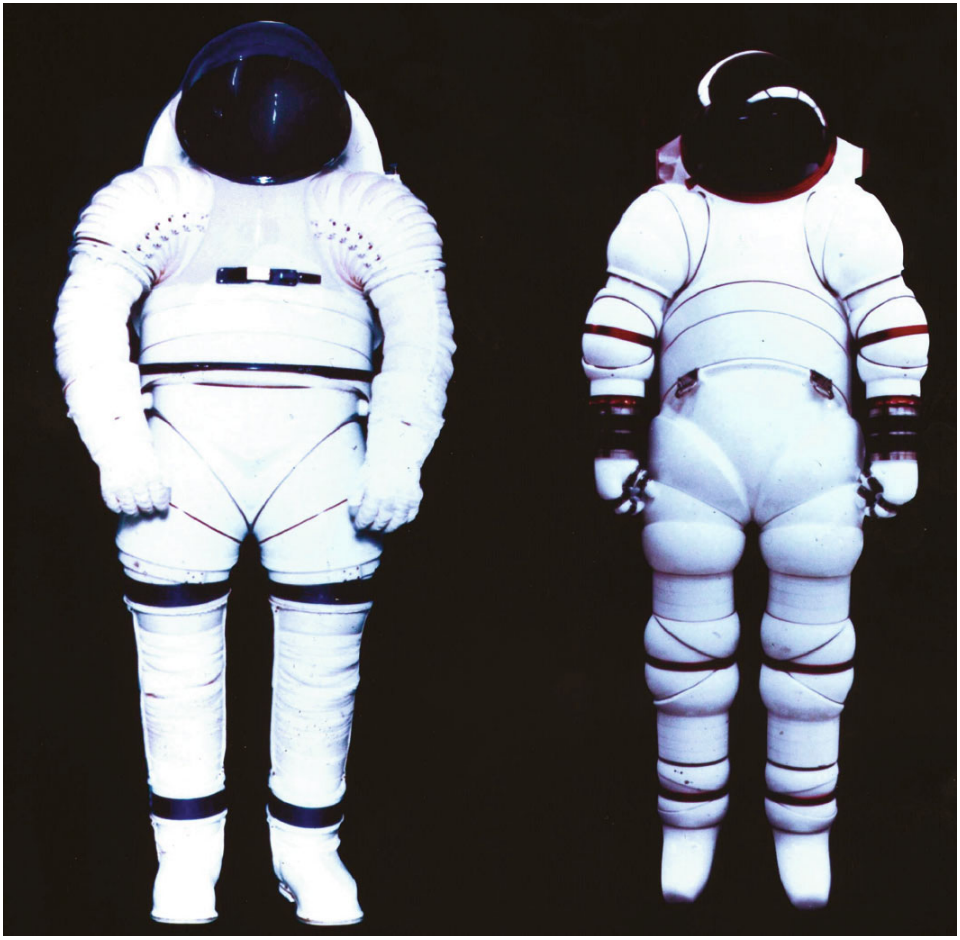

Figure 11.1.15. Testing JSC's Mark III (left) and Ames' AX-5 (right) (courtesy Hamilton Sundstrand).

manual backup in case of failure of voice activation circuitry. Thus, some of the benefits originally thought to accrue from the approach did not materialize. Additionally, the system was to have modular life support subsystems designed to be maintained or replaced on orbit. This concept was called the "on-orbit replaceable unit" (ORU). The ORU systems were to include the voice recognition system, checkout service and maintenance system, the power coordinating module, and the data management module.

Due to reductions in SSF budgets, Lockheed elected to assume the role of integrator of the AEMU in 1989. Also in 1989 in response to budget constraints, NASA funded two independent cost/benefit studies and conducted an internal cost review. In February 1990, these reviews resulted in the AEMU program termination

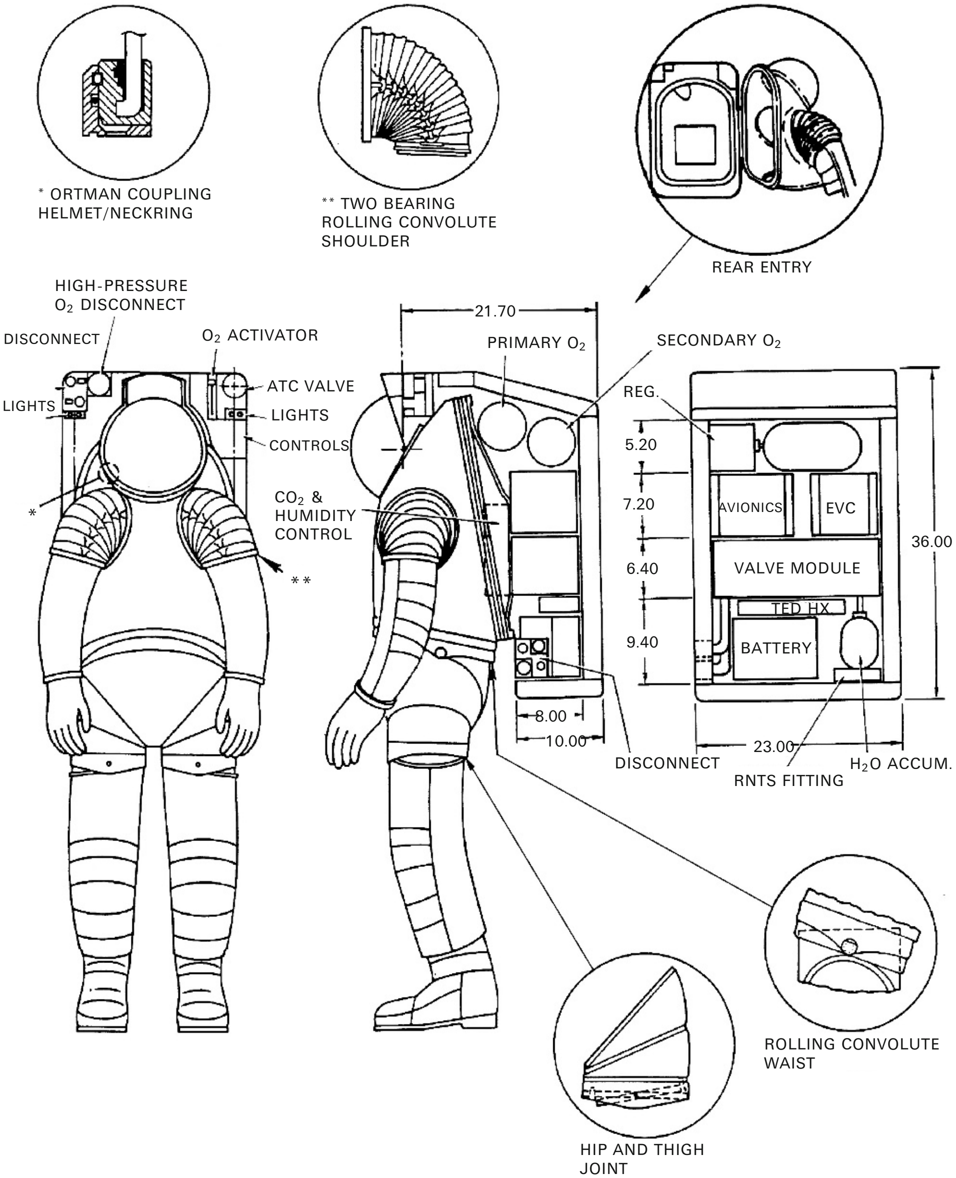

Figure 11.1.16. 1989 advanced EMU diagram (courtesy Hamilton Sundstrand).

in favor of evolutionary enhancements for the 4.3 psi (30 kPa) Shuttle EMU to meet Space Station needs. The only complete suit system from the AEMU program was a Mark III–based Neutral Buoyancy Laboratory evaluation unit (Figure 11.1.17).

A direct transition/continuation from the SSF AEMU to the enhanced Shuttle EMU was the regenerable metal oxide CO_2 removal system for Space Station service and as an option for Shuttle flights.

Figure 11.1.17. Final (Mark III–based) SSF prototype (courtesy NASA).

A less direct influence of the SSF AEMU was in the area of gloves. The ILC Mark III glove was considered for use in the Shuttle EMU as the 5000 series glove. While this configuration did not reach full flight service, a derivation of the design continued development as the Phase VI glove. The Phase VI went on to become the current pressure glove system of the enhanced EMU.

Continued advanced pressure glove efforts (1991–1999)

NASA's higher pressure mobility development did not end with the termination of the SSF AEMU. One potential "enhancement" to the Shuttle EMU that was considered but not implemented was higher (5.3 psi, 36.5 kPa) operating pressure. One of the key factors in not implementing the higher pressure was unfavorable long-duration glove evaluations by crewmembers.

In 1991 NASA funded the David Clark Company (DCC) for the development of a Phase IV glove design. This prototype glove system featured evolutionary improvements in the wrist and metacarpal areas over the 1985 Phase III effort. The Phase IV effort included DCC exploration of a TMG outer glove with silicone palm and palm-side finger sections to offer excellent flexibility with lower grasp torque. This was followed by NASA's funding of DCC Phase V in 1992.

With Phase V, DCC demonstrated the ability to develop effective high-pressure gloves using flat pattern finger restraint designs similar to DCC Gemini and high-altitude pressure suit gloves. This exploration was complemented by evolutionary improvements in the metacarpal and wrist joints. Phase V also featured more exploration of low-torque glove TMGs.

While the focus of next-generation spacesuit systems and subsystems in the mid 1990s principally turned to lunar/Mars-related technologies—as illustrated by the topics that follow—non-fatiguing mobility at higher pressure was still recognized as an important need. To that end, NASA funded DCC to perform a Phase VI effort in 1999.

For Phase VI, DCC returned to Nomex Link-net finger restraint systems for the fingers. Phase VI produced two pairs of gloves for comparative testing. The focus of the comparison was in wrist technologies, specifically "soft" and "hard" wrists. The soft wrist was DCC's further exploration of a two-gimbal/convolute wrist technology (Figure 11.1.18, top) similar to their Phase I glove design and the modern Russian EVA systems that feature a 5.8 psi (40 kPa) operating system. The hard wrist was yet another evolution of the wrist system used in DCC's Phases III, IV, and V. To complement the evaluation of complete glove systems Phase VI provided yet another evolutionary step in low-torque glove TMGs (Figure 11.1.18, bottom). However, not all the higher pressure glove efforts of the past decade and a half have been by DCC.

Under a federal university/industry grant, the University of Maryland Space Systems Laboratory teamed up with ILC to develop a self-contained power-assisted actuation system in 1999. The goal of this study was to facilitate gloved motion of the metacarpal joint. To combat the problem of fatigue, an actuator was unobtrusively configured into the dorsal side of the glove (Figure 11.1.19). This

Figure 11.1.18. DCC 1999 Phase VI pressure glove configurations (courtesy David Clark Co.).

Figure 11.1.19. University of Maryland/ILC power-assisted glove (courtesy ILC Dover LP).

provided torque to counterbalance the spring-back characteristic induced by the pressurized glove. This in turn enhanced hand mobility while reducing fatigue.

Oceaneering Space Systems (OSS), a new competitor (1988)

The parent corporation, Oceaneering International, was founded in 1964 and grew from an air-and-mixed-gas diving business in the Gulf of Mexico to a diversified, deepwater-diving technology provider operating around the world. In 1977, one of Oceaneering's professional deep sea divers and project engineers was Michael L. Gernhardt (Ph.D.). By 1984, Gernhardt joined management and by 1988 rose to Vice President of Special Projects. In 1988 he became the founder and first Vice President of Oceaneering Space Systems (OSS), a division formed to transfer subsea technology and operational experience to the NASA space program. From 1988 until his selection by NASA into the astronaut corps in 1992, he worked on the development of new astronaut and robot-compatible tools for performing maintenance on Space Station *Freedom* (SSF). OSS went on to become a key EVA tooling contractor.

Also starting in 1988, OSS proposed a new primary life support system (PLSS) for EVA based on cryogenic oxygen for life support and heat removal. While this did not win NASA funding, it generated interest in relation to Space Station *Freedom* (SSF).

In 1991, the SSF concept had EVA astronauts moving from one location to another inside the truss sections of the Space Station. Practicing this on Earth in neutral buoyancy tanks using traditional umbilical life support systems would have been difficult. Work-arounds to accommodate the umbilicals could introduce training differences that could impact human performance in orbit. In 1991, NASA funded OSS for a prototype neutral buoyancy portable life support system. In 1992, NASA conducted successful manned testing with the OSS prototype at the underwater facilities at JSC and other locations. Funding limitations and the change from the SSF to the International Space Station (ISS) with its planned, totally external EVA traverses brought an end to the neutral buoyancy PLSS, but OSS progression continued.

11.2 INTERNATIONAL COOPERATION AND CROSS-INFLUENCES

The study of spacesuits shows how small a planet the Earth is and how the spacesuit community has a natural tendency to be international. During the 1960s, Soviet counterparts followed U.S. spacesuit development closely. The first tangible evidence of U.S. influence on Russian spacesuit design may be the appearance of ILC A7L Apollo-like gloves appearing on Russian spacesuit prototypes in the 1970s. It has been told that U.S. astronaut Michael Collins presented an Apollo glove to Soviet cosmonaut Vitali Sevastianov in 1972. Sevastianov showed it to Guy Severin, the Chief Designer for the factory producing Russian spacesuits. Severin ordered the making of a copy, which was evaluated. This resulted in Apollo-based gloves being used in two types of Russian spacesuits.

Russian Apollo replicas saw extravehicular service in the Orlan series of Russian spacesuits as the inner pressure glove of the Orlan-D and DM glove system reaching space service with the first Salyut extravehicular activity (EVA) on December 20, 1977. In the Orlan application, the difference from the Apollo glove was in the use of a Russian-designed disconnect. This design continued in *Mir* Space Station use through the Orlan-DM design until the introduction of the Orlan-DMA in 1988. In the first two Orlan-DMA EVAs, one suit used the new Russian design inner glove and the other used the Apollo-based design.

An Apollo-like design also appeared on Russian Sokol Model KV-2 rescue suit (launch/entry/IVA) prototypes starting in 1973. Except for a Russian suit glove disconnect, simplified single-axis wrist restraints, and some material substitutions, the Apollo design reached flight service in 1980 as the Russian KV-2 gloves. With the end of the Cold War, the Russian factory that was founded in 1952 to produce aviation pressure suits and other aviation-related systems and had been the sole producer of spacesuits for the Soviet Union became NPP Zvezda in 1994. The Apollo-based design was phased out of Sokol KV-2 use in 2003–2004 with the introduction of an all new Zvezda-designed pressure glove using separate bladder and restraint layers for greater mobility, durability, and ease of manufacture.

U.S./Russian influence was not just one way. Russia developed a rear-entry hatch approach in the 1960s that would be a hallmark of their extravehicular spacesuits from the 1970s to the present. Starting in the 1980s, many U.S. efforts (see pp. 355–357 and 376) would recognize the benefits and utilize the approach.

U.S. spacesuit technical influence was not limited to Russia. By the late 1970s, China had developed a space pressure suit that used a David Clark/Gemini-style rear-entry system and a Link-net like restraint system. Yet another twist in U.S. influence on Chinese spacesuit technology came in the early 1990s when China bought Russian space technology to bolster the Chinese space program. This gave China access to additional Russian technology including the Russian KV-2 rescue suit. The model of Chinese spacesuit used on China's first manned spaceflight, Shenzhou V, was essentially a duplication of the Russian KV-2 including the Apollo-influenced gloves of the time. The Apollo-based design appears to still be in service in the Chinese Shenzhou launch, re-entry, IVA-type spacesuits.

The creation of Space Station *Freedom* (SSF) started a Western cross-pollination of space technology knowledge. The European Space Agency (ESA) had highly ambitious goals going into SSF. ESA planned not only to provide modules to SSF but also have separate, smaller, manned and unmanned orbiting space platforms as part of the Columbus program. To support this array of activities, ESA was to design its own reusable Shuttle spacecraft named "Hermes" and develop an EVA spacesuit called the "European spacesuit system".

The first European spacesuit system feasibility studies were performed in 1986–1987. In 1987, Dornier was selected prime contractor for the program and life support subsystem contractor, with Laben in Italy being selected as contractor for the chestpack/data management and communication subsystem. Dassault of France was selected as the pressure suit subsystem contractor. While the pressure suit never reached a complete pressurizable level, published technical descriptions of the suit system showed NASA/ILC Mark III and Shuttle EMU–like restraint systems. Additionally, Dornier elected to use the U.S. organization of Hamilton Standard as a supporting subcontractor for system and life support subsystem engineering.

The European spacesuit system (Figure 11.2.1) was to have an operating pressure of 7.25 psi (500 hPa) and a rear-entry hatch. However, development of this system would be affected by the opening of the Soviet Union in 1990 that resulted in contracts for system engineering and suit enclosure support from Zvezda, the Russian spacesuit system provider. In 1992, ESA reevaluated the European spacesuit system program due to budgetary considerations. The reevaluation resulted in a new program under the name of "EVA Suit 2000". This program drew ESA into partnership with the Russian Space Agency (RSA), with Dornier and

Figure 11.2.1. The European Space Agency's extravehicular spacesuit system concept (courtesy A. I. Skoog).

Zvezda becoming co-contractors for the EVA Suit 2000 program. The operating pressure of the new suit system was reduced to 6.1 psi (420 hPa).

In 1990, the Cold War was fading. The world had a limited number of suppliers for space life support and spacesuits. The first U.S. space community organization to recognize the potential mutual benefits for similar U.S. and Soviet space businesses to work together and take the initiative appears to have been Hamilton Standard (HS). During 1990–1991, HS established working and business agreements with Russian aerospace companies including Zvezda, the Russian spacesuit system design and manufacturing organization. In September of 1993, HS brought the first example of current Russian spacesuit technology to the U.S. by negotiating and funding the lease of an Orlan-DMA suit. The Orlan-DMA was the Russian *Mir* EVA suit. HS performed technical evaluations, shared knowledge from this effort with the U.S. technical community, and provided the DMA suit to NASA for additional evaluations. One Orlan feature that interested NASA-JSC was the Zvezda-developed dual-gimbal wrist joint. This would influence U.S. glove developments in the 1990s and would ultimately be incorporated in the enhanced Shuttle EMU Phase VI gloves.

In 1993, SSF was expanded to include the Russian Space Agency under the name of the International Space Station (ISS). ESA and the Russian Space

Agency (RSA) lobbied for U.S. support on a joint development of a new spacesuit based on the EVA Suit 2000 to become the one and only spacesuit system common to all nations on the ISS. However, the U.S. enhanced EMU was already too far along for such consideration. The EVA Suit 2000 program eventually faltered due to budget pressures but not before a first pressurized prototype had been successfully tested. The Russian ISS suit, the Orlan-M, incorporated several of the features jointly developed by Zvezda and Dornier in the EVA Suit 2000 program.

Starting in 1997, Zvezda of Russia and Hamilton Standard (HS, now Hamilton Sundstrand) cooperated in a series of research and development studies aimed at planetary exploration. In the first effort, HS internally funded Zvezda for a planetary lower-torso study. It is important to remember that the Soviet Union had its own lunar EVA suit development program and, while the resulting spacesuit system became the orbital system known as the Orlan, its maker Zvezda had given consideration to planetary walking features that were not embodied in the Orlans that saw orbital flight service. The study was to provide Russian recommendations for a possible walking lower-torso system. While it was considered, this did not result in a lower-torso prototype. Nevertheless, it was the precursor to boot/ankle mobility prototypes.

The Zvezda and HS boot/ankle mobility study focused on providing enhanced foot and ankle mobility and security needed to walk on sloping and uneven terrain. Component level design studies and testing were conducted in 1998 to identify a candidate configuration for manned pressure suit testing. During 1999, HS funded Zvezda to manufacture test boots that incorporated the selected multidirectional ankle joint and bearing location. Manned testing was conducted at HS's Windsor Locks, Connecticut facility using one of the two HS-owned U.S. Shuttle training EMUs. For the testing, a test facility was created that allowed establishing virtually any angle slope and placement of a variety of irregularly shaped objects in the walk path (Figure 11.2.2). Testing included a series of defined tasks such as standing on the slope, walking up and down on the slope, evaluating speed and stability while walking, walking on an uneven surface, making a 360-degree turn as rapidly as possible, and rotating the torso with the waist bearing locked in position and the feet fixed. This study verified that integration of a boot featuring a multidirectional ankle joint was both possible and practical. These features demonstrated a significant benefit for walking mobility on a planetary surface in terms of comfort, security, and walking speed. It also enabled a more natural walking motion in a pressure suit: less learning and concentration were required. The results of this study were subsequently shared with NASA and the international technical community. The spacesuit community response was sufficiently favorable that HS funded further advanced boot development in 2001.

One suit system area where NASA and the RSA were able to conduct a joint activity was in the development of the Russian Simplified Aid For EVA Rescue (SAFER). The SAFER was initially developed in the U.S. as an element of the enhanced EMU. The need for a system such as the SAFER arose from the realization that, should the primary crewmember-to-station restraint tether fail, there was no backup means of retrieving the crewmember, since the ISS could not maneuver

Figure 11.2.2. Study of walking on uneven terrain (courtesy Hamilton Sundstrand).

for rescue as could the Orbiter. Redundant tethers were deemed too cumbersome and the likelihood of entanglement too great. The SAFER reached EVA service aboard Shuttle flight STS-64 on September 16, 1994 (Figure 10.3.2). NASA and the RSA agreed in late 1995 that ISS safety requirements necessitated the development of a Russian version of the SAFER to interface with the Russian Orlan EVA system. This drew into interaction NASA, the RSA, Zvezda (the maker of the Orlan), and HS (as liaison and technical support for NASA).

Based on the SAFER requirements and drawings of the Orlan suit, NASA developed initial concepts of how the Russian SAFER might fit on the Orlan (then DMA) suit. Several iterations of Russian SAFER mockups were made in the U.S. in support of this project as the Orlan-M was completing development and certification. In parallel, the RSA and Zvezda reviewed the NASA design and began developing their own version to meet RSA requirements. In 2002, Zvezda completed the development of the Russian version of the SAFER system that was designed for use with the Orlan-M spacesuit. A limited number of training and flight units were produced by Zvezda in the next few years but the RSA ultimately deferred their delivery to the International Space Station to conduct flight testing.

In the later 1990s, HS would internally fund limited development with Zvezda in relationship to planetary exploration.

The days when astronauts always used U.S.-made spacesuits and cosmonauts always used Russian (Zvezda) made suits came to an end on April 29, 1997 when the

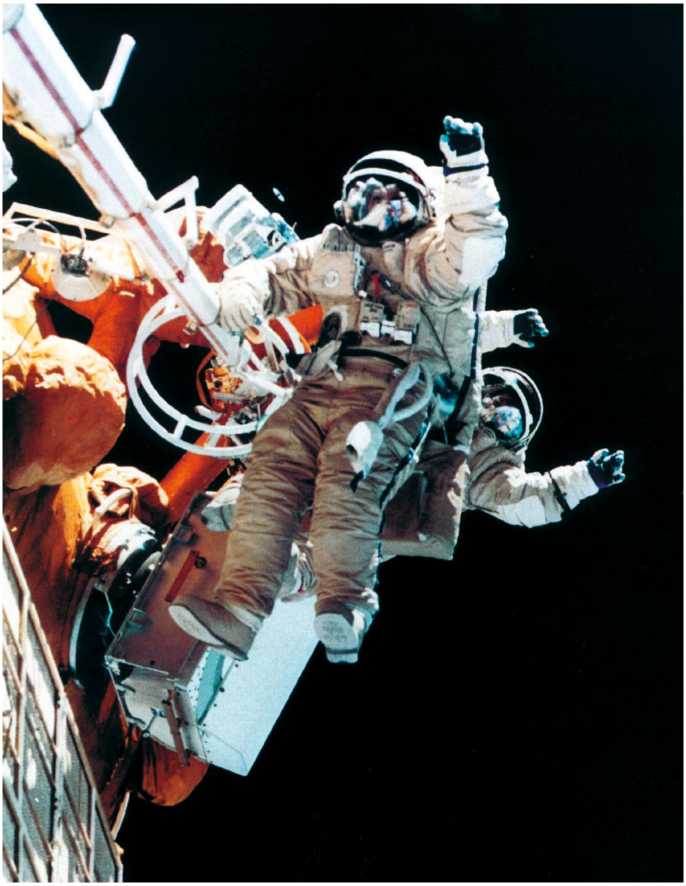

Figure 11.2.3. Zvezda Orlan-M suits in first U.S./Russian EVA (courtesy NASA).

Orlan-M made its EVA debut. This was the world's first Russian/U.S. crewmember EVA (Russian EVA #78, U.S. EVA #77) (Figure 11.2.3). After this activity, astronauts and cosmonauts would use Russian and U.S.-made spacesuit systems interchangeably with increasing frequency. In yet another revision of identity, the Russian Space Agency was renamed the Russian Federal Space Agency (FSA) in April 2004. The FSA is also frequently called Roscosmos.

11.3 BACK-TO-THE-MOON AND ON-TO-MARS IDEAS OTHER THAN PROJECT CONSTELLATION

The early 1990s brought a resurgence in interest for a human revisit to the Moon (Figure 11.3.1) and progressing onto Mars (Figure 11.3.2). This interest brought new participants and a mix of NASA and internally funded developments that were

Figure 11.3.1. In situ resource processing on the Moon (courtesy NASA).

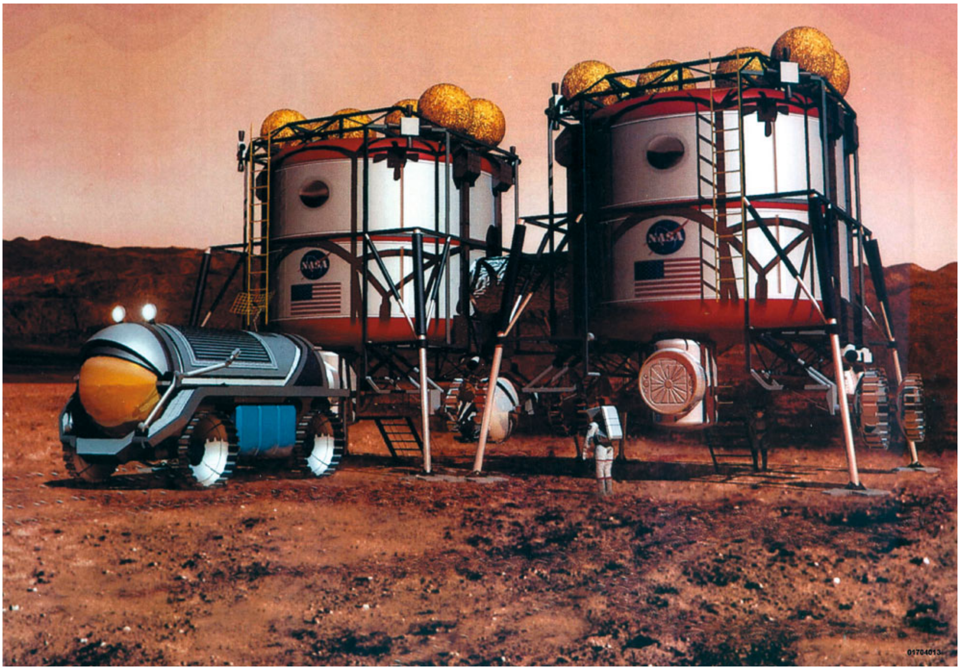

Figure 11.3.2. In situ resource processing on Mars (courtesy NASA).

expected precursors to next-generation spacesuit system developments. This ultimately led to NASA's Constellation Spacesuit System (CSSS). However, in parallel, non-CSSS lunar/Mars spacesuit activities continued. While it is unclear if CSSS will survive and, if so, in what form, this section attests to development continuing to support the vision of human deep-space exploration.

Entrepreneurial EVA spacesuit efforts (1989–present)

The vision of back-to-the-Moon and Mars missions brought newcomers from outside the traditional NASA spacesuit community. While what role these entrepreneurs will play in extravehicular history is unclear, it is certain that their presence adds flavor to the EVA spacesuit story.

The most interesting U.S. suit idea from the 1980s probably was the proactive Brand Norman Griffin command/control pressure suit concept. Griffin was Boeing's Advanced Civil Space Systems Project Manager during the 1989–1990 period. As an independent pursuit, Griffin along with Paul Hudson concepted the suit system to have a "portable command center" hard upper torso (HUT) named "the rigid upper torso/helmet". This HUT was to feature flat glass panes with disposable scratch guards protecting against abrasive lunar dust. Adjustable louvers and a removable gold-coated faceplate shield would guard against fierce sunlight. The HUT's interior would have color liquid crystal screens mounted on side rails and at the astronaut's forehead locations to display maps, suit data, remote camera views, checklists, and other information.

Like the preceding NASA Space Station *Freedom* advanced EMU, this suit system was to have an 8.3 psi (57 kPa) operating pressure to preclude pure oxygen pre-breathe, use a rear hatch for entry, and utilize voice-activated controls, thus freeing the chest area of cumbersome control boxes. The rear hatch would also provide the attachment point for a modular, replaceable, interchangeable life support system backpack.

Griffin's project progressed to the creation of a mockup HUT designed to interface with existing ILC Shuttle EMU arms, gloves, and lower-torso assembly. Through NASA's loaning of training EMU components, Griffin was able to assemble a vent pressure (less than 1.0 psi/6.9 kPa) demonstrator (Figure 11.3.3) that was tried out by many including Apollo 17 astronaut Harrison Schmitt. The demonstrator was additionally evaluated in lunar and Mars gravity aboard NASA's KC-135 before the NASA suit components were returned and the technical evaluation of this concept came to a close. However, the command/control pressure suit's greatest visibility was yet to come. The Smithsonian's National Air and Space Museum was looking for a Mars suit for a space exploration exhibit entitled *Where Next, Columbus?* and contacted Griffin and Hudson. They produced two donnable replicas for static display. One unit remained on Smithsonian exhibit for a decade.

Research for *The Origins and Technology of the Advanced Extravehicular Space Suit* led the author, Garry L. Harris, to become launch and entry spacesuit designer for Weaver Aerospace in the early 1990s. While his mission was

Figure 11.3.3. 1990 Griffin command/control pressure suit upper-torso prototype (courtesy G. L. Harris/B. Griffin).

intravehicular-type suits, his supporting testbed prototype (see Figure 11.3.4) had a rear-entry hard upper torso, which seemed to better fit the theme of his book. Harris would later team up with an aerospace engineer named Pablo de León for the suit efforts discussed later in this chapter and in Chapter 4.

In 1990, the University of Maryland created the Space Systems Laboratory, based on personnel and technology that originated at the Massachusetts Institute of Technology. At the same time, the University of Maryland began the development of the Neutral Buoyancy Research Facility, based around a 50 ft. (15.2 m) diameter by 25 ft. (7.6 m) deep water tank for space simulation. This facility opened in 1992. In 1996, the University's Space Systems Laboratory started a neutral buoyancy suit system effort entitled MX-1. This was accomplished by 1999 through University internal funding and student labor. The MX-1 demonstrated the challenges to creating a functional neutral buoyancy spacesuit analog system and provided the experience base for the MX-2 effort that followed. By 1999, the University of Maryland had also teamed up with the ILC Dover subsidiary of ILC Industries Incorporated on a power-assisted space glove (p. 366) and had completed a research effort for NASA developing in-suit bioinstrumentation for measurement of body joint angles and neuromuscular activity.

In 1999, the University of Maryland started development of a second NBL suit system, the MX-2. The body of the MX-2 suit analog consists of a hard upper torso of handcrafted resin and fiberglass with an integrated hemispherical helmet and rear-entry hatch, which were adopted from the MX-1 design. The three layers of arm and lower-torso softgoods are a urethane-coated nylon pressure bladder, a nylon restraint layer, and an integral ballast garment. Designed for human use at 3 psi (21 kPa), the MX-2 will provide an appreciation for the outer envelope and joint restrictions of operational pressure suits. It will also deliver realistic visual and audio environments and a "dry" interior for instrumentation. By 2002, dry surface tests of simple joints had compared MX-2 (Figure 11.3.5) joint torques with those of an EMU elbow. By 2004, the MX-2 had gained an umbilical open-loop life support system. In 2005, the MX-2 completed manned rating, by internal standards, for use in the University of Maryland's Neutral Buoyancy Research Facility.

In 2005, the University of North Dakota (UND) started on the path of joining the fraternity of spacesuit developers by retaining Pablo de León as principal investigator to start a human spaceflight component for the Department of Space Studies. De León formerly provided the same role for an Argentinian neutral buoyancy suit effort that successfully produced a series of prototypes in the 1990s that were similar in configuration to the U.S. Shuttle extravehicular mobility unit. In 2002, de León emigrated to the U.S. where he met Gary Harris, the author of *The Origins and Technologies of the Advanced Extravehicular Space Suit* and former suit designer during a brief Weaver Aerospace effort (discussed in Chapter 4).

In 2004, UND hired de León as a project manager to enhance their space efforts. One of the first projects was a prototype spacesuit effort. UND originally called their suit project the North Dakota experimental planetary spacesuit. It won a $100,000 NASA Aerospace Workforce Development grant in 2005. Hamilton Sundstrand and NASA were technical monitors of the project. Completed in April 2006, the dual-plane, mid-entry prototype gained the name "North Dakota Experimental #1" (NDX-1) suit. The NDX-1 was unveiled in Badlands testing (Figure 11.3.6, left; note de León in background). The softgoods (Figure 11.3.6, right) were designed and fabricated by Harris. The helmet and various other suit elements were fabricated by faculty and students. Pressure testing unmanned was conducted up to 5 psi (34.5 kPa) but manned testing was limited to only 2 psi (13.8 kPa) for safety reasons. While this prototype was well received in the world press, this would prove to be an iterative step.

In 2004, de León and Harris also started collaboration on a prototype under the auspices of De Leon Technologies LLC. This prototype, named the DL-H1, is discussed in Chapter 4.

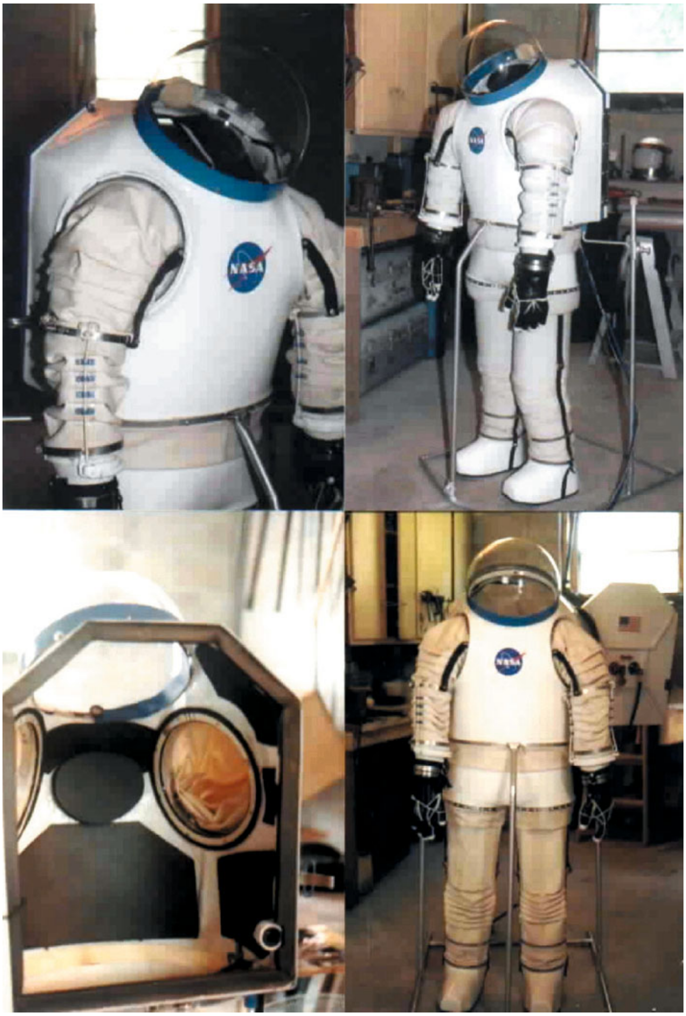

Figure 11.3.4. 1996 (circa) Harris–Weaver EVA study suit (courtesy G. L. Harris).

In 2008, de León and Harris started development on a second planetary extravehicular design under the auspices of the UND. Unlike the NDX-1, the NDX-2 was funded by NASA and did not have student project structural elements in the project that led to technical compromises in the resulting architecture. Student assistance was limited to assembly and refinements.

By the end of 2009, the NDX-2 emerged as a sophisticated rear-entry system featuring soft upper torso and shoulders (Figure 11.3.7). The NDX-2 is designed to operate at 4.5 psi (31 kPa) and with an Earth weight of 105.8 lb (48 kg) indicates a potential to perform the functions needed in lunar and Martian exploration. Of course, this is not the only university working on lunar/Mars spacesuits.

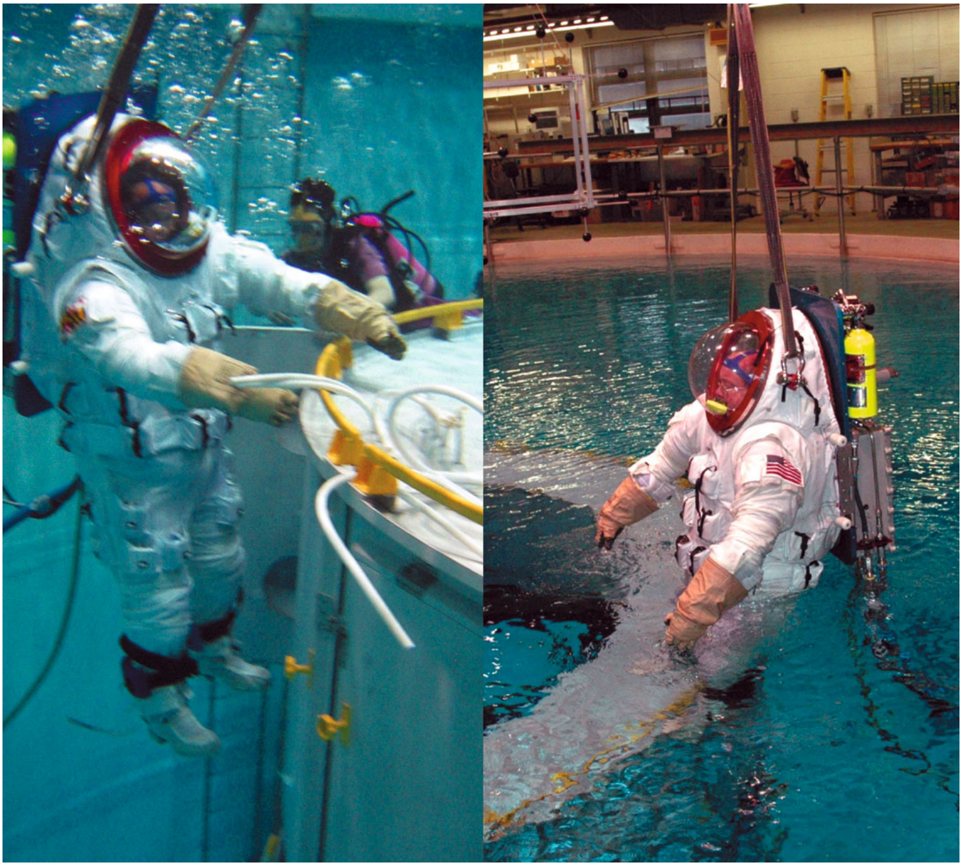

Figure 11.3.5. 2002 MX-2 suit (courtesy University of Maryland).

At the Massachusetts Institute of Technology (MIT), Aeronautics and Astronautics and Engineering Systems professor Dr. Dava J. Newman is the driving force behind an alternative approach to spacesuits. Rather than pressure suits, MIT's bio-suit effort builds on the mechanical counter-pressure approach of Dr. Paul Webb's "skin suit" efforts of the 1960s and 1970s (Figures 7.2.16 and 7.2.17). However, Dr. Newman additionally draws from another spacesuit pioneer, Arthur Iberall, and his theory of "lines of non-extension". Where past mechanical counter-pressure efforts were plagued with uneven pressure issues, Newman is attempting to develop systems to uniformly provide mechanical counter-pressure over the entire body that adjusts to the gas pressure in the lungs and helmet interior. While the research and development are currently being performed at the element level, Newman has additionally created a suit system mockup to illustrate how the spacesuit might appear and perform (Figure 11.3.8).

Figure 11.3.6. 2006 NDX-1 prototype (with and without cover garments) (courtesy University of North Dakota).

NASA-funded efforts leading to Project Constellation (1994–2007)

NASA's initial response to the need for a planetary pressure suit system had two approaches. One was exploration for making the preceding Space Station *Freedom* Mark III suit light enough to support lunar/Mars exploration. This was captured in NASA's hybrid suit effort. The other was funding soft suit research. The first EVA spacesuits were lighter, simpler, and less expensive (per unit) soft suits that also supported launch/entry. NASA's renewed research was to see if lightweight fabric pressure suits could be made sufficiently mobile, durable, and reliable for planetary exploration. In 1997, NASA funded two prototypes, designation "I" and "D" suits manufactured by the ILC Dover subsidiary of ILC Industries Incorporated (ILC) and David Clark Company (DCC). For these efforts, NASA specified that the prototypes should be mid-entry without zippers and be as light as possible while supporting a Gemini/Apollo-like 3.7 psi (25.5 kPa) operating pressure. For the three-suit comparison, none of the mockup cover garments included functional Martian or lunar-type insulation.

Figure 11.3.7. 2010 NDX-2 suit (without cover garments) (courtesy University of North Dakota).

NASA/ILC hybrid "H" suit effort (1994–2000)

The "H" designation stems from the suit being a hybrid mixture of hard and soft suit elements. This suit was originally NASA's advanced prototype Mark III suit from the late 1980s. In the 1990s, the Mark III started to evolve to a lighter system aimed at operation in a gravitational environment. In this evolution, metallic

Figure 11.3.8. 2009 MIT bio-suit concept (courtesy Massachusetts Institute of Technology).

components were systematically replaced by advanced composite graphite fiber equivalents and a waist bearing was added. These graphite fiber substitutions included an A-L made graphite fiber/honeycomb-filled hard upper torso and ILC-manufactured graphite fiber lower-torso assembly hard elements. NASA-JSC added the waist bearing.

The resulting H-suit prototype (Figure 11.3.9) was one of the three NASA-funded advanced suits (the H, I, and D) of the mid 1990s that were part of comparative testing that included KC-135 Mars and lunar gravity evaluations (Figure 11.3.10). NASA uses a specially modified KC-135 aircraft to fly to maximum altitude and then, by going into a very precisely controlled descent, is able to effectively reduce the gravity to Martian ($\frac{3}{8}g$), lunar ($\frac{1}{6}g$), or zero for periods of less than a minute. This permits somewhat short but amazingly accurate Earth testing of non-terrestrial conditions. The H-suit was by far the heaviest of the three suits but had the best mobility. The H-suit test configuration was far from a potentially minimal weight. The evolution of the H-suit continues as funding for development is found.

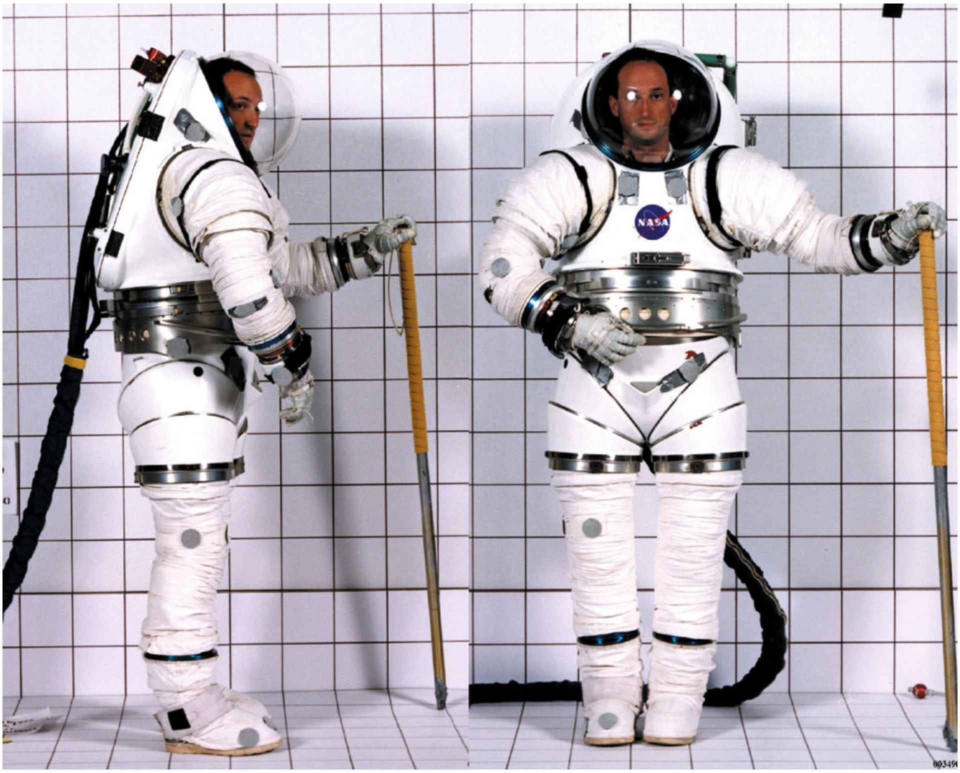

Figure 11.3.9. NASA/ILC hard/soft element hybrid H-suit (courtesy NASA).

ILC (NASA-funded) "I" suit (1997)

During the period of its creation, the "I-suit" (for ILC) was also known as the "L-suit" (for ILC's Apollo lunar development designation) or "M-suit" (for Mars). The I-suit (Figure 11.3.11 was primarily a soft suit, yet it incorporated a number of bearings at the shoulder, upper arm, and hip/thigh areas. The suit was mid entry (like the Shuttle EMU) but it featured a soft upper torso (SUT) in place of the hard fiberglass equivalent.

The helmet (less visor assembly) and suit-side helmet disconnect were Shuttle EMU style and late Apollo/Skylab style, respectively.

The SUT was made from Shuttle restraint fabric and bladder cloth and had internal restraints to determine the position of the waist, scye, and helmet rings. The SUT had three Air-Lock Apollo-style umbilical disconnects mounted on the back. Two were for ventilation inlet and exhaust, respectively. The third connector accommodated both inlet and outlet for cooling water to a liquid-cooling garment.

A body seal closure of ILC design and manufacture provided the interface between the SUT and the lower-torso assembly (LTA). The opening shape and size were essentially that of a large-size Shuttle EMU. The shoulder, waist, thigh,

Figure 11.3.10. H-suit in lunar/Mars gravity walking tests (courtesy NASA).

and ankle joints on this suit were fabric joints with axial restraints and symmetric convolutes formed by sewn sections. The waist was a fabric joint that utilized sewn fabric sections to create break/fold points similar to the shoulder. The waist joint also used a film bladder. The I-suit brief, like that of the H-suit, had a multibearing design that allowed much greater lower-torso mobility than that of the Shuttle and Apollo EMUs. In this area, ILC had obtained information on different brief designs from the Ames Research Center before initiating their design. The leg was very similar to that of the baseline Shuttle EMU. The boots started as commercially available work boots but were extensively modified with an inflatable bladder for foot-sizing adjustment and to permit interface with the ankle joint of the pressure suit. The operating pressure of the I-suit was 3.75 psi (25.8 kPa).

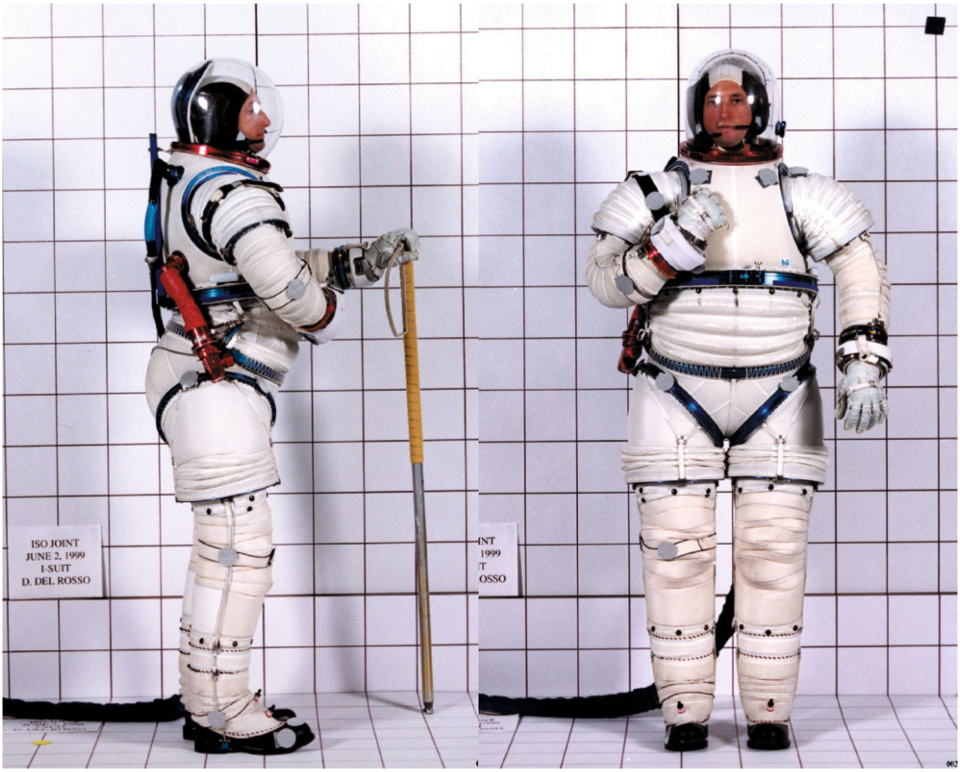

Figure 11.3.11. ILC "I" lunar/Mars soft suit (courtesy NASA).

The shoulder and arm had bearings in locations similar to those of the Shuttle EMU. The bearings were commercial items installed into housings that interfaced with the fabric sections. The lower arms were similar to Shuttle units but had loops for sizing adjustment. The bladder material in most locations was Shuttle EMU urethane-coated orange nylon cloth, but ILC tried a new proprietary vacuum-formed urethane film approach in most of the convolute locations. The suit used Shuttle EMU gloves.

In the H, I, and D-suit KC-135 testing, I-suit (Figure 11.3.12) overall mobility was a close second to the H-suit and was the middleweight of the three pressure suits. Beyond this NASA-funded effort, ILC internally funded a follow-on second-generation I-suit (see Section 11.2) and has continued development.

David Clark (NASA-funded) "D" suit (1997)

Early in the proposal/development process, various parties referred to this suit as either the C-suit (for David Clark Company's Gemini/Apollo designation) or the D-suit. The D-suit was the official/final designation. The D-suit built on an advanced Apollo fabric suit concept of the late 1960s (Figure 7.2.11). Like the I-suit and the

Figure 11.3.12. I-suit in lunar/Mars gravity walking tests (courtesy NASA).

Shuttle EMU, the D-suit (Figure 11.3.13) was mid-entry and had bearings only in the arms immediately above the elbows. Without its cover garments in place, the black restraint outer fabric probably made this suit the most dynamic appearing of the three prototypes. The helmet used with the D-suit was a NASA-furnished Apollo "bubble" mated to an Apollo neckring.

The upper torso utilized a very different technical approach for mobility than the H or I-suits. The outer restraint fabric was a very sheer (thin/lightweight) synthetic. The chest's Link-net restraint system attached at the bottom at the body seal closure but was otherwise free floating. The shoulder cable restraints were a 1960s-style, metallic cable system that was provided for shoulder mobility. Each shoulder cable started at the top of a rear mounting plate, looped over the shoulder, looped at a front mounting plate, looped back over the shoulder and then terminated

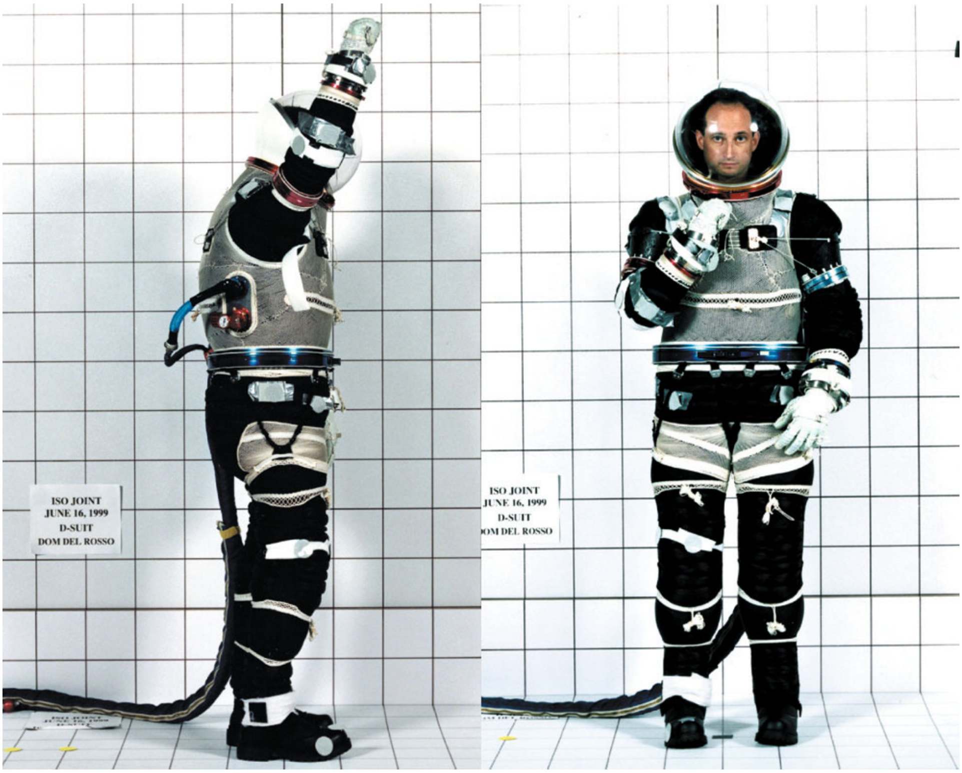

Figure 11.3.13. DCC "D" lunar/Mars soft suit (courtesy NASA).

at the rear plate. The bladder material in the upper torso was common to Shuttle launch entry suits. The arms incorporated convolute mobility joints with webbing axial restraints. The life support connectors were located on the back as specified by NASA. The mid-entry body seal closure (BSC) was of Air-Lock (wholly owned subsidiary of David Clark Company) manufacture and was a derivation of the size large EMU BSC. The D-suit BSC differed from the EMU type in that the upper-torso side was made of aluminum and lacked mini-workstation mounts, which are front protrusions to the Shuttle EMU BSC for attachment of the EMU's work table and toolkit system. The H, I, and D-suit all had no accommodations for carrying tools other than tether attachment points.

The lower-torso assembly utilized a restraint and mobility configuration like that of the arms. The bladder material was an experimental polymer material. The boots started as winter hiking boots that were modified to integrate the ankle pressure joints.

In the H, I, and D-suit KC-135 testing, the D-suit (Figure 11.3.14) was found to be less mobile than the other two pressure suits. However, it is expected that the D-suit would have a comfort advantage when used in conjunction with riding in the

Figure 11.3.14. D-suit in lunar/Mars gravity walking tests (courtesy NASA).

seated position on rover-type vehicles or in launch/entry scenarios. Of the three suits, the D-suit was the lightest, weighing just 22 lb (10 kg) including helmet, gloves, and mockup cover garments.

OSS extravehicular life support system (ELSS, 1997–present)

Starting in 1996, NASA funded OSS to develop an advanced cryogenic portable life support system (AC PLSS) for lunar and/or Mars missions field simulations. NASA utilized an AC PLSS in conjunction with its hybrid or H-suit (formerly Mark III) to support manned testing in 1997 and performed evaluation of the AC PLSS in the deserts of Arizona in 1998. Over a period of two weeks, NASA completed eight 2-hour manned tests with the OSS backpack and NASA

Figure 11.3.15. The OSS ELSS in 2006 "desert rats" evaluation (courtesy NASA).

spacesuit. The name of this system transitioned to the extravehicular life support system (ELSS). The AC PLSS or ELSS would additionally be used with configurations of I-suits, as well as the H-suit, to support a variety of subsequent evaluations such as "desert rats" over the coming years (Figure 11.3.15).

In 2007–2008, the competition for spacesuits to take humans back to the Moon and Mars was given the name of "Constellation Spacesuit System" (CSSS). The strategic presence of the ELSS and OSS in almost all NASA spacesuit development activities spanning a decade probably contributed significantly to OSS winning the CSSS competition.

Honeywell/University mechanical counter-pressure efforts (2000–2002)

Since the 1960s, mechanical counter-pressure (MCP) has been viewed as having the potential for low-effort, almost unrestricted range of motion and simple heat removal in spacesuits. Pursuit of MCP did not end with the last "Webb suit" of the early 1970s (Figures 7.2.16 and 7.2.17), but continued in the 1980s and 1990s at an experimental level at the University of California San Diego (UCSD) and other locations.

In parallel, Honeywell had interest in developing MCP into a viable suit system technology. The aforementioned academic community, NASA, and Honeywell

Figure 11.3.16. Honeywell mechanical counter-pressure (MCP) glove (courtesy NASA).

interests transformed into a NASA-funded 3-year study under Honeywell with the University of California San Diego as a partner. Referred to by many as the ‘‘skin suit’’, this technical approach is far different from the traditional full pressure suit, as it replaces the inflated suit enclosure with a compressive garment. The first element of this study was a MCP glove, which was in test in 2000 (Figure 11.3.16) and progressed to other limb elements. The overall effort provided insight into MCP effects on human physiology and the potential feasibility of this technology in the future.

NASA-JSC ‘‘desert rats’’ advanced suit field studies (1998–present)

NASA’s Desert Research and Technology Studies team of scientists and engineers periodically conduct field studies with advanced suits in Arizona’s Meteor Crater and Cinder Lake area as this is an Earth location that provides a surrogate planet surface. The team is principally led by Johnson Space Center (JSC) Advanced Suit Laboratory personnel that draw on a variety of contractor organizations for support. This permits gaining experience and testing experimental systems in a challenging planetary-like setting (Figure 11.3.17). The pressure suits used in desert rats were almost exclusively the NASA/ILC H-suit and the various I-suit iterations. These experiments were supported by the previously discussed, autonomous (non-umbilical) OSS ELSS.

To augment advanced suit field studies NASA-JSC additionally started building an on-site ‘‘rock pile’’ for real time evaluations in preparation for full scale field

Figure 11.3.17. NASA's H-suit with the Field Science Team (courtesy NASA).

trials. In 2003, the rock pile gained some significant upgrading as part of an overall plan to create a high-fidelity Mars analog.

In 2007, NASA ordered vent pressure, suit port analog suits (derivations of a Mark III replica "movie suit') from Global Effects to support NASA's small pressurized rover evaluations the following year (Figure 11.3.18).

NASA Haughton Mars Project (1999–present)

In the 1990s, NASA's Ames Research Center (ARC) had specialized in Mars analog studies here on Earth. Pascal Lee, then a postdoctoral researcher at NASA Ames, proposed to investigate Haughton Crater located on Devon Island in the Canadian High Arctic. Haughton is a 15-mile wide impact crater that was created over 23 million years ago by a large meteorite. This crater is unique in that it is set in a Mars-like environment: a cold, windy, dusty, rocky, and generally dry environment that is mostly unexplored. Impact craters are likely exploration sites because they provide access to planetary bedrock and are possible locations of liquid water activity, at least at the time of crater formation. In addition to the crater, the surrounding terrain on Devon Island proved to present a wide range of other analog features: canyons, valley networks, and gullies.

Figure 11.3.18. 2008 NASA small pressurized rover using Global Effects suits (courtesy NASA).

With the realization that this site was of great value for science and exploration, NASA-ARC formalized the NASA Haughton Mars Project (HMP) to study the Mars analog terrain and evaluate tasks that geologists, biologists, and other explorers will need to perform during the scientific exploration of a planetary surface, be it the Moon or Mars. The HMP studies are fundamentally similar, if only in part, to scientific content, geological setting, and logistical limitations of what could be expected in the early exploration of Mars. For the creation of the NASA HMP base in 1999 and subsequent annual study efforts, ARC partnered with the SETI Institute and many other organizations, public and private, domestic and international, including the Canadian Space Agency, Hamilton Sundstrand, and a wide variety of academic institutions and non-profit organizations.

The Haughton Mars Project continues to provide a unique opportunity to observe potential Mars suit users in a realistic terrain as they explore and work. These studies have included suited and unsuited activities such as the evaluation of biological work site terrain, geological exploration and use of field tools, evaluating suit-system-to-vehicle effects on transportation to work sites, testing of advanced field communications and informational display systems, and overall surface operations and mobility systems.

Figure 11.3.19. Evaluating transportation/suit interfaces (courtesy Hamilton Sundstrand).

The suits used in these studies thus far have been Hamilton Sundstrand Mars concept suits (Figure 11.3.19 and Section 11.3.3) and Mars Society spacesuit facsimiles. In 2001, Mars Society facsimile canvas suits (Figure 11.3.20) were created to support HMP timeline studies and to allow "Haughtonauts" limited exposure to the realities of performing surface exploration in spacesuits. The facsimile suits weighed approximately 25 lb (11.3 kg) and required assistance plus 30 to 40 minutes to don. The weight of the garment and the suit's thick gloves provided encumbrance, sensory restriction, and (to a limited degree) a spacesuit feel. It was recognized that the facsimiles were much more mobile than full pressure spacesuits. However, the suit's battery-powered fan providing limited ventilation flow probably provided humidity and carbon dioxide challenges like those of a pressure suit. Additionally, the time needed to don the facsimiles approximated the time needed to fully check out a real spacesuit before venturing out into space. These studies enhanced the understanding of Mars EVA system requirements and demonstrated how planetary spacesuit features such as mobility, integration, and reduced weight have not yet been adequately developed. Also, these canvas suits were used for public outreach activities that summer.

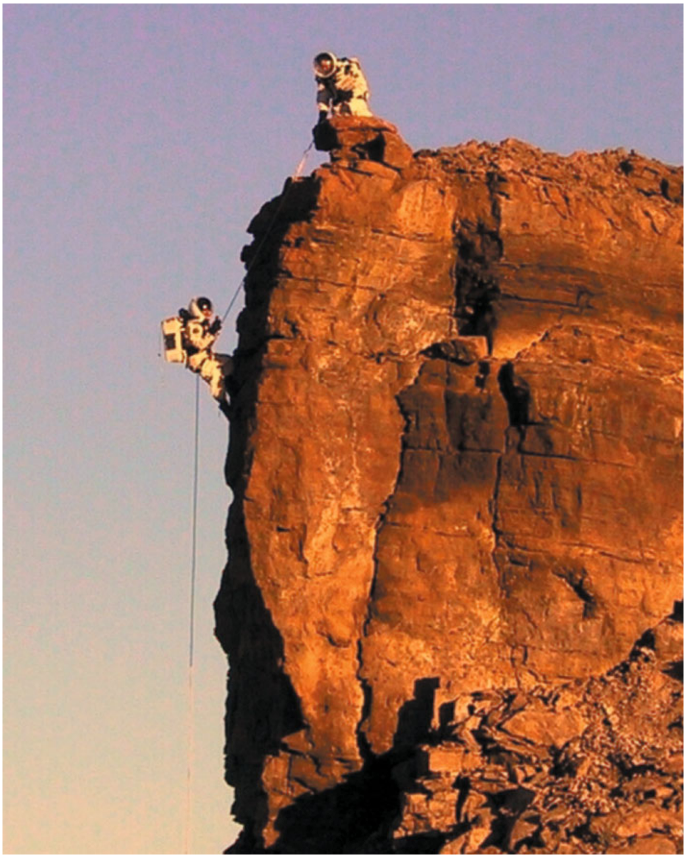

Figure 11.3.20. Geologists collecting difficult-to-reach samples (courtesy NASA Haughton Mars Project/P. Lee).

Proactive contractor efforts (1996–present)

In keeping with space community goals of going back to the Moon and on to Mars, two NASA contactors chose to self-fund lunar/Mars spacesuit developments in advance of and then in parallel to Project Constellation. The contractors were Hamilton and ILC Industries. While these developments were, for the most part, independent activities following different paths, they appeared to share a common or complementary vision of the future.

Hamilton Sundstrand efforts (1996–present)

Starting in 1994, Hamilton Standard (HS, now Hamilton Sundstrand) started expending internal resources on spacesuit system development studies focused on

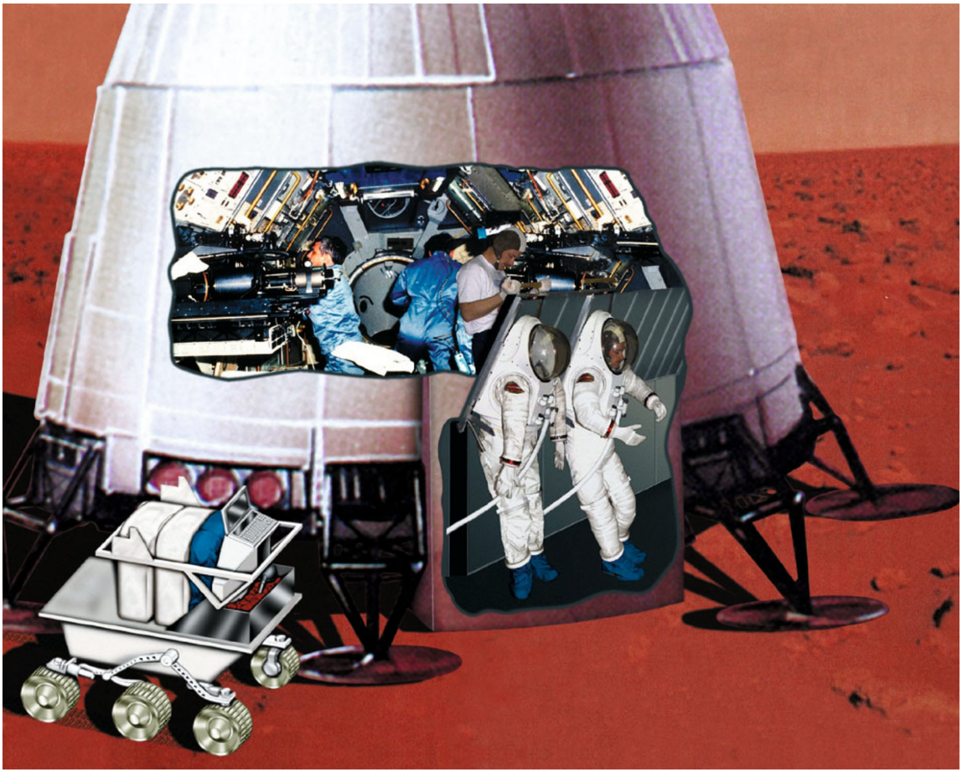

Figure 11.3.21. 1998 HSSSI's Mars habitat concept (courtesy Hamilton Sundstrand).

back-to-the Moon and on-to-Mars ideas. In 1996, a formal team was established, which in 1997 was funded to produce a system level spacesuit prototype. While the NASA-funded activities were focused on full pressure suits, HS's focus was on the other elements of a potential lunar/Mars suit system such as overall architecture, communications, interfacing with vehicles/habitat/robotic support vehicles, and life support systems. A prototype system was concepted specifically for a Martian mission as it was considered the greatest technical challenge (Figures 11.3.21 and 11.3.22).

The 1998 prototype or mockup was a vent pressure (less than 1.0 psi or 7 kPa) system to minimize cost and maximize safety while concepting a planetary exploration suit. The suit portion featured a novel rear/top-entry concept where the hatch was actually larger than the hard upper-torso (HUT) opening. This provided a blowout-proof mechanical retention around the parameter of the hatch. The suit was provided a closed-loop environment that demonstrated adding and removing thermal overgarments to help control internal temperatures by taking advantage of the normally cold Martian environment for heat rejection. The backpack life support was a minimalist concept that offered changeable-during-mission interfaces and light

Figure 11.3.22. Changeable PLSS and removable garments mockup (courtesy Hamilton Sundstrand).

weight (i.e., no battery or moving parts in the gas recirculation system) and a regenerable CO_2 removal system (no replacement of cartridges required). Hearkening back to the Gemini ELSS, an ejector powered by makeup oxygen breathing gas provided ventilation flow. A small amount of gas was vented overboard, thus aiding humidity control and lowering CO_2 removal demand. The suit system also featured a voice recognition system (VRS) communications system to control spacesuit functions and also to control a robotic support vehicle. The full name of the support vehicle was "fully independent delivery of operational expendables" (FIDOE). FIDOE's on-board guidance system allowed the vehicle to follow the crewmember at a prescribed distance while avoiding obstacles. FIDOE would also stop (stay) or move on voice command. Two versions of the HS testbed were made. The first was a working "breadboard" lab system that could be demonstrated. As the lab unit was most often disassembled for further development, a mockup representation of the concept was created to allow visitors and customers to understand the concept. The testbed would later be retroactively designated the "HS Lunar–Mars Spacesuit Concept Number 1" (LMS-1) suit.

From 1997 to 2001, HS internally funded the planetary ankle and boot development studies in conjunction with Zvezda, the Russian spacesuit manufacturer (discussed in Section 11.2).

HS funded a follow-on lunar/Mars study in 1999 that was to ultimately produce a lower cost Neutral Buoyancy Laboratory suit representing advanced planetary and orbital features. To achieve a reduction in cost, commercially available parts were to be used wherever possible. This started with an updated requirements review that benefited from the preceding lunar/Mars testbed effort and progressed to comparative analysis of all possible suit system variations against those requirements. The study then selected a suit system architecture, did a preliminary design, and started the build of a full pressure prototype. The 1999 goal was to produce the hard upper torso (HUT) element of the suit. The HUT was to be both lighter and less expensive to manufacture than equivalent Shuttle EMU components. This HUT differed from the preceding HS design in that it utilized a rear hatch, roughly based on the Russian Orlan configuration. The resulting man-ratable HUT prototype met those requirements and embodied features to support an adjustable "two-sizes-fit-all" sizing system, and a planetary suit-to-user harness system. However, a changing vision of what the next-generation spacesuit should be caused this activity not to be funded in 2000. This short-lived effort is sometimes referred to as HS's LMS-2.

Also in 1999, as follow-on to the portable life support system (PLSS) of the 1996–1998 lunar/Mars integrated testbed, HS internally funded another advanced PLSS study. The objectives of the study were to evaluate the performance and integration of several promising advanced life support technologies and to use these technologies to design, assemble, and test an integrated portable life support subsystem adaptable to use in the space vacuum or in the Martian atmosphere. This effort produced a flexible benchtop testbed suitable for further use in future life support technology integration studies. The most notable technology elements of this testbed were a cryogenic oxygen storage system, a continuously regenerable CO_2 removal system, and a supersonic ejector ventilation gas drive. The cryogenic storage system demonstrated regenerative heating for pressure control that was practical and saved significant weight over a comparable gaseous oxygen system. The continuously regenerating CO_2 removal subsystem proved capable of operation in orbital, lunar, and Martian environments. The supersonic ejector ventilation gas drive illustrated the viability of variable geometry in making gas circulation within the spacesuit without battery power or fan systems potentially low cost to manufacture.

In 2000, HS modified their 1998 Mars vent pressure prototype to support the various Haughton Mars Project (HMP) studies. This provided a complete "Mars suit" (Figure 11.3.19) weighing 70 lb (32 kg) (corresponding to a target-sensed weight for an actual suit on Mars) supporting interface and requirements studies. It was understood that the lack of full pressure rigidity did not provide a fully realistic encumbrance. However, the logistics of transporting and supporting a vent pressure prototype in Arctic Canada was significantly easier than what would have been required for a full pressure suit system. In 2001–2004, Hamilton used just the suit's upper torso as a spacesuit-like platform to support communications studies (Figure 11.3.23) and a range of interface investigations centered on the nature of data displays and the nature of information to be made available during field exploration.

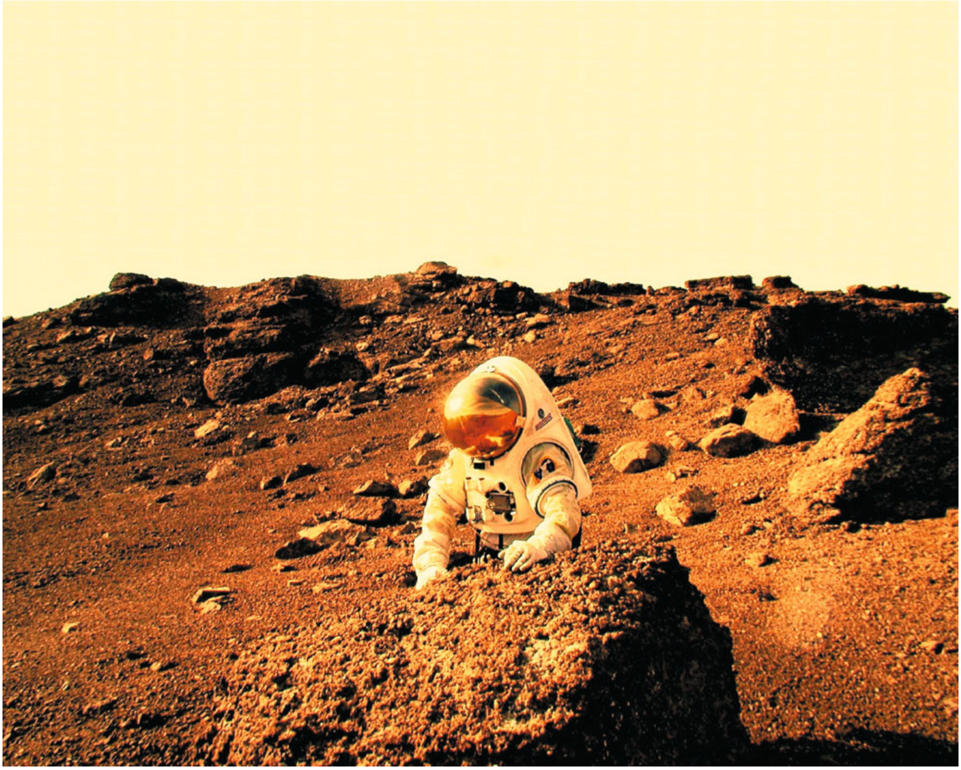

Figure 11.3.23. Advanced communications testing (courtesy NASA Haughton Mars Project/ P. Lee).

For 2004, 2005, and 2006, HS designed and manufactured a new suit facsimile each year representing entry and interface architectures for HMP evaluation. These were non-pressurized volumetric suit system mockups. The 2004 HS LMS-3 saw one evaluation season with technical features never reaching the public domain. The 2005 LMS-4 and 2006 LMS-5 units featured the rear hatch and life support being donned first—like a hiker's backpack—before donning the remainder of the suit. These were used together for rescue simulations in the 2006 through 2008 Haughton seasons.

In August 2006, Hamilton and ILC reached a teaming agreement for the Constellation Spacesuit System (CSSS). To create a more competitive contractual structure, HS and ILC Dover formed a consortium organization named Exploration Systems & Technology (EST).

For the 2009 HMP, HS resurrected the LMS-2 HUT suit port mockup and much of the architecture. Completing the mockup analog as a vent pressure suit system of a somewhat revised configuration (LMS-2A), the suit port was integrated into the rear of an HMP Humvee for simulated pressurized rover and field evalua-

Figure 11.3.24. 2009 Arctic evaluation of HS's fifth Mars concept analog (courtesy Hamilton Sundstrand, Windsor Locks, CT).

tions (Figure 11.3.24). To supply a second suit analog for the HMP 2009, HS provided its LMS-5 mockup suit system.

For the 2010 HMP, HS developed and completed its sixth vent pressure analog suit system (LMS-6), which included a suit port. The HS LMS-6 incorporated changes based on feedback from the 2009 season. The LMS-2A provided a second suit and suit port to support NASA's HMP 2010.

ILC Industries' next-generation activities (2000–present)

In the annals of American spacesuit history, ILC Industries has the distinction of demonstrating commitment through internal funding and being a consistent promoter/participant in next-generational activities. After 1998, ILC's continued commitment to next-generational development took the form of four more I-suit configurations. The first came in 2000–2001 with ILC committing internal funding for a second-generation (mid-entry) I-suit. The first focus of this suit (Figure 11.3.25) was to adapt and improve their latest design for use with the existing 4.3 psi (30 kPa) Shuttle life support system to potentially evolve into flight service. For this, ILC

Figure 11.3.25. 2000 ILC second-generation I-suit (courtesy ILC Dover, Fredrica, DE).

developed a "neck wedge" or "Swedge" that introduced an elliptical fighter canopy pressure visor that departed from the Apollo helmet and neckring of preceding suit design. ILC has used this prototype as a testbed for mobility systems and features to possibly support launch/entry scenarios.

The third generation of I-suit came in 2005 with the introduction of rear entry (Figure 11.3.26). Their 2001 internal prototype was retrofitted with a planetary-type (Figure 11.3.27) soft upper torso (SUT). ILC developed this soft rear-entry system and SUT with the goal of designing a lightweight system to support exploration in Mars' heavier-than-lunar gravity. In order to eliminate as much weight as possible, bladder and restraint "Superfabric" replaced most of the SUT, leaving only the rear hatch frame and interfaces to the pressure visor, arms, and lower-torso assembly (LTA) as metal structures. The LTA is the same as was used on the waist entry I-suit, but with the addition of Superfabric kneepads.

In 2006, ILC teamed up with Hamilton Sundstrand (HS) for the Project Constellation Spacesuit System (CSSS) under a consortium named Exploration

Figure 11.3.26. Rear-entry 2005 ILC third-generation I-suit (courtesy ILC Dover, Fredrica, DE).

Systems & Technology (EST). In support of the EST proposal, ILC internally funded a fourth-generation I-suit prototype of their proposed launch, entry, and abort (LEA) and contingency EVA suit configuration (Figures 11.3.28 and 11.3.29). This was not a requirement of the request for proposal (RFP), nor was such an inclusion banned by the RFP. The prototype featured the flip pressure visor ILC had earlier developed under a CSSS pre-competition study contract (Figure 11.4.3) and included the features ILC deemed necessary to support LEA and EVA. The design represented a modular adaptive architecture permitting, with minimum switching to additional modules, the suit to be reconfigured to an ‘‘early lunar’’ rear-entry system. EST lost the competition for CSSS. However, the contract award was contested (see Section 11.4.2) and NASA announced a recompetition.

In the recompetition, the suit requirements for the first phase of CSSS had changed. This made the 2007 ILC CSSS prototype obsolete. In anticipation of this possibility, ILC internally funded the development of a fifth-generation I-suit that featured an all soft torso and shoulders with a mid zipper entry system for the CSSS recompetition (Figure 11.3.30).

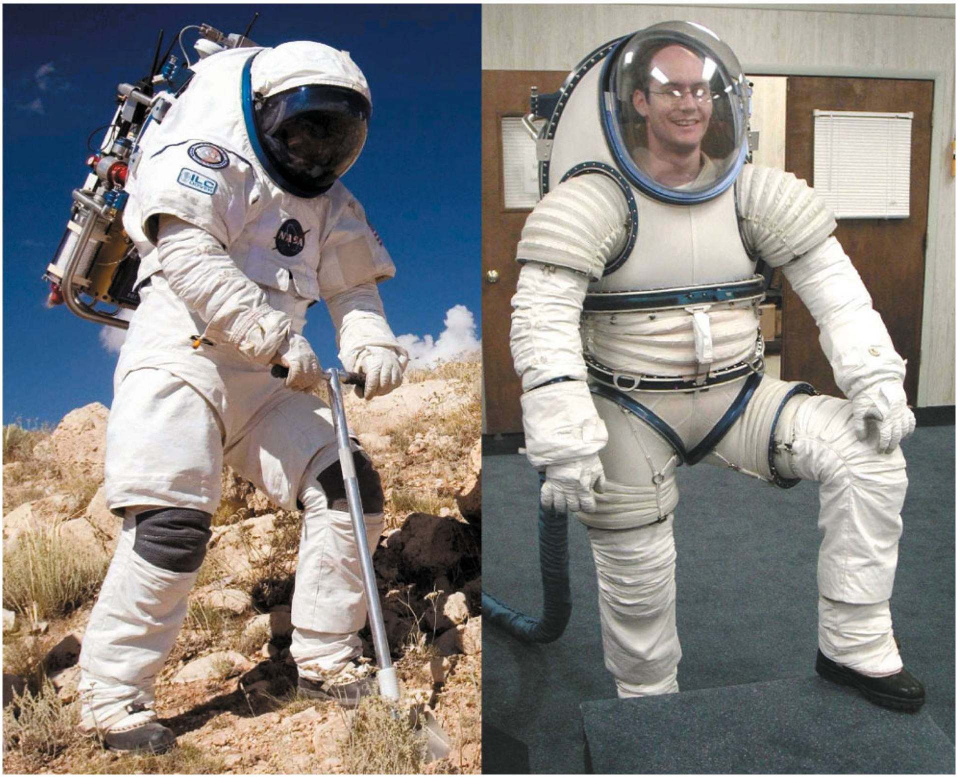

Figure 11.3.27. Planetary third-generation mobility (courtesy ILC Dover, Fredrica, DE).

Figure 11.3.28. 2007 ILC fourth-generation CSSS competition I-suit (courtesy ILC Dover, Fredrica, DE).

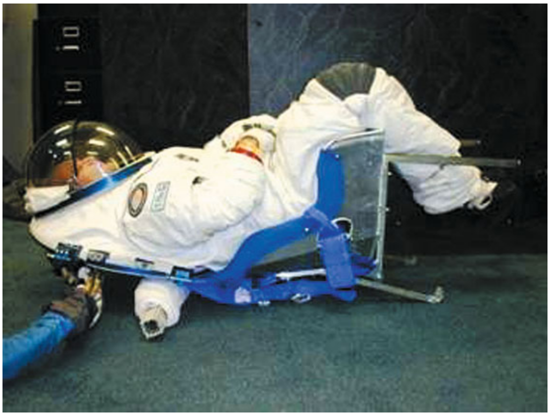

Figure 11.3.29. ILC fourth-generation I-suit in launch comfort demo (courtesy ILC Dover, Fredrica, DE).

Figure 11.3.30. 2008 fifth-generation all soft recompetition I-suit (courtesy ILC Dover, Fredrica, DE).

11.4 CONSTELLATION SPACESUIT SYSTEM (2007–2010)

As Section 11.1 will attest, the last quarter century has seen many next-generation spacesuit efforts. Most have focused on planetary exploration. None have progressed past the prototype level to see space service. With the new millennium, NASA's human space exploration efforts continued under the name of "Project Constellation". This program is to create a new generation of spacecraft consisting primarily of the Ares I and V launch vehicles, the Orion Crew Capsule, the Earth Departure Stage, and the Lunar Surface Access Module. These spacecraft will be capable of performing a variety of missions, from Space Station resupply to lunar and later Martian landings. To support these missions, NASA elected to implement an adaptable suit system named the "Constellation Spacesuit System" (CSSS).

Development studies leading up to the CSSS competition

Three key CSSS development contracts were awarded in October 2006. One contract was for the design and prototyping of two spacecraft-to-suit umbilical systems. With the spacecraft-to-suit umbilical systems, one was to connect crewmembers to the spacecraft life support system to preserve life should the vehicle lose cabin pressure or if the atmosphere inside the craft became contaminated. The other was for an extravehicular activity (EVA) umbilical system. While the IVA umbilical would be essentially a connection/pass-through, the EVA umbilical would have to address all the functions of NASA's current Shuttle extravehicular mobility unit (EMU) life support system (i.e., ventilation flow, oxygen supply, CO_2 removal, humidity control, crewmember and probably electronics thermal control). The umbilical contract was won by Oceaneering Space Systems (OSS).

The second contract was for lightweight bearing development. This was won by Air-Lock (A-L) Inc. (a subsidiary of David Clark Company, or DCC). A-L had been the supplier of the bearings and disconnects of all NASA spacesuits since Gemini and has been prototyping advanced composite spacesuit components since the early 1990s.

The third study contract went to DCC for an enhanced mobility derivation of its advanced crew escape suit or EM-ACES (Figures 11.4.1 and 11.4.2). This potentially represented a first configuration of CSSS suit that would support launch, entry, and contingency extravehicular activity (EVA). The EM-ACES was different from preceding DCC Shuttle suits in that it operated at 4.3 psi (30 kPa) and had mobility systems to support both extravehicular activity (EVA) and provide more effective crew escape and survival in intravehicular emergencies. The suit system prototype included two helmet configurations: one the traditional launch and entry style with movable pressure visor that is used with Shuttle crew escape suits (Figure 11.4.1) and the other a full polycarbonate bubble helmet (Figure 11.4.2) that would be used in conjunction with an extravehicular visor system for spacewalks. The suit system prototype also included a separately donned crew escape harness with automatic inflation devices for water-landing bailouts.

Figure 11.4.1. Enhanced mobility ACES (courtesy David Clark Co., Worcester, MA).

In strategically less important study contracts, NASA funded ILC for the development of a robust flip-up pressure visor to support a launch, entry, and abort (LEA) configuration suit. The result design was tested in conjunction with an existing I-suit prototype (Figure 11.4.3). NASA also funded ILC to upgrade NASA's existing 1998 mid-entry I-suit to ILC's 2005 I-suit rear-entry configuration. During this period, NASA funded A-L to manufacture a lighter hard upper torso for A-L's H-suit. These contracts, in turn, set the stage for the competition that followed.

Figure 11.4.2. EM-ACES with torso cover garments (courtesy David Clark Co., Worcester, MA).

The CSSS competition, contract, and cancelation

The CSSS proved to be a program of surprises. It started rather routinely with a competition in 2007. The competition was for an adaptable spacesuit system. By changing portions of the suit system, the spacesuit could adapt to three very different phases of use. The baseline or first phase of the contract was for a launch, entry, and abort (LEA) pressure suit that could additionally support contingency extra-vehicular activity (EVA) and umbilical systems. The next phase, Option 1, would be a continuation of the baseline contract without competition. Option 1 would

Figure 11.4.3. CSS study ILC flip visor (courtesy ILC Dover, Fredrica, DE).

produce a lunar EVA adaptation of the baseline contract spacesuit to support the U.S. return to the Moon. The third phase, Option 2, would be another contract continuation without competition. This would be for an adaptation of the Option 1 spacesuit to support human exploration of Mars.

Now, the story of spacesuits has always been more than fabrics, other non-metallics, and metal parts. It is also a story of organizations. First, NASA is not a monolith but rather a large organization comprised of people with potentially differing views. NASA Headquarters in Washington delegates to its centers specific areas of responsibility. The centers are organized into administrative, technical, and quality functions. The center management assigns personnel to programs or tasks. Not all the people are going to agree on how to accomplish those activities. This is illustrated by the contrast in NASA approaches between the Shuttle extravehicular mobility unit (EMU) and the CSSS programs that would run in parallel.

From the outset of the Shuttle EMU program, NASA elected to retain management of just communications and tools. NASA vended the coordination of the other aspects of the spacesuit to a contractor leading a team of subcontractors. In 1977, this was Hamilton Standard. In 1985, NASA elected to remove the crew training and field processing of EVA hardware from the Hamilton contract and restructure it under a separate NASA-JSC subelement for what was hoped to be better management. Field processing was competed and was won by Boeing, which later became part of United Space Alliance (USA). Having the manufacturing and technical support answering to one NASA-JSC subelement and the field processing and flight support to another NASA-JSC subelement caused coordination difficulties and costs. NASA finally chose to merge all EMU activities, including communications and tools, under one program that was issued to Hamilton Sundstrand (HS, previously Hamilton Standard) in 2004. Under the contract, HS and ILC provide EMU components and administrative support to NASA, Oceaneering Space Systems (OSS) supports tools, and USA provides field processing. The program started as a separate contract during Shuttle and continues as a contract under the Space Station.

For the CSSS, NASA elected to take a different management approach and assume the role of systems integrator, just as NASA had done in Mercury, Gemini, most of Apollo, and all of Skylab. This made NASA responsible for all program management and coordination. The approach works successfully for NASA at the Jet Propulsion Laboratory in California for its satellite programs. Many in the NASA spacesuit community believe this approach can provide equal quality with lower cost. NASA issued a request for proposal (RFP) for the CSSS contract in 2007. Two contractor teams submitted proposals in December.

One team was jointly led by a collaboration of Hamilton Sundstrand (HS) and ILC Dover Corporation (ILC). The other team was led by Oceaneering Space Systems (OSS). To pursue and win the CSSS contract, HS and ILC Dover partnered to form a consortium organization named Exploration Systems & Technology (EST). Other team members in the HS/ILC proposal included Lockheed Martin, Raytheon, and Carleton Life Support Systems. In support of the proposal, ILC internally funded a prototype of what ILC envisioned what the first-phase suit for CSSS should be (discussed on p. 402; see Figures 11.3.28 and 11.3.29).

The other CSSS contractor team, led by Oceaneering Space Systems (OSS), included David Clark Company, United Space Alliance, Honeywell Corporation, and Paragon Corporation. The OSS contractor team did not build a suit prototype for the competition.

The evaluation process took almost half a year as there are many steps in the government contracting system. The NASA proposal evaluation team declined to evaluate the ILC prototype suit citing the need to maintain a level playing field between the contractor teams.

On June 12, 1908, NASA announced the selection of OSS as the contractor for Project Constellation's spacesuit system. Under normal circumstances, this would have meant that OSS, DCC, and the rest of OSS's team would progress on to develop and implement the spacesuits to support use of the Orion spacecraft, the return to the Moon, and human exploration of Mars. However, there were surprises ahead.

EST (i.e., HS and ILC) requested a meeting with NASA to gain a better understanding of why they were not selected. This is a right of unsuccessful bidders under the government contracting system and is a common practice so that contractors can learn how to craft better proposals for subsequent competitions. While most of the details of subsequent events are not in the public domain, what followed was unusual. On July 15, 2008, EST (HS and ILC) filed a protest of NASA's contract award with the Government Accounting Office (GAO). This started a preliminary investigation by the GAO that was expected to take up to

100 days. In a document to the GAO dated August 14, 2008, NASA stated that it would not be responding to GAO inquiries "because it has decided to take corrective action". On August 15, 2008, NASA canceled the OSS contract. By the end of September 2008, NASA announced there would be a recompetition.

The recompetition request for proposal (RFP) was issued in November 2008 for delivery of proposals in the next month. Not all sections of the RFP were opened for the reproposal, which limited the opportunity to change the outcome.

In parallel to these events, NASA developments had continued. Testing on cadavers had convinced NASA that the first configuration of the CSSS suit could not have shoulder bearings or hard mid-entry closures. This made the 2007 ILC CSSS prototype obsolete. In anticipation of this possibility, ILC had internally funded the development of an all soft competition suit with a mid-entry zipper system (Figure 11.3.30).

The next surprise came in December 2008 when Oceaneering International (OSS's parent organization), HS, and ILC announced that their organizations had elected to team together under OSS leadership, with NASA concurrence, to support the CSSS. This eliminated a recompetition entirely. In February 2009, the CSSS contract was again, formally, awarded to OSS.

Probably the last surprise of the CSSS came in February 2010 when the Obama administration's 2011 budget was released with no funding for Project Constellation. The administration instead favored increased funding for commercial, less regulated, less proven spacecraft providers to support astronaut and ISS cargo travel to low-Earth orbit. As space programs are established by joint resolutions of Congress (i.e., Congressional acts with long-term support pledged by both political parties), this left the fate of Project Constellation and the CSSS to negotiation.

The administration initially countered by leaving the Orion Crew Capsule as a surviving part of Project Constellation, but making it an escape vehicle for the International Space Station. In this new role, the capsule would most likely have been designed to interface with non–EVA type Russian spacesuits.

The negotiations progressed to an "Orion Light" minimum-cost compromise. This allowed the capsule to continue as a full spacecraft but on a lower development budget; it would also be launched on existing lift systems. The budget for Project Constellation and the CSSS formally ended on October 11, 2010. While there were CSSS prototypes, the time constraints probably caused the development suits to be minor evolutionary derivations of existing technology embodied in the preceding suits, which is in the public domain. As the CSSS program was under Defense Department technical information restrictions, it is unclear when the CSSS prototypes will be declassified to allow public discussion.

The need for minimum cost to save most aspects of the Orion craft appears to have caused extravehicular activity to be dropped from the Orion program. What would have been the CSSS will now be an intravehicular suit system (discussed in Chapter 4). The cancellation of the back-to-the-Moon portion of U.S. space exploration pushes out the need for a planetary extravehicular spacesuit by years. After the retirement of the Shuttle, the enhanced version of the Shuttle extravehicular mobility unit (EMU) is scheduled to support International Space Station (ISS) maintenance operations until at least 2020. The Shuttle's retirement will result in EMUs not returning to Earth for refurbishment until return capacity cargo spaceships become operational. If this does not occur as planned, out-of-life EMUs may be loaded into cargo craft, like the Russian Progress vehicle, that are not equipped with heatshields and entry thermal control. The resulting return would be a fiery disposal over the Pacific. This would eventually reduce the enhanced EMU inventory necessitating a need for replacement orbital EVA spacesuits and the opportunity for a new configuration.

While the near term future of EVA is uncertain, as long as people are working in space there will be a need for EVA spacesuits.

12

Epilogue

In just four short decades, man has moved from brief sorties into space to living and working there. This space odyssey started as a competition between nations and into cooperation between nations. As we interact in this emerging international community, the technical distinctions between Russian spacesuits and U.S. spacesuits have started to blur, as Russians, Americans, and other nationalities used Russian and U.S. spacesuits interchangeably in the construction of the International Space Station and will continue to do so for maintenance. Thus far humanity has placed only 10 people in space at one time. This will grow. People have not been to the Moon in over three decades. Not only will that come to pass, but people will go onto places of which we can currently only dream.

Spacesuit systems are an integrated part of a space program, which is itself part of an overall space plan. Human exploration of Mars is still planned. This provides even greater challenger than those faced on the Moon. To address those Martian challenges, more spacesuit designs will emerge. These are elements of the future U.S. spacesuit story.

This future will undoubtedly build on the experiences of the past. Under the aegis of that legacy, U.S. spacesuits have kept many hundreds of crewmembers safe on their space journeys and made it possible for people to accrue over 2,500 man-hours thus far in U.S. spacesuits, for a worldwide total of over 3,700 hours, while exploring or working in the vast openness of space.

K.S. Thomas and H.J. McMann, *U. S. Spacesuits*, Springer Praxis Books,
DOI 10.1007/978-1-4419-9566-7_12, © Springer Science+Business Media, LLC 2012

Appendix A

U.S. spaceflight suit system overview

K.S. Thomas and H.J. McMann, *U. S. Spacesuits*, Springer Praxis Books,
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MERCURY IVA SPACESUIT (Figure A.1)

Description: The Mercury spacesuit designed and manufactured by the B.F. Goodrich Aerospace Corporation of Akron, Ohio, U.S.A. (now Goodrich Corporation, headquartered in Charlotte, North Carolina, U.S.A., New York Stock Exchange: GR) for the purpose of providing emergency atmosphere retention in the event of vehicle decompression.

Development and operational dates: Evaluation/selection/contract award was in 1959 for the adaptation of an existing aviation high-altitude pressure suit design to be used in an intravehicular activity (IVA) space application. This design supported six space flights from 1961 to 1963.

Technical characteristics

Function:	IVA spacesuit
Operating pressure (nominal):	3.7 psi (25.5 kPa)
PGA weight @ $1g$:	22 lb (10 kg)
Life support system, primary:	Vehicle provided
Life support system, backup:	Vehicle provided

Quantities manufactured: At least four development units and 32 flight configuration pressure suits were made.

Figure A.1. B.F. Goodrich Mercury IVA spacesuit (courtesy NASA).

X-15 A/P 22S-2 AVIATION/SPACESUIT (Figure A.2)

Description: The X-15 pressure suit assemblies were designed and manufactured by the David Clark Company of Worcester, Massachusetts, U.S.A. The purpose of the suit was to provide atmosphere retention until the craft could descend to a breathable altitude.

Development and operational dates: Program competition and contract award was in 1957. The first X-15 suit, the MC-2, started aviation flight service in 1959. The A/P 22S-2 was a follow-on that reached flight service in 1962 in advance of the first X-15 "space flight" that year. Eight pilots earned astronaut wings in the X-15 program. The last X-15 incursion into space (suborbital space flight #11) came in 1967. The X-15 ended operations in 1968 after 199 flights.

Technical characteristics

Function:	Aviation PGA and IVA spacesuit
Operating pressure (nominal):	3.5 psi (24.1 kPa)
PGA weight @ 1g:	25 lb (11.3 kg)
Life support system, primary:	Vehicle provided
Life support system, backup:	Vehicle provided

Quantities manufactured: At least 20 A/P 22S-2 suits were made.

Figure A.2. The David Clark Company A/P 22S-2 X-15 aviation/spacesuit (courtesy NASA).

GEMINI G3C SPACESUIT (Figure A.3)

Description: The Gemini G3C intravehicular activity (IVA) spacesuit was designed and manufactured by the David Clark Company of Worcester, Massachusetts, U.S.A. This suit system included parachute and flotation systems to enhance crew survivability. The system was additionally capable of providing atmosphere retention in the event of vehicle decompression.

Development and operational dates: Contact award was in 1962 for an intravehicular activity (IVA) spacesuit that was a rear-entry derivation of the X-15 A/P 22S-2 pressure suit design. This model supported the flight of Gemini 3 in March 1965 before becoming obsolete by the need to additionally have an extravehicular capability.

Technical characteristics

Function:	IVA spacesuit
Operating pressure (nominal):	3.7 psi (25.5 kPa)
PGA weight @ $1g$:	23.5 lb (10.7 kg)
Life support system, primary:	Vehicle provided
Life support system, backup:	Vehicle provided

Quantities manufactured: At least 15 evaluation configuration suits (model GX1C and G1C) and 31 training configuration units (model G2C) preceded the G3C configuration. Production of the G3C consisted of 14 suit assemblies.

Figure A.3. David Clark Company Gemini III G3C IVA spacesuit (courtesy NASA).

GEMINI IV IEVA SPACESUIT SYSTEM (Figure A.4)

Description: The Gemini IV suit system consisted of G4C spacesuits and a NASA/AiResearch Ventilation Control Module (VCM). The particular configuration of G4C and the VCM life support system were unique to the Gemini IV mission.

Development and operational dates: Development of this suit system started in March 1965 using existing designs and hardware wherever possible. The Gemini G4C intra/extravehicular activity (IEVA) spacesuit was designed and manufactured by the David Clark Company of Worcester, Massachusetts, U.S.A, to be able to support extravehicular activity (EVA) and also launch/entry/rescue functions. Like the G3C, the G4C suit system included parachute and flotation systems. The Gemini IV G4C differed from the Gemini 3 G3C in that the G4C included thermal overgarments and helmet sunvisors to permit EVA. NASA was the system level integrator and developed the VCM using existing design and (where possible) made hardware with an AiResearch-supplied umbilical in response to the Soviet Union's world's first EVA performed by Aleksey Leonov. The VCM and umbilical provided Astronaut Ed White with life support on the first U.S. EVA mission. The system flew and supported a successful 36-minute EVA in June 1965.

Technical characteristics

Function:	Both IVA and EVA
Operating pressure (nominal):	3.7 psi (25.5 kPa)
PGA weight @ 1*g*:	34 lb (15.4 kg)
EVA life support system, primary: VCM	Umbilical, not time limited
EVA life support system, backup: VCM	9 minutes
VCM weight @ 1*g*:	7.75 lb (3.52 kg)

Quantities manufactured: As G4C suits were used on all the later missions (except Gemini VII) and the non-flown suits associated with Gemini IV were rolled into other program functions, determining "Gemini IV" quantities is not possible. Therefore, the quantities are included in the "Gemini V, VI, and VIII to XII IEVA spacesuit system" summary later in this Appendix. It is believed that only three VCM units were made.

Figure A.4. Gemini IV DCC G4C suit, NASA/AiResearch ventilation control module (courtesy NASA).

GEMINI V, VI, AND VIII TO XII IEVA SPACESUIT SYSTEM (Figure A.5)

Description: The base Gemini V through XII (except VII) suit system utilized the G4C spacesuit and an extravehicular life support system (ELSS) to support EVA. The G4C spacesuit was a product of the David Clark Company of Worcester, Massachusetts, U.S.A. Except for common thermal cover garments for Gemini V and VI, all other G4C cover garments were mission specific. The ELSS was developed and manufactured by AiResearch (now Honeywell) of Torrance, California, U.S.A. The ELSS was flown on missions VIII through XII. NASA was the systems integrator of the EVA system. The ELSS was designed to optionally utilize suitborne oxygen and power sources to provide autonomous, in addition to umbilical, EVA capability. One autonomous oxygen supply system backpack unit developed by NASA for Gemini VIII was the extravehicular support package (ESP). The other oxygen supply system developed was by Hamilton Standard and was part of the astronaut maneuvering unit developed by Ling–Temco–Vought. Due to mission difficulties unrelated to these autonomous supply systems, none of the non-umbilical supply configurations saw EVA.

Development and operational dates: Development of the G4C started in March 1965 and saw flight in June 1965 on board Gemini IV. Gemini V and VI G4C lacked EVA sunvisors, overjackets, and overgloves. The Gemini VIII through XII G4C suits all had mission-specific cover garments. Development of the ELSS was a planned Gemini program activity that started in 1963, but was extensively revised during development. The ELSS first flight was Gemini VIII and the first EVA was Gemini IX-A. This system was used by four astronauts to log 11 hours 49 minutes of total EVA time in four EVAs.

Technical characteristics

Function:	IVA (without ELSS) and EVA (with accessories)
Operating pressure (nominal):	3.7 psi (25.5 kPa)
PGA weight @ 1*g*:	34 lb (15.4 kg)
EVA life support system, primary: ELSS	Umbilical, not time limited
EVA life support system, backup: ELSS	30 minutes
ELSS weight @ 1*g*:	47 lb (21.3 kg)

Quantities manufactured: At least 42 G4C suits were made supporting Gemini IV through VI and VIII through XII, of which 16 saw flight. Eight chestpacks were built, of which four were used during EVA. All chestpacks used during EVA were jettisoned into space before entry.

Figure A.5. Gemini V to XII DCC G4C suit and AiResearch ELSS (courtesy NASA).

GEMINI VII G5C IVA SPACESUIT (Figure A.6)

Description: The Gemini G5C intravehicular activity (IVA) spacesuit was designed and manufactured by the David Clark Company of Worcester, Massachusetts, U.S.A. While this suit system included a parachute/flotation harness system and was capable of providing atmosphere retention in the event of vehicle decompression to enhance crew survivability, it was lightened with as many hard parts removed as possible to enhance astronaut comfort for the Gemini VII 206 orbit/14-day mission.

Development and operational dates: Development of this suit system started in April 1965 and was based on the G4C. The system flew in December 1965.

Technical characteristics

Function:	IVA spacesuit
Operating pressure (nominal):	3.7 psi (25.5 kPa)
PGA weight @ 1*g*:	16 lb (7.2 kg)
Life support system, primary:	Vehicle provided
Life support system, backup:	Vehicle provided

Quantities manufactured: At least 11 G5C suits were manufactured. Two were flown.

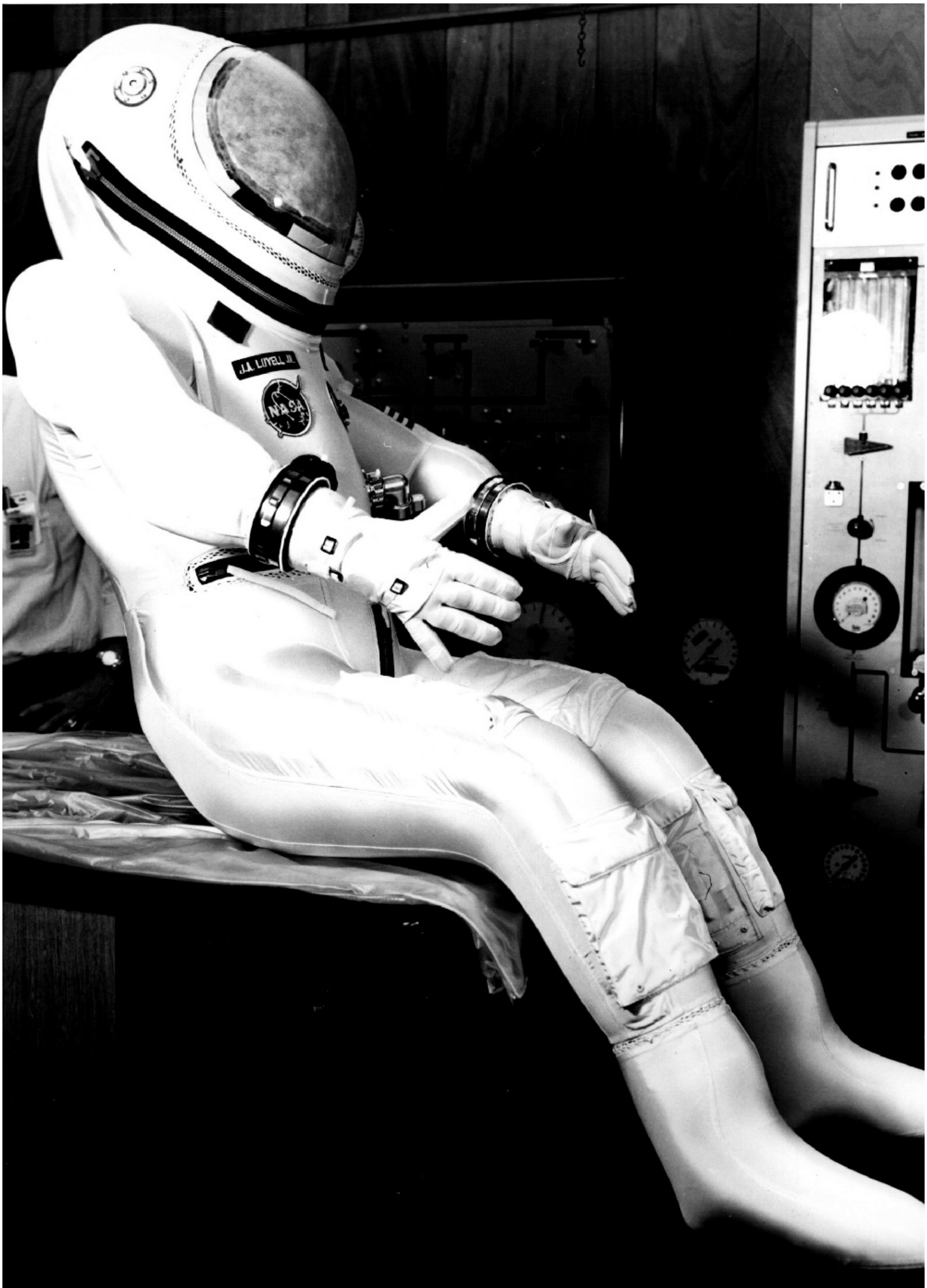

Figure A.6. DCC Gemini VII G5C IVA spacesuit (courtesy NASA).

APOLLO 7 THROUGH 10 EXTRAVEHICULAR MOBILITY UNIT (Figure A.7)

Description: The Apollo 7–10 EMU had two configurations. One was extravehicular (EV) for the Lunar Module's crew. The other was for the Command Module pilot (CMP). The EV configuration consisted of an Apollo 7–10 type A7L pressure suit assembly (PSA), a "-5" (dash five) portable life support system (PLSS), and a "-1" (dash one) oxygen purge system (OPS, backup life support). The Apollo EMU was a modular system. Without EV accessories, the PSA served as an intravehicular activity (IVA) suit supporting launch and entry. By donning a visor assembly, EV gloves, lunar overboots, PLSS, and OPS, the Apollo EMU converted to an EV suit system. The CMP configuration was just a PSA that differed from the EV in that CMP suits had only one pair of life support connectors, no arm bearings, and less insulation in the cover garments. The A7L PSA was designed and manufactured by International Latex Corporation (ILC) of Dover, Delaware, U.S.A. The PLSS/OPS was developed and manufactured by Hamilton Standard of Windsor Locks, Connecticut, U.S.A.

Development and operational dates: Program competition and contract award was in 1962. In 1968, this configuration started flight service and performed its first and only EVA on Apollo 9. This style of EMU supported four flights in an IVA capacity and one EVA (one PLSS, one on umbilical) for a total of 1.5 man-hours in space.

Technical characteristics

Function:	IVA and EVA (with PLSS and accessories)
Operating pressure (nominal):	3.7 psi (25.5 kPa)
IVA PSA weight @ 1*g*:	62 lb (28 kg)
EVA PSA weight @ 1*g*:	76 lb (34.5 kg)
LSS weight @ 1*g*:	125 lb (56.7 kg)
EVA system weight @ 1*g*:	200 lb (91 kg)
Minimum hatch size:	30 in. × 30 in. (762 mm × 762 mm)
LSS, EVA, primary: PLSS	6 hours certified, longest use 46 minutes
LSS, EVA, backup: OPS	30 minutes certified, never used in flight

Quantities manufactured: As A7L suits were used on all the later missions and suits associated with Apollo 7–10 that were not flown were rolled into other program functions, determining "Apollo 7–10" quantities is not possible. Therefore, the quantities are included in the "Apollo 11–14" summary that follows. The Apollo PLSSs were retrofitted from one configuration to the next, the PLSS total is provided in the Apollo 15–17 summary.

Figure A.7. Apollo 9 and 10: EMU (ILC A7L suit, HS-5 portable life support system) (courtesy Hamilton Sundstrand). *Note*: Development/certification EMU shown.

APOLLO 11–14 EXTRAVEHICULAR MOBILITY UNIT (Figure A.8)

Description: The Apollo 11–14 EMU had two configurations. The extravehicular (EV) configuration consisted of an Apollo 11–13 or Apollo 14 type A7L pressure suit assembly (PSA) with EV accessories, a "-6" (dash six) portable life support system (PLSS), and a -1 oxygen purge system (OPS, backup life support). The Apollo 11–14 CMP PSA differed from the EV in that CMP suits had only one pair of life support connectors, no arm bearings, and less insulation. The A7L PSA was designed and manufactured by International Latex Corporation (ILC) of Dover, Delaware, U.S.A. The Apollo PLSS/OPS was developed and manufactured by Hamilton Standard of Windsor Locks, Connecticut, U.S.A.

Development and operational dates: Both the PSA and PLSS were incremental improvements to the Apollo 7–10 system. For Apollo 11–13, the visor assembly of the PSA gained an outer shell and thermal cover. For Apollo 14, the visor assembly was again revised to add an external opaque center sunshade. This would also be used on the Apollo 15–17 EMUs. The Apollo 11–14 PLSS had its remote control unit chest-mounted display and control unit revised to make it easier to operate with pressure-gloved hands and to add a camera mount on the front. This configuration supported five two-astronaut EVAs for a total of 39.1 man-hours outside the spacecraft.

Technical characteristics

Function:	IVA and EVA (with PLSS and accessories)
Operating pressure (nominal):	3.7 psi (25.5 kPa)
IVA PSA weight @ 1*g*:	62 lb (28 kg)
EVA PSA weight @ 1*g*:	76 lb (34.5 kg)
LSS weight @ 1*g*:	125 lb (56.7 kg)
EVA system weight @ 1*g*:	201 lb (91.3 kg)
Minimum hatch size:	30 in. × 30 in. (762 mm × 762 mm)
LSS, EVA, primary: PLSS	6 hours certified, longest use 4.8 hours
LSS, EVA, backup: OPS	30 minutes certified, never used in flight

Quantities manufactured: At least 105 A7L suits were made. These suits supported Apollo 7 through 14 and Apollo 15–17 CMP usage (see next topic). As the Apollo PLSSs were retrofitted from one configuration to the next, the PLSS total is provided in the Apollo 15–17 EMU summary.

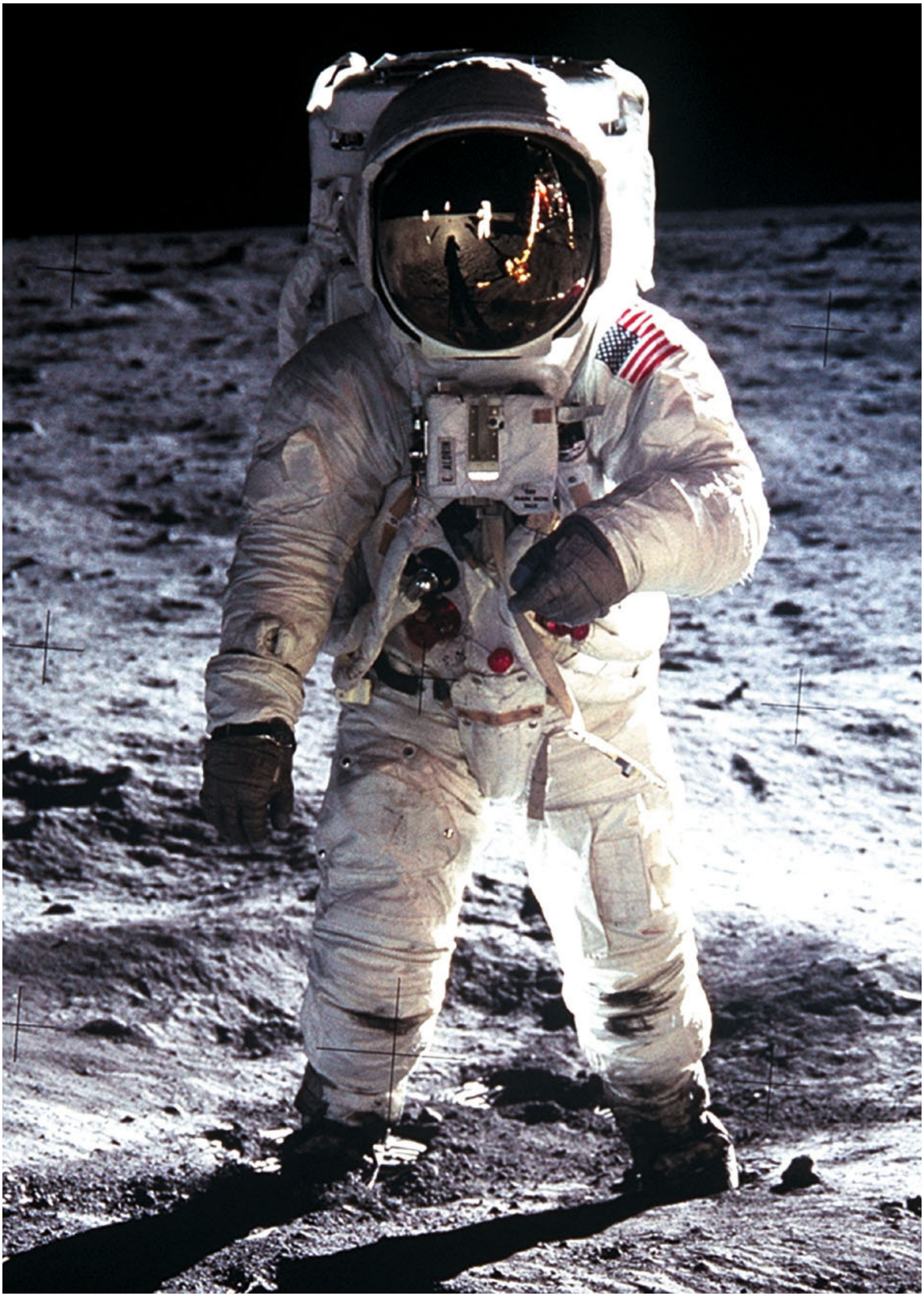

Figure A.8. Apollo 10–14: EMU (ILC A7L suit, HS-6 portable life support system, Aldrin Apollo 11) (courtesy NASA).

APOLLO 15-17 EMU (Figure A.9) AND APOLLO SOYUZ TEST PROJECT (ASTP) SUITS

Description: The Apollo 15–17 EMU (extravehicular mobility unit) had two configurations. The extravehicular (EV) configuration consisted of a side/mid-entry Apollo A7LB EV pressure suit assembly (PSA), a "-7" (dash seven) portable life support system (PLSS), and a -2 (dash 2) oxygen purge system (OPS, backup life support). The creation of the A7LB EV configuration was to support Lunar Rover usage and more effective surface exploration. Most of the 15–17 Apollo Command Module pilot (CMP) A7LB PSAs were retrofitted A7L EV PSAs with a limited quantity of new-build A7LB CMP PSAs to support Apollo 17. These A7LB CMP PSAs were rear entry like the A7L. For ASTP, NASA elected to use a slightly modified version of the Apollo 15–17 A7LB CMP PSA. The A7LB PSAs were designed and manufactured by ILC Industries of Dover, Delaware, U.S.A. (a separate business entity partially owned by International Latex Corporation). The Apollo PLSS/OPS was developed and manufactured by Hamilton Standard of Windsor Locks, Connecticut, U.S.A.

Development and operational dates: Development for this configuration started in 1968 and there were evolutionary improvements on the preceding systems. The first flight was in 1971. This last Apollo EMU supported three flights, 13 EVAs (12 two-astronaut, one single-person standup EVA) for a total of 127.8 man-hours outside the spacecraft.

Technical characteristics

Function:	IVA and EVA (with PLSS and accessories)
Operating pressure (nominal):	3.7 psi (25.5 kPa)
IVA PSA weight @ 1*g*:	64.6 lb (29.3 kg)
EVA PSA weight @ 1*g*:	78 lb (35.4 kg)
LSS weight @ 1*g*:	134 lb (60.8 kg)
EVA system weight @ 1*g*:	212 lb (96.2 kg)
Minimum hatch size:	30 in. × 30 in. (762 mm × 762 mm)
LSS, EVA, primary: PLSS	7 hours certified, longest use 7.62 hours
LSS, EVA, backup: OPS	30 minutes certified, never used in flight

Quantities manufactured: At least 30 side/mid-entry A7LB EV suits were made for Apollo. While most of the A7LB Command Module pilot (CMP) suits were retrofitted A7L EV suits, at least four new-build A7LB CMP suits were manufactured. There were 34 Apollo PLSSs manufactured from 1965 to 1972 to support development, certification, training, and missions. At least nine rear-entry A7LB PSAs were manufactured in support of ASTP.

Figure A.9. Apollo 15–17: EMU (ILC A7LB suit, HS-7 portable life support system) (courtesy G. L. Harris).

SKYLAB EXTRAVEHICULAR MOBILITY UNIT (Figure A.10)

Description: The Apollo Skylab EMU configuration consisted of an adaptation of the side/mid-entry Apollo A7LB extravehicular pressure suit assembly (PSA) and an astronaut life support system (ALSA). The A7LB PSA was designed and manufactured by ILC Industries of Dover, Delaware, U.S.A. The winner of the ALSA competition and contract was the AiResearch Division of Garrett Aerospace Corporation located in Torrance, California, U.S.A. During ALSA development, AiResearch became part of AlliedSignal Corporation (now Honeywell) by merger. The Torrance division continued to be the manufacturer of the ALSA.

Development and operational dates: Program competition and contract award was in 1969. The Skylab EMU first flight was in 1973.

Technical characteristics

Function:	IVA and EVA (with ALSA and accessories)
Operating pressure (nominal):	3.7 psi (25.5 kPa)
IVA PSA weight @ 1*g*:	64.6 lb (29.3 kg)
EVA PSA weight @ 1*g*:	72 lb (32.7 kg)
LSS weight @ 1*g*:	71 lb (32.3 kg) (PCU plus SOP)
EVA system weight @ 1*g*:	143 lb (64.9 kg) on Earth, nothing in space
Minimum hatch size:	Trapezoidal shape; approx. 15 in. (380 mm) wide at top and approx. 22 in. (560 mm) wide at the bottom × 30 in. (762 mm) in height
LSS, EVA, primary: ALSA	Longest EVA was 7 hours 1 minute
LSS, EVA, backup: SOP	30 minutes certified, never used in flight

Quantities manufactured: At least 35 Skylab A7LB suits and 16 ALSAs[*] were made for Skylab.

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[*] The ALSA consisted of a PCU, an SOP, and an LSU. One additional LSU was also manufactured.

Figure A.10. Skylab EMU (ILC A7LB suit, AiResearch astronaut life support system) (courtesy NASA).

SHUTTLE EJECTION ESCAPE SUIT IVA SPACESUIT (Figure A.11)

Description: The Shuttle ejection escape suit (EES) intravehicular activity (IVA) spacesuit was designed and manufactured by the David Clark Company of Worcester, Massachusetts, U.S.A. This suit system included parachute and flotation systems to enhance crew survivability. The system was additionally capable of providing atmosphere retention in the event of vehicle decompression.

Development and operational dates: Contact award was in 1978 for an intravehicular activity (IVA) full pressure spacesuit that was a derivation of the U.S. Air Force Model S1030 pilot's protective assembly. The ejection escape suit supported flight STS-1 through STS-4 and become obsolete by the Shuttle completing its certification missions.

Technical characteristics

Function:	IVA spacesuit
Operating pressure (nominal):	2.7 psi (18.6 kPa)
PGA weight @ 1*g*:	40 lb (18 kg)
Life support system, primary:	Vehicle provided
Life support system, backup:	Vehicle provided

Quantities manufactured: For the Shuttle program, 13 ejection escape suits were made. Of these, five were later converted to Model S1030 suits for U.S. Air Force use in SR-71 flights.

Figure A.11. DCC Shuttle ejection escape IVA spacesuit (courtesy NASA).

SHUTTLE BASELINE EMU EVA SPACESUIT SYSTEM (Figure A.12)

Description: The baseline Shuttle EMU was the first U.S. exclusively EVA spacesuit system to reach flight. This EMU is not one spacesuit assembly but rather a collection of modules, called contract end items or CEIs, which are delivered separately in the required quantities to support flight and are mixed and matched to provide a near custom fit to crewmembers. The pressure suit portion of the Shuttle EMU, called the spacesuit assembly (SSA), was not capable of discretely separate pressurization and operation without life support system (LSS) CEIs or facsimiles in place due to system integration to minimize volume. NASA's contractor and systems integrator for the EMU was Hamilton Standard (HS) of Windsor Locks, Connecticut, U.S.A. until 1999 when HS became Hamilton Sundstrand. HS is also the provider of LSS CEIs. The integrator and principal designer/manufacturer of SSA CEIs for HS was ILC Industries of Fredrica, Delaware, U.S.A. ILC became an entirely separate entity from International Latex Corporation in 1984.

Development and operational dates: HS/ILC started internally funded development in 1974 in advance of the 1976 Shuttle EMU competition. The contract award was in 1977. The first flight was 1981 in an emergency EVA capacity. The first EVA was in 1983 on STS-6. In 1998, this configuration began being slowly phased out in favor of the enhanced EMU configuration. The last baseline EMU flight and EVA was on STS-110 in 2002.

Technical characteristics

Function:	EVA
Operating pressure (nominal):	4.3 psi (29.6 kPa)
SSA weight @ 1g:	109 lb (49.4 kg), nominally
LSS weight @ 1g:	145 lb (65.8 kg)
EMU weight @ 1g:	254 lb (115 kg), nominally
Minimum hatch size:	20 in. × 30 in. (508 mm × 762 mm)
LSS, EVA, primary: PLSS	8 hours nominally, longest used 8.48 hours
LSS, EVA, backup: SOP	30 minutes certified, never used in flight

Quantities manufactured: 52 SSAs (based on hard upper torso quantities) and 17 LSSs were made during the baseline EMU era. Typically, the SSA CEIs started as flight units and were downgraded later to support training. Generally, 24 SSAs and 12 LSSs were available to support flight at any time.

Figure A.12. HS/ILC Shuttle baseline EMU EVA spacesuit system (courtesy NASA).

SHUTTLE LAUNCH/ENTRY SUIT IVA SPACESUIT SYSTEM (Figure A.13)

Description: Starting with STS-26, each crewmember has been provided with a crew escape system (CES) suit and supporting equipment. Until 1994, the CES contained a partial pressure suit system (Model S1032) named the launch entry suit (LES). The LES was an exclusively intravehicular activity (IVA) spacesuit designed and manufactured by the David Clark Company of Worcester, Massachusetts, U.S.A. The pressure suit portion of the assembly was principally made in nine sizes of a standardized 12-size system (1 custom). This suit system included parachute and flotation systems to enhance crew survivability. The system was additionally capable of providing atmosphere retention in the event of vehicle decompression.

Development and operational dates: Contract award was in 1986 for an intravehicular activity (IVA) partial pressure spacesuit that was a derivation of an existing U.S. Air Force suit system Model S1031. The LES supported flight from 1988 to the end of 1995 being phased out in 1994 by the introduction of the advanced crew escape suit.

Technical characteristics

Function:	IVA spacesuit
Operating pressure (nominal):	2.7 psi (18.6 kPa)
Suit weight @ $1g$:	30 lb (13.6 kg), approximately
Parachute and survival systems @ $1g$:	64 lb (29 kg), approximately
Life support system, primary:	Vehicle provided
Life support system, backup: EOS	10 minutes

Quantities manufactured: 49 LESs were made for the Shuttle program between 1987 and 1989.

Figure A.13. DCC Shuttle launch/entry IVA spacesuit system (courtesy David Clark Co.).

SHUTTLE ADVANCED CREW ESCAPE SUIT IVA SPACESUIT SYSTEM (Figure A.14)

Description: Starting in 1994, the advanced crew escape suit (ACES) Model S1035 began being delivered and used as part of the crew escape system (CES). Unlike the launch entry suit (LES), ACES is a full pressure system that is designed to be lighter and more comfortable than the LES. Like the LES, the ACES is also an exclusively intravehicular activity (IVA) spacesuit designed and manufactured by the David Clark Company of Worcester, Massachusetts, U.S.A. This suit system includes parachute and flotation systems to enhance crew survivability. The system is additionally capable of providing atmosphere retention in the event of vehicle decompression.

Development and operational dates: Development started in 1990 as a planned replacement of an expiring existing system and consisted of adaptation of the U.S. Air Force Model S1034. The ACES began flight service in 1994 becoming the exclusive Shuttle IVA suit system by the end of 1995.

Technical characteristics

Function:	IVA spacesuit
Operating pressure (nominal):	3.5 psi (24.1 kPa)
Suit weight @ 1*g*:	28 lb (12.7 kg), approximately
Parachute and survival systems @ 1*g*:	64 lb (29 kg), approximately
Life support system, primary:	Vehicle provided
Life support system, backup: EOS	10 minutes

Quantities manufactured: For the Shuttle program, 63 ACES have been delivered with seven additional suits planned.

Figure A.14. DCC Shuttle advanced crew escape IVA spacesuit system (courtesy David Clark Co.).

SHUTTLE ENHANCED EMU EVA SPACESUIT SYSTEM (Figure A.15)

Description: The baseline Shuttle EMU was improved to an enhanced configuration to support the unique needs of the International Space Station (ISS). These enhancements included differing ISS and Shuttle modules (contract end items or CEIs), an optional propulsion module for self-return of a crewmember who has accidentally floated away, on-orbit replaceability of suit CEIs, heating and heat retention systems for more effective working in extreme cold, and improved lights and camera systems. Hamilton Sundstrand (HS) of Windsor Locks, Connecticut, U.S.A. remained NASA's systems integrator/prime contractor and provider of the EMU's life support system (LSS) CEIs. ILC Industries of Fredrica, Delaware, U.S.A., remained HS's integrator and principal designer/manufacturer for the spacesuit assembly (SSA) CEIs. NASA is the supplier of the Simplified Aid For Extravehicular Rescue (SAFER) propulsion system.

Development and operational dates: Development of the enhanced configuration started in 1990 with the decision not to implement an all new Space Station suit system. The modular nature of the EMU permitted enhanced CEIs to be developed and go into flight service as parallel activities. The first flight of an enhanced CEI was 1994. The debut of a fully enhanced EMU was 1998. After STS-110 in 2002, the enhanced EMU was the only Shuttle EVA suit system. On the ISS, Russian Orlan-M suits provide an alternative EVA capacity.

Technical characteristics

Function:	EVA
Operating pressure (nominal):	4.3 psi (29.6 kPa)
SSA weight @ 1*g*:	122 lb (55.3 kg) nominally for both Shuttle and ISS
LSS weight @ 1*g*:	153 lb (69.4 kg) Shuttle, 187 lb (85 g) ISS
EMU/SAFER weight @ 1*g*:	275 lb (124.7 kg) Shuttle, 309 lb (140 kg) ISS, 374 lb (169.6 kg) ISS EMU/SAFER
Minimum hatch size:	22 in. × 30 in. (559 mm × 762 mm)
LSS, EVA, primary: PLSS	8 hours nominally, longest used 8.93 hours
LSS, EVA, backup: SOP	30 minutes certified, never used in flight

Quantities manufactured: 44 SSAs (based on hard upper torso quantities) and one additional life support system were made to support the enhanced era. Currently, 24 pressure suits/13 life support systems are nominally available to support flight.

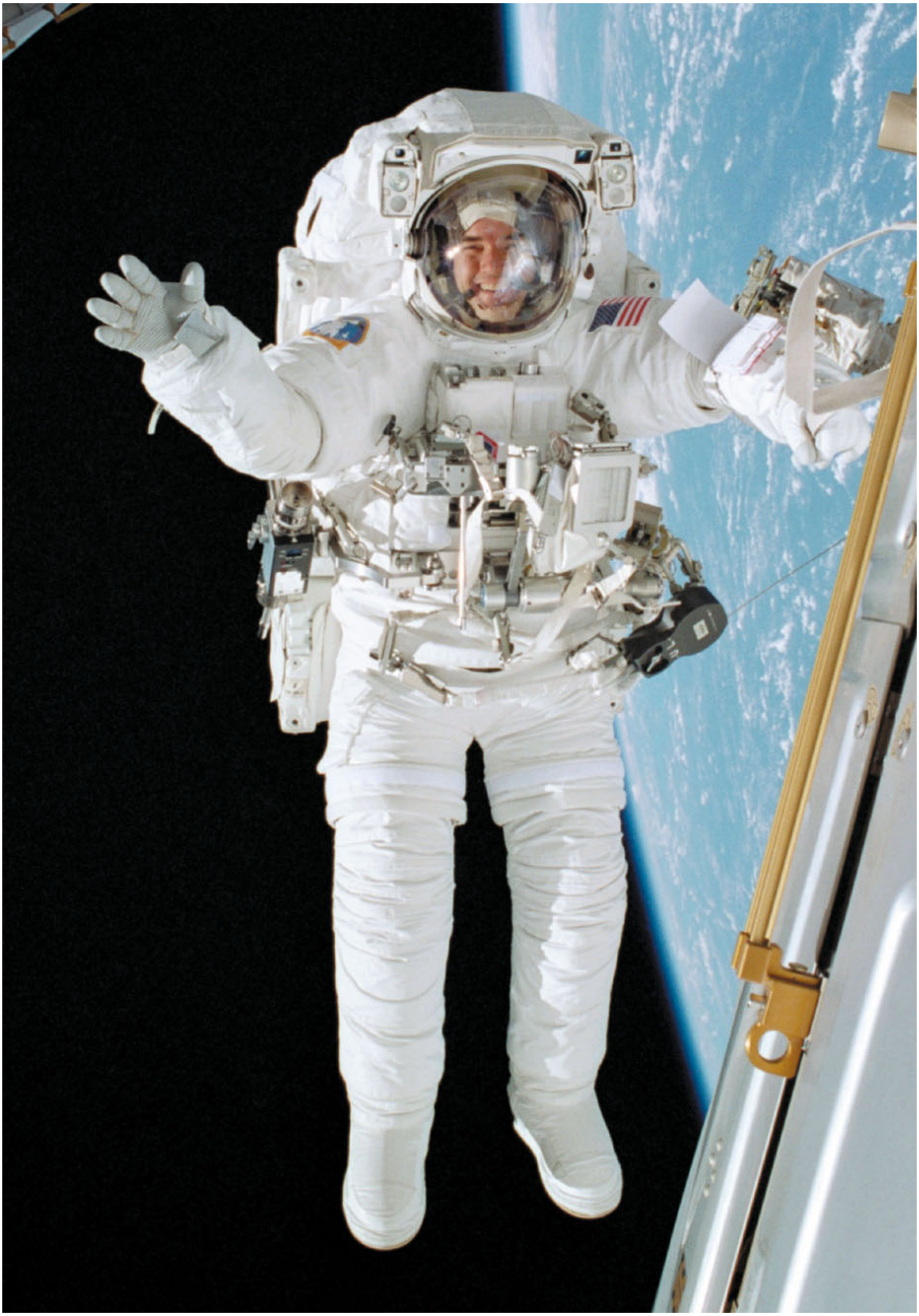

Figure A.15. HS/ILC Shuttle enhanced EMU EVA spacesuit system (courtesy NASA).

Appendix B

U.S. EVA information

Program and mission	*U.S. EVA #*	*EVA crewmember*	*Date*	*EV1*	*Spacesuit configuration*	*Male (M)/ Female (F)*	*EVA* (h)	*EVA* (min)
Gemini 4	1	1	6/3/65	White, E.	(1)	M	0	36
Gemini 9	2	1	6/5/66	Cernan, E.	(2)	M	2	09
Gemini 10	3	1	7/19/66	Collins, M.	(2)	M	0	49
Gemini 10	4	1	7/20/66	Collins, M.	(2)	M	0	39
Gemini 11	5	1	9/13/66	Gordon, R.	(2)	M	0	38
Gemini 11	6	1	9/14/66	Gordon, R.	(2)	M	2	08
Gemini 12	7	1	11/12/66	Aldrin, E.	(2)	M	2	18
Gemini 12	8	1	11/13/66	Aldrin, E.	(2)	M	2	09
Gemini 12	9	1	11/14/66	Aldrin, E.	(2)	M	1	11
Apollo 9	10	1	3/6/69	Schweikart, R.	(3)	M		
		2		Scott, D.	(4)	M	0	46
Apollo 11	11	1	7/21/69	Armstrong, N.	(5)	M		
		2		Aldrin, E.	(5)	M	2	32
Apollo 12	12	1	11/19/69	Conrad, C.	(5)	M		
		2		Bean, A.	(5)	M	3	39
Apollo 12	13	1	11/19/69	Conrad, C.	(5)	M		
		2		Bean, A.	(5)	M	3	48

Program and mission	*U.S. EVA #*	*EVA crewmember*	*Date*	*EV1*	*Spacesuit configuration*	*Male (M)/ Female (F)*	*EVA (h)*	*EVA (min)*
Apollo 14	14	1	2/5/71	Shepard, A.	(5)	M		
		2		Mitchell, E.	(5)	M	4	49
Apollo 14	15	1	2/6/71	Shepard, A.	(5)	M		
		2		Mitchell, E.	(5)	M	4	46
Apollo 15	16	1	7/30/71	Scott, D.	(6)	M	0	33
Apollo 15	17	1	7/31/71	Scott, D.	(7)	M		
		2		Irwin, J.	(7)	M	6	34
Apollo 15	18	1	8/1/71	Scott, D.	(7)	M		
		1		Irwin, J.	(7)	M	7	13
Apollo 15	19	1	18/2/71	Scott, D.	(7)	M		
		2		Irwin, J.	(7)	M	4	20
Apollo 15	20	1	8/5/71	Worden, A.	(8)	M	0	41
Apollo 16	21	1	4/21/72	Young, J.	(7)	M		
		2		Duke, C.	(7)	M	7	11
Apollo 16	22	1	4/22/72	Young, J.	(7)	M		
		2		Duke, C.	(7)	M	7	23
Apollo 16	23	1	4/23/72	Young, J.	(7)	M		
		2		Duke, C.	(7)	M	5	40
Apollo 16	24	1	4/25/72	Mattingly, T.	(8)	M	1	24
Apollo 17	25	1	12/11/72	Cernan, E.	(7)	M		
		2		Schmitt, H.	(7)	M	7	12
Apollo 17	26	1	12/12/72	Cernan, E.	(7)	M		
		2		Schmitt, H.	(7)	M	7	37
Apollo 17	27	1	12/13/72	Cernan, E.	(7)	M		
		2		Schmitt, H.	(7)	M	7	16
Apollo 17	28	1	12/17/72	Evans, R.	(8)	M	1	07
Skylab 2	29	1	5/25/73	Weitz, P.	(9)	M	0	40
Skylab 2	30	1	6/7/73	Conrad, C.	(10)	M		
		2		Kerwin, J.	(10)	M	3	25
Skylab 2	31	1	6/19/73	Conrad, C.	(10)	M		
		2		Weitz, P.	(10)	M	1	36
Skylab 3	32	1	8/6/73	Garriott, O.	(10)	M		
		2		Lousma, J.	(10)	M	6	31
Skylab 3	33	1	8/24/73	Garriott, O.	(10)	M		
		2		Lousma, J.	(10)	M	4	31
Skylab 3	34	1	9/22/73	Bean, A.	(10)	M		
		2		Garriott, O.	(10)	M	2	41

Program and mission	*U.S. EVA #*	*EVA crewmember*	*Date*	*EV1*	*Spacesuit configuration*	*Male (M)/ Female (F)*	*EVA (h)*	*EVA (min)*
Skylab 4	35	1	11/22/73	Pogue, W.	(10)	M		
		2		Gibson, E.	(10)	M	6	33
Skylab 4	36	1	12/25/73	Carr, G.	(10)	M		
		2		Pogue, W.	(10)	M	7	01
Skylab 4	37	1	12/29/73	Carr, G.	(10)	M		
		2		Gibson, E.	(10)	M	3	29
Skylab 4	38	1	2/3/74	Carr, G.	(10)	M		
		2		Gibson, E.	(10)	M	5	16
STS-6	39	1	4/7/83	Musgrave, S.	(11)	M		
		2		Perterson, D.	(11)	M	4	10
STS-41B	40	1	2/7/84	McCandless, B.	(11)	M		
		2		Stewart, R.	(11)	M	5	55
STS-41B	41	1	2/9/84	McCandless, B.	(11)	M		
		2		Stewart, R.	(11)	M	6	17
STS-41C	42	1	4/8/84	Nelson, G.	(11)	M		
		2		van Hoften, J.	(11)	M	2	38
STS-41C	43	1	4/11/84	Nelson, G.	(11)	M		
		2		van Hoften, J.	(11)	M	6	44
STS-41G	44	1	10/11/84	Leestma, D.	(11)	M		
		2		Sullivan, K.	(11)	F	3	29
STS-51A	45	1	11/12/84	Allen, J.	(11)	M		
		2		Gardner, D.	(11)	M	6	00
STS-51A	46	1	11/14/84	Allen, J.	(11)	M		
		2		Gardner, D.	(11)	M	5	42
STS-51D	47	1	4/16/85	Hoffman, J.	(11)	M		
		2		Griggs, D.	(11)	M	3	06
STS-51I	48	1	8/31/85	Fisher, W.	(11)	M		
		2		van Hoften, J.	(11)	M	7	20
STS-51I	49	1	9/1/85	Fisher, W.	(11)	M		
		2		van Hoften, J.	(11)	M	4	26
STS-61B	50	1	11/29/85	Ross, J.	(11)	M		
		2		Springer, S.	(11)	M	5	32
STS-61B	51	1	12/1/85	Ross, J.	(11)	M		
		2		Springer, S.	(11)	M	6	41

Program and mission	*U.S. EVA #*	*EVA crewmember*	*Date*	*EV1*	*Spacesuit configuration*	*Male (M)/ Female (F)*	*EVA* (h)	*EVA* (min)
STS-37	52	1	4/7/91	Ross, J.	(11)	M		
		2		Apt, J.	(11)	M	4	26
STS-37	53	1	4/8/91	Ross, J.	(11)	M		
		2		Apt, J.	(11)	M	5	47
STS-49	54	1	5/10/92	Thuot, P.	(11)	M		
		2		Hieb, R.	(11)	M	3	43
STS-49	55	1	5/11/92	Thuot, P.	(11)	M		
		2		Hieb, R.	(11)	M	5	30
STS-49	56	1	5/13/92	Thuot, P.	(11)	M		
		2		Hieb, R.	(11)	M		
		3		Akers, T.	(11)	M	8	29
STS-49	57	1	5/14/92	Thornton, K.	(11)	F		
		2		Akers, T.	(11)	M	7	44
STS-54	58	1	1/17/93	Harbaugh, G.	(11)	M		
		2		Runco, M.	(11)	M	4	28
STS-57	59	1	6/25/93	Low, G. D.	(11)	M		
		2		Wisoff, P.	(11)	M	5	50
STS-51	60	1	9/16/93	Newman, J.	(11)	M		
		2		Walz, C.	(11)	M	7	05
STS-61/HST-1	61	1	12/4/93	Musgrave, S.	(11)	M		
		2		Hoffman, J.	(11)	M	7	54
STS-61/HST-1	62	1	12/5/93	Thornton, K.	(11)	F		
		2		Akers, T.	(11)	M	6	47
STS-61/HST-1	63	1	12/6/93	Musgrave, S.	(11)	M		
		2		Hoffman, J.	(11)	M	7	21
STS-61/HST-1	64	1	12/7/93	Thornton, K.	(11)	F		
		2		Akers, T.	(11)	M	6	36
STS-61/HST-1	65	1	12/8/93	Musgrave, S.	(11)	M		
		2		Hoffman, J.	(11)	M	6	50
STS-64	66	1	9/16/94	Lee, M.	(11)	M		
		2		Meade, C.	(11)	M	6	51
STS-63	67	1	2/9/95	Foale, M. (U.K./U.S.)	(11)	M		
		2		Harris, B.	(11)	M	4	39
STS-69	68	1	9/16/95	Voss, J. (James)	(11)	M		
		2		Gernhardt, M.	(11)	M	6	46

Program and mission	U.S. EVA #	EVA crewmember	Date	EV1	Spacesuit configuration	Male (M)/ Female (F)	EVA (h)	EVA (min)
STS-72	69	1	1/15/96	Chiao, L.	(11)	M		
		2		Barry, D.	(11)	M	6	09
STS-72	70	1	1/17/96	Chiao, L.	(11)	M		
		2		Scott, W.	(11)	M	6	54
STS-76	71	1	3/27/96	Clifford, M.	(11)	M		
		2		Godwin, L.	(11)	F	6	02
STS-82/HST-2	72	1	2/13/97	Lee, M.	(11)	M		
		2		Smith, S.	(11)	M	6	42
STS-82/HST-2	73	1	2/14/97	Harbaugh, G.	(11)	M		
		2		Tanner, J.	(11)	M	7	27
STS-82/HST-2	74	1	2/15/97	Lee, M.	(11)	M		
		2		Smith, S.	(11)	M	7	11
STS-82/HST-2	75	1	2/16/97	Harbaugh, G.	(11)	M		
		2		Tanner, J.	(11)	M	6	34
STS-82/HST-2	76	1	2/17/97	Lee, M.	(11)	M		
		2		Smith, S,	(11)	M	5	17
STS-86/Mir7	77	1	10/1/97	Parazynski, S.	(11)	M		
		2		Titov, V. (Russia)	(11)	M	5	01
STS-87	78	1	11/24/97	Scott, W.	(11)	M		
		2		Doi, T. (JAXA)	(11)	M	7	43
STS-87	79	1	12/2/97	Scott, W.	(11)	M		
		2		Doi, T. (JAXA)	(11)	M	4	59
STS-88/ISS-2A	80	1	12/7/98	Ross, J.	(11)	M		
		2		Newman, J.	(12)	M	7	21
STS-88/ISS-2A	81	1	12/9/98	Ross, J.	(11)	M		
		2		Newman, J.	(12)	M	7	02
STS-88/ISS-2A	82	1	12/12/98	Ross, J.	(11)	M		
		2		Newman, J.	(12)	M	6	59
STS-96/ISS-2A.1	83	1	5/29/99	Jernigan, T.	(11)	F		
		2		Barry. D.	(12)	M	7	55
STS-103/HST-3A	84	1	12/22/99	Smith, S.	(11)	M		
		2		Grunsfeld, J.	(12)	M	8	15
STS-103/HST-3A	85	1	12/23/99	Foale, M. (U.K./U.S.)	(12)	M		
		2		Nicollier, C. (F)	(12)	M	8	10
STS-103/HST-3A	86	1	12/24/99	Smith, S.	(11)	M		
		2		Grunsfeld, J.	(12)	M	8	08

Program and mission	*U.S. EVA #*	*EVA crewmember*	*Date*	*EV1*	*Spacesuit configuration*	*Male (M)/ Female (F)*	*EVA (h)*	*EVA (min)*
STS-101/ISS-2A.2a	87	1	5/21/00	Voss, J. (James)	(12)	M		
		2		Williams, J.	(12)	M	6	44
STS-106/ISS-2A.2b	88	1	9/11/00	Lu, E.	(12)	M		
		2		Malenchenko, Y. (Rus.)	(12)	M	6	14
STS-92/ISS-3A	89	1	10/15/00	Chiao, L.	(11)	M		
		2		McArthur, W.	(12)	M	6	28
STS-92/ISS-3A	90	1	10/16/00	Wisoff, J.	(12)	M		
		2		Lopez-Alegria, M.	(11)	M	7	07
STS-92/ISS-3A	91	1	10/17/00	Chiao, L.	(11)	M		
		2		McArthur, W.	(12)	M	6	48
STS-92/ISS-3A	92	1	10/18/00	Wisoff, J.	(12)	M		
		2		Lopez-Alegria, M.	(11)	M	6	56
STS-97/ISS-4A	93	1	12/4/00	Tanner, J.	(12)	M		
		2		Noriega, C.	(12)	M	7	33
STS-97/ISS-4A	94	1	12/5/00	Tanner, J.	(12)	M		
		2		Noriega, C.	(12)	M	6	37
STS-97/ISS-4A	95	1	12/7/00	Tanner, J.	(12)	M		
		2		Noriega, C.	(12)	M	5	10
STS-98/ISS-5A	96	1	2/10/01	Curbeam, R.	(11)	M		
		2		Jones, T.	(12)	M	7	34
STS-98/ISS-5A	97	1	2/12/01	Curbeam, R.	(11)	M		
		2		Jones, T.	(12)	M	6	50
STS-98/ISS-5A	98	1	2/14/01	Curbeam, R.	(11)	M		
		2		Jones, T.	(12)	M	5	25
STS-102/ISS-5A.1	99	1	3/11/01	Voss, J. (James)	(12)	M		
		2		Helms, S.	(12)	F	8	56
STS-102/ISS-5A.1	100	1	3/13/01	Richards, P.	(12)	M		
		2		Thomas, A. (Austrakua)	(12)	M	6	30
STS-100/ISS-6A	101	1	4/22/01	Hadfield, C. (Canada)	(12)	M		
		2		Parazynski, S.	(11)	M	7	10
STS-100/ISS-6A	102	1	4/24/01	Hadfield, C. (Canada)	(12)	M		
		2		Parazynski, S.	(11)	M	7	40

Program and mission	*U.S. EVA #*	*EVA crewmember*	*Date*	*EV1*	*Spacesuit configuration*	*Male (M)/ Female (F)*	*EVA (h)*	*EVA (min)*
STS-104/ISS-7A	103	1	7/14/01	Gernhardt, M.	(12)	M		
		2		Reilly, J.	(12)	M	5	59
STS-104/ISS-7A	104	1	7/17/01	Gernhardt, M.	(12)	M		
		2		Reilly, J.	(12)	M	6	29
STS-104/ISS-7A	105	1	7/20/01	Gernhardt, M.	(12)	M		
		2		Reilly, J.	(12)	M	4	02
STS-105/ISS-7A.1	106	1	8/16/01	Barry, D.	(12)	M		
		2		Forrester, P.	(12)	M	6	16
STS-105/ISS-7A.1	107	1	8/18/01	Barry, D.	(12)	M		
		2		Forrester, P.	(12)	M	5	29
STS-108/ISS-UF1	108	1	12/10/01	Godwin, L.	(12)	F		
		2		Tani, D.	(12)	M	4	12
Inc 4, ISS EVA #1	109	1	2/20/02	Walz, C.	(12)	M		
		2		Bursch, D.	(12)	M	5	49
STS-109/HST-3B	110	1	3/4/02	Grunsfeld, J.	(12)	M		
		2		Linnehan, R.	(12)	M	7	01
STS-109/HST-3B	111	1	3/5/02	Newman, J.	(12)	M		
		2		Massimino, M.	(12)	M	7	16
STS-109/HST-3B	112	1	3/6/02	Grunsfeld, J.	(12)	M		
		2		Linnehan, R.	(12)	M	6	48
STS-109/HST-3B	113	1	3/7/02	Newman, J.	(12)	M		
		2		Massimino, M.	(12)	M	7	30
STS-109/HST-3B	114	1	3/8/02	Grunsfeld, J.	(12)	M		
		2		Linnehan, R.	(12)	M	7	20
STS-110/ISS-8A	115	1	4/11/02	Smith, S.	(12)	M		
		2		Walheim, R.	(12)	M	7	48
STS-110/ISS-8A	116	1	4/13/02	Ross, J.	(11)	M		
		2		Morin, L.	(12)	M	7	30
STS-110/ISS-8A	117	1	4/14/02	Smith, S.	(12)	M		
		2		Walheim, R.	(12)	M	6	27
STS-110/ISS-8A	118	1	4/16/02	Ross, J.	(11)	M		
		2		Morin, L.	(12)	M	6	37
STS-111/ISS-UF2	119	1	6/9/02	Chang-Díaz, F.	(12)	M		
		2		Perrin, P. (F)	(12)	M	7	14
STS-111/ISS-UF2	120	1	6/11/02	Chang-Díaz, F.	(12)	M		
		2		Perrin, P. (F)	(12)	M	5	00
STS-111/ISS-UF2	121	1	6/13/02	Chang-Díaz, F.	(12)	M		
		2		Perrin, P. (F)	(12)	M	7	17

Program and mission	*U.S. EVA #*	*EVA crewmember*	*Date*	*EV1*	*Spacesuit configuration*	*Male (M)/ Female (F)*	*EVA (h)*	*EVA (min)*
STS-112/ISS-9A	122	1	10/10/02	Wolf, D.	(12)	M		
		2		Sellers, P. (U.K.)	(12)	M	7	01
STS-112/ISS-9A	123	1	10/12/02	Wolf, D.	(12)	M		
		2		Sellers, P. (U.K.)	(12)	M	6	04
STS-112/ISS-9A	124	1	10/14/02	Wolf, D.	(12)	M		
		2		Sellers, P. (U.K.)	(12)	M	6	36
STS-113/ISS-11A	125	1	11/26/02	Lopez-Alegria, M.	(12)	M		
		2		Herrington, J.	(12)	M	6	45
STS-113/ISS-11A	126	1	11/28/02	Lopez-Alegria, M.	(12)	M		
		2		Herrington, J.	(12)	M	6	10
STS-113/ISS-11A	127	1	11/30/02	Lopez-Alegria, M.	(12)	M		
		2		Herrington, J.	(12)	M	7	00
Inc 6, ISS EVA #2	128	1	1/15/03	Bowersox, K.	(12)	M		
		2		Pettit, D.	(12)	M	6	51
Inc 6, ISS EVA #3	129	1	4/8/03	Bowersox, K.	(12)	M		
		2		Pettit, D.	(12)	M	6	26
STS-114/ISS-LF1	130	1	7/30/05	Robinson, S.	(12)	M		
		2		Noguchi, S. (JAXA)	(12)	M	6	50
STS-114/ISS-LF1	131	1	8/1/05	Robinson, S.	(12)	M		
		2		Noguchi, S. (JAXA)	(12)	M	7	14
STS-114/ISS-LF1	132	1	8/3/05	Robinson, S.	(12)	M		
		2		Noguchi, S. (JAXA)	(12)	M	6	01
Inc 12, ISS EVA #4	133	1	11/7/05	McArthur, W.	(12)	M		
		2		Tokarev, V. (Russia)	(12)	M	5	22
STS-121/ISS-LF1.1	134	1	7/8/06	Sellers, P. (U.K.)	(12)	M		
		2		Fossum, M.	(12)	M	7	31
STS-121/ISS-LF1.1	135	1	7/10/06	Sellers, P. (U.K.)	(12)	M		
		2		Fossum, M.	(12)	M	6	47
STS-121/ISS-LF1.1	136	1	7/12/06	Sellers, P. (U.K.)	(12)	M		
		2		Fossum, M.	(12)	M	7	11
Inc 13, ISS EVA #5	137	1	8/3/06	Williams, J.	(12)	M		
		2		Reiter, T. (D)	(12)	M	5	54

Program and mission	*U.S. EVA #*	*EVA crewmember*	*Date*	*EV1*	*Spacesuit configuration*	*Male (M)/ Female (F)*	*EVA (h)*	*EVA (min)*
STS-115/ISS-12A	138	1	9/12/06	Tanner, J.	(12)	M		
		2		Stefanyshyn-Piper, H.	(12)	F	6	26
STS-115/ISS-12A	139	1	9/13/06	MacLean, S. (Canada)	(12)	M		
		2		Burbank, D.	(12)	M	7	11
STS-115/ISS-12A	140	1	9/15/06	Tanner, J.	(12)	M		
		2		Stefanyshyn-Piper, H.	(12)	F	6	42
STS-116/ISS-12A.1	141	1	12/12/06	Curbeam, R.	(12)	M		
		2		Fugelsang, C.	(12)	M	6	36
STS-116/ISS-12A.1	142	1	12/14/06	Curbeam, R.	(12)	M		
		2		Fugelsang, C.	(12)	M	5	00
STS-116/ISS-12A.1	143	1	12/16/06	Curbeam, R.	(12)	M		
		2		Williams, S.	(12)	F	7	31
STS-116/ISS-12A.1	144	1	12/18/06	Curbeam, R.	(12)	M		
		2		Fugelsang, C.	(12)	M	6	38
Inc 14, ISS EVA #6	145	1	1/31/07	Lopez-Alegria, M.	(12)	M		
		2		Williams, S.	(12)	F	7	55
Inc 14, ISS EVA #7	146	1	2/4/07	Lopez-Alegria, M.	(12)	M		
		2		Williams, S.	(12)	F	7	11
Inc 14, ISS EVA #8	147	1	2/8/07	Lopez-Alegria, M.	(12)	M		
		2		Williams, S.	(12)	F	6	40
STS-117/ISS-13A	148	1	6/11/07	Reilly, J.	(12)	M		
		2		Olivas, J.	(12)	M	6	15
STS-117/ISS-13A	149	1	6/13/07	Forrester, P.	(12)	M		
		2		Swanson, S.	(12)	M	7	16
STS-117/ISS-13A	150	1	6/15/07	Reilly, J.	(12)	M		
		2		Olivas, J.	(12)	M	7	58
STS-117/ISS-13A	151	1	6/17/07	Forrester, P.	(12)	M		
		2		Swanson, S.	(12)	M	6	29
Inc 15, ISS EVA #9	152	1	7/23/07	Anderson, C.	(12)	M		
		2		Yurchikhan, F.	(12)	M	7	39
STS-118/ISS-13.1A	153	1	8/11/07	Mastracchio, R.	(12)	M		
		2		Williams, D.	(12)	M	6	17
STS-118/ISS-13.1A	154	1	8/13/07	Mastracchio, R.	(12)	M		
		2		Williams, D.	(12)	M	6	28
STS-118/ISS-13.1A	155	1	8/15/07	Mastracchio, R.	(12)	M		
		2		Anderson, C.	(12)	M	5	28
STS-118/ISS-13.1A	156	1	8/17/07	Mastracchio, R.	(12)	M		
		2		Anderson, C.	(12)	M	5	02

Program and mission	*U.S. EVA #*	*EVA crewmember*	*Date*	*EV1*	*Spacesuit configuration*	*Male (M)/ Female (F)*	*EVA (h)*	*EVA (min)*
REDSTS-120/ISS-10A	157	1	10/23/07	Parazynski, S.	(12)	M		
		2		Wheelock, D.	(12)	M	6	14
STS-120/ISS-10A	158	1	10/26/07	Parazynski, S.	(12)	M		
		2		Tani, D.	(12)	M	6	33
STS-120/ISS-10A	159	1	10/28/07	Parazynski, S.	(12)	M		
		2		Wheelock, D.	(12)	M	7	08
STS-120/ISS-10A	160	1	11/1/07	Parazynski, S.	(12)	M		
		2		Wheelock, D.	(12)	M	7	19
Inc 16, ISS EVA #10	161	1	11/9/07	Whitson, P.	(12)	F		
		2		Malenchenko, Y. (Rus.)	(12)	M	6	56
Inc 16, ISS EVA #11	162	1	11/20/07	Whitson, P.	(12)	F		
		2		Tani, D.	(12)	M	6	40
Inc 16, ISS EVA #12	163	1	11/24/07	Whitson, P.	(12)	F		
		2		Tani, D.	(12)	M	7	04
Inc 16, ISS EVA #13	164	1	12/18/07	Whitson, P.	(12)	F		
		2		Tani, D.	(12)	M	6	56
Inc 16, ISS EVA #14	165	1	1/30/08	Whitson, P.	(12)	F		
		2		Tani, D.	(12)	M	7	10
STS-122/ISS-1E	166	1	2/11/08	Walheim, R.	(12)	M		
		2		Love, S.	(12)	M	7	58
STS-122/ISS-1E	167	1	2/13/08	Walheim, R.	(12)	M		
		2		Schlegel, H. (Germany)	(12)	M	6	45
STS-122/ISS-1E	168	1	2/15/08	Walheim, R.	(12)	M		
		2		Love, S.	(12)	M	7	25
STS-123/ISS-1J/A	169	1	3/13/08	Linnehan, R.	(12)	M		
		2		Reisman, G.	(12)	M	7	01
STS-123/ISS-1J/A	170	1	3/15/08	Linnehan, R.	(12)	M		
		2		Foreman, M.	(12)	M	7	08
STS-123/ISS-1J/A	171	1	3/17/08	Linnehan, R.	(12)	M		
		2		Behnken, R.	(12)	M	6	53
STS-123/ISS-1J/A	172	1	3/20/08	Foreman, M.	(12)	M		
		2		Behnken, R.	(12)	M	6	24
STS-123/ISS-1J/A	173	1	3/22/08	Foreman, M.	(12)	M		
		2		Behnken, R.	(12)	M	6	02

Program and mission	*U.S. EVA #*	*EVA crewmember*	*Date*	*EV1*	*Spacesuit configuration*	*Male (M)/ Female (F)*	*EVA* (h)	*EVA* (min)
STS-124/ISS-1J	174	1	6/3/08	Fossum, M.	(12)	M		
		2		Garan, R.	(12)	M	6	48
STS-124/ISS-1J	175	1	6/5/08	Fossum, M.	(12)	M		
		2		Garan, R.	(12)	M	7	11
STS-124/ISS-1J	176	1	6/8/08	Fossum, M.	(12)	M		
		2		Garan, R.	(12)	M	6	33
STS-126/ISS-ULF2	177	1	11/18/08	Stefanyshyn-Piper, H.	(12)	F		
		2		Bowen, S.	(12)	M	6	52
STS-126/ISS-ULF2	178	1	11/20/08	Stefanyshyn-Piper, H.	(12)	F		
		2		Kimbrough, S.	(12)	M	6	45
STS-126/ISS-ULF2	179	1	11/22/08	Stefanyshyn-Piper, H.	(12)	F		
		2		Bowen, S.	(12)	M	6	57
STS-126/ISS-ULF2	180	1	11/24/08	Bowen, S.	(12)	M		
		2		Kimbrough, S.	(12)	M	6	07
STS-119/ISS-15A	181	1	3/19/09	Swanson, S.	(12)	M		
		2		Arnold, R.	(12)	M	6	07
STS-119/ISS-15A	182	1	3/21/09	Swanson, S.	(12)	M		
		2		Acaba, J.	(12)	M	6	30
STS-119/ISS-15A	183	1	3/23/09	Acaba, J.	(12)	M		
		2		Arnold, R.	(12)	M	6	27
STS-125/HST-4	184	1	5/14/09	Grunsfeld, J.	(12)	M		
		2		Feustel, A.	(12)	M	7	20
STS-125/HST-4	185	1	5/15/09	Massimino, M.	(12)	M		
		2		Good, M.	(12)	M	7	56
STS-125/HST-4	186	1	5/16/09	Grunsfeld, J.	(12)	M		
		2		Feustel, A.	(12)	M	6	36
STS-125/HST-4	187	1	5/17/09	Massimino, M.	(12)	M		
		2		Good, M.	(12)	M	8	02
STS-125/HST-4	188	1	5/18/09	Grunsfeld, J.	(12)	M		
		2		Feustel, A.	(12)	M	7	02
STS-127/ISS-2J/A	189	1	7/18/09	Wolf, D.	(12)	M		
		2		Kopra, T.	(12)	M	5	32
STS-127/ISS-2J/A	190	1	7/20/09	Wolf, D.	(12)	M		
		2		Marshburn, T.	(12)	M	6	53
STS-127/ISS-2J/A	191	1	7/22/09	Wolf, D.	(12)	M		
		2		Cassidy, C.	(12)	M	5	59
STS-127/ISS-2J/A	192	1	7/24/09	Marshburn, T.	(12)	M		
		2		Cassidy, C.	(12)	M	7	12
STS-127/ISS-2J/A	193	1	7/27/09	Marshburn, T.	(12)	M		
		2		Cassidy, C.	(12)	M	4	54

Program and mission	*U.S. EVA #*	*EVA crewmember*	*Date*	*EV1*	*Spacesuit configuration*	*Male (M)/ Female (F)*	*EVA* (h)	*EVA* (min)
STS-128/ISS-17A	194	1	9/1/09	Olivas, J.	(12)	M		
		2		Stott, N.	(12)	F	6	35
STS-128/ISS-17A	195	1	9/3/09	Fugelsang, C.	(12)	M		
		2		Olivas, J.	(12)	M	6	39
STS-128/ISS-17A	196	1	9/5/09	Fugelsang, C.	(12)	M		
		2		Olivas, J.	(12)	M	7	00
STS-129/ISS-ULF3	197	1	11/19/09	Foreman, M.	(12)	M		
		2		Satcher, R.	(12)	M	6	37
STS-129/ISS-ULF3	198	1	11/21/09	Foreman, M.	(12)	M		
		2		Bresnik, R.	(12)	M	6	08
STS-129/ISS-ULF3	199	1	11/23/09	Satcher, R.	(12)	M		
		2		Bresnik, R.	(12)	M	5	42
STS-130/ISS-20A	200	1	2/12/10	Behnken, R.	(12)	M		
		2		Patrick, N.	(12)	M	6	32
STS-130/ISS-20A	201	1	2/14/10	Behnken, R.	(12)	M		
		2		Patrick, N.	(12)	M	5	54
STS-130/ISS-20A	202	1	2/17/10	Behnken, R.	(12)	M		
		2		Patrick, N.	(12)	M	5	48
STS-131/ISS-19A	203	1	4/9/10	Mastracchio, R.	(12)	M		
		2		Anderson, C.	(12)	M	6	27
STS-131/ISS-19A	204	1	4/11/10	Mastracchio, R.	(12)	M		
		2		Anderson, C.	(12)	M	7	26
STS-131/ISS-19A	205	1	4/13/10	Mastracchio, R.	(12)	M		
		2		Anderson, C.	(12)	M	6	24
STS-132/ISS-ULF4	206	1	5/17/10	Reisman, G.	(12)	M		
		2		Bowen, S.	(12)	M	7	25
STS-132/ISS-ULF4	207	1	5/19/10	Bowen, S.	(12)	M		
		2		Good, M.	(12)	M	7	09
STS-132/ISS-ULF4	208	1	5/21/10	Good, M.	(12)	M		
		2		Reisman, G.	(12)	M	6	46
Inc 24, ISS EVA #15	209	1	8/7/10	Wheelock, D.	(12)	M		
		2		Caldwell Dyson, T.	(12)	F	8	03
Inc 24, ISS EVA #16	210	1	8/11/10	Wheelock, D.	(12)	M		
		2		Caldwell Dyson, T.	(12)	F	7	26
Inc 24, ISS EVA #17	211	1	8/16/10	Wheelock, D.	(12)	M		
		2		Caldwell Dyson, T.	(12)	F	7	20

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(1) GT4 configuration David Clark G4C pressure suit assembly and NASA ventilation control module umbilical life support.
(2) David Clark G4C PSA and AiResearch umbilical extravehicular life support systems (ELSS).
(3) International Latex Corporation (ILC) A7L PSA and Hamilton Standard (HS) -5 portable life support system (PLSS).
(4) ILC A7L PSA and HS pressure control valve (PCV) and umbilical to Command Module.
(5) ILC A7L PSA and HS -6 PLSS.
(6) ILC (now ILC Industries) EV (Extra-Vehicular/Lunar Module) A7LB PSA and umbilical to Lunar Module.
(7) ILC A7LB PSA and HS -7 PLSS.
(8) ILC CMP (Command Module pilot configuration) A7LB and HS pressure control valve (PCV)/umbilical.
(9) ILC Skylab configuration A7LB and umbilical to vehicle life support system.
(10) ILC Skylab configuration A7LB and AlliedSignal (umbilical) astronaut life support assembly.
(11) HS/ILC baseline configuration of the extravehicular mobility unit (EMU).
(12) HS/ILC enhanced configuration of EMU (based on use of orbit replaceable unit components).

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