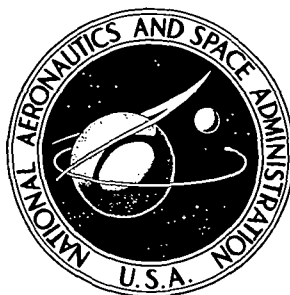


APPLICATIONS OF AEROSPACE TECHNOLOGY



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LIQUID COOLED GARMENTS

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INTRODUCTION

How does new knowledge, acquired for one purpose, develop into useful technology having significant impact and benefits to society? This is one case study in a series of detailed investigations tracing the origins of new knowledge developed to solve specific problems of manned space exploration, and its subsequent modification and application to commercial needs.

What differences exist between the technology required for space exploration and the requirements for application to earthly problems? What factors determine the time required to convert new knowledge into viable economic benefits? Various case examples disclose differing patterns of technological development. By comparing the common and contrasting findings it may be possible to understand better how new knowledge generates real benefits.

Starting from a specific "knowledge contribution" previously identified from an analysis of astronaut life support requirements, the origins, adaptations, and eventual significance of the new technology are presented.

LIQUID COOLED GARMENTS

Knowledge Contribution Previously Identified

The cooling capacity of gas ventilated suits was found to be inadequate to protect working space crews from heat stress. The manned space effort developed the concept of the liquid cooled garment and extended it to maintain the thermal balance of mobile, working astronauts. Maintaining skin temperatures within desired ranges permitted long exposure to hot environments with minimum decrement in mental and physical performance. Liquid cooling can minimize heat stress from external sources as well as internal metabolic heat.

Early experience with conductive liquid cooled undergarments showed that removing heat from the body was extremely powerful--potentially capable of overwhelming normal regulatory mechanisms, and producing abnormal responses. Manual thermal regulation control has been used successfully on all Apollo flights; automatic control may be desirable for advanced missions.

Liquid cooled garments have been employed in several applications in which severe heat is encountered. LCGs to replace air-line cooling units now employed in a variety of industrial processing situations, where severe heat is encountered, are in the advanced experimental stage. As costs continue to decline aerospace engineers foresee a broad range of applications in industry, as well as the use of liquid cooled garments to study responses of the body to heat, cold, and exercise.

I. What They Are

Liquid cooled garments (LCG) denote a variety of special hoods, jackets or underwear which actively cool and protect persons exposed to hot environments. Cool liquid flowing through channels close to the body carries away excess metabolic heat, and prevents external heat from reaching the wearer. The user can be kept comfortable, and can perform heavy work at high efficiency without sweating. Heat stress and fatigue are greatly reduced, and the risk of heat exhaustion or collapse can be avoided even in extremely hot situations.

The original water cooled suits that were developed for thermal protection of the astronauts covered the body from shoulders to ankles. Simple garments covering only part of the body, but more convenient to put on, were developed later. Commercial modifications of Apollo liquid cooled garments are finding use in industry, sports, mining, surgery, and agriculture.

In addition, specialized garments have been developed for a variety of applications not directly related to protection from heat. These applications can be traced to growing acceptance of the advantages derived from precise control over the heat balance of the human body.

II. Development History

A. Heat Stress and Work Load

Heat generated by the human body must be transferred to the surroundings in order to avoid overheating. When a hot environment prevents adequate heat dissipation, the body temperature rises causing discomfort, followed by more serious physiological effects if body temperature becomes too high.

The body burns food at a rate depending on how hard it has to work. Viewed as a machine, man has a low efficiency; he produces large amounts of thermal energy for relatively small increases in the amount of useful work accomplished. The more vigorous activities generate so much heat in the active muscles that peak output can be maintained only for limited periods (see Table 1).

Heat stress is a problem that occurs whenever heat input to the body exceeds heat dissipation. In industry, mining, and farming, there are many situations in which workers are unable to achieve thermal equilibrium. Excess heat is stored within the body, causing a gradual increase in body core temperature. Because tolerance of forced heat storage is strictly limited, eventually the worker has to retire and recover in a cooler environment. Prolonged work in hot situations causes a flushed skin, and inattention to work. The heart rate rises above 160 beats per minute, and subjects report fatigue, headache, giddiness and nausea. Work capacity is greatly reduced, leading eventually to heat exhaustion and collapse. Where the skilled performance of critical or dangerous tasks is involved, heat storage must be stopped far short of the physiological limits just described.

To combat the effect of heat stress there are two defenses: one can either reduce heat input to the body; or, increase heat loss from the body. The usual recourse is to cool the environment. However, there are situations where it is impractical or too costly to control the temperature of the surroundings, and individual cooling of the workers is required.

TABLE 1

METABOLIC HEAT OUTPUT FOR VARIOUS ACTIVITIES

<u>Work Activity</u>	<u>Average Metabolic Heat Output Btu/Hour</u>
Sleep (age 30-40)	280
Seated, at ease	360
Seated, typing	410
Standing, at ease	470
Slow walking	720
■ Apollo 11 Lunar Exploration (Aldrin; duration 168 minutes)	1,118
Rowing for pleasure	1,190
Pushing wheelbarrow, 220 lb on level	1,320
Army Drill	1,680
Jogging, 4.5 mph	1,820
Lumberjacks	2,105
■ Gemini IX space walk	2,200
Weight lifting, 44 lb floor to shoulder, 10 per minute	2,590
Mountain climbing	2,860
Mailman, climbing stairs	2,880
Two-Step heart test	3,830
Swimming, breast stroke, 2 mph	6,900
Running, 13 mph	11,400

Source: Midwest Research Institute.

High external heat loads on workers exist in the metal working, glass and ceramics industries, boiler rooms of ships, and the cockpits of high performance aircraft. For many years before man first ventured into space there had been continuing efforts to control the debilitating effects of heat on persons who must work in hot environments. General ventilation, exhaust fans, sun screens, and heat shields were used to reduce the heat load, and provide some measure of relief. Acclimatization to heat is used to prepare workers for physical labor in hot environments, and also to screen out individuals who may be heat intolerant. Protection from furnaces and radiant heat sources required reflective insulated clothing and short exposure to the heat load. For those environments that would otherwise be intolerable, individual cooling becomes essential. Ducted blowers or portable "man-cooling" fans are widely used for spot cooling. Where it was not practical to cool the surroundings, or reduce the thermal load on the workers, it was necessary to wear elaborate and expensive ventilated suits that provided a generous flow of air from a trailing air hose. The cooling capacity of the air stream is largely due to the evaporation of perspiration, sometimes leading to severe dehydration. However, since the air hose restricted mobility, and air suits were none too comfortable to wear for extended periods, the use of air-cooled clothing was mostly limited to emergency activities such as fire fighting or industrial furnace repair.

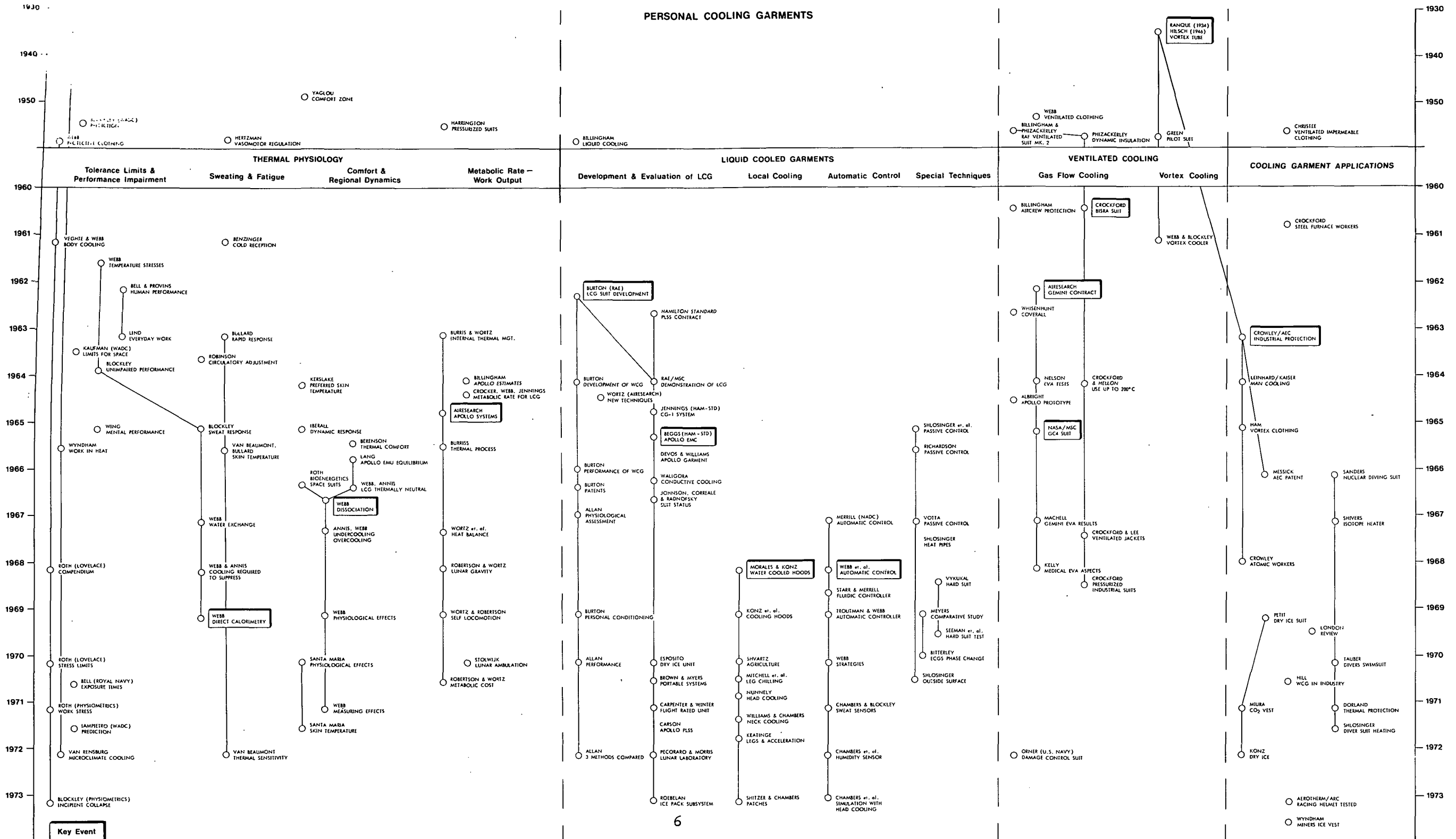
The ideas, events, and discoveries that contributed to the development and use of today's liquid cooled garment technology are documented in greater detail in the chronology section. The major lines of development and application are depicted schematically in Figure 1 which has been simplified to emphasize the parallel advances in each of the related areas.^{1/} As a direct consequence of the requirements for cooling astronauts in space, knowledge of thermal physiology has been greatly increased, and more practical advances in personal cooling have been achieved in the last decade than in all the preceding years.

Analysis of the historical pattern of development in liquid cooled garments discloses several distinctive features:

- * The technology has evolved almost totally within the aerospace context. Biomedical researchers, NASA Centers, aerospace contractors, and university groups have carried the development forward with relatively minor involvement of manufacturing firms or potential users.
- * The perseverance and the mobility of the principal contributors are noteworthy. Continuously over the past 15 years, about a dozen organizations throughout the world have remained centers for scientific studies and engineering developments which

^{1/} Those interested in the origins and evolution of water cooled garments prior to 1970 will find an analysis and discussion in the excellent article by Nunneley, S.A., "Water Cooled Garments: A Review," Life Sciences 2 335-360 (1970).

PERSONAL COOLING GARMENTS



have advanced the technology of personal cooling garments. The investigators frequently moved from one organization to another, usually continuing their previous lines of research and development.

- * A high degree of interdependence and interaction can be seen between basic studies in biology, medicine and physiology, and the corresponding engineering, design, development and testing of liquid cooled garments. This continual interplay between basic studies and practical development is characteristic of a technology that is still evolving. The technology has not progressed smoothly in sequence from research, to development, to application. On the contrary, progress has been alternately paced first by practical development, then followed by basic physiological studies, or biophysical measurements which eventually lead to simpler, more effective and more useful methods of personal cooling.

B. Thermal Control for Mercury and Gemini Astronauts

The first protective suits used in the space program were modified versions of the standard Navy Mark IV pressure suit--an air ventilated, full pressure suit developed to protect crewmen against cabin pressure failure at high altitudes. This suit was under continuing development throughout the Mercury flights, and into the Gemini program. By the time of America's first two-man space flight--Virgil Grissom and John Young aboard Gemini III, in March 1965--the space suit had evolved into a four-layer garment in which the breathing oxygen was ducted through the suit for ventilation and cooling. Gas cooling was generally believed to be adequate for orbital flights and extravehicular activities, but it was anticipated that gas cooling would be marginal for lunar exploration. As it actually turned out, the greatest cooling requirement was encountered during the Gemini space walks. By the time men first walked on the moon, the superiority of liquid-cooling techniques had been clearly demonstrated.

C. Water Cooled Garments

The first liquid cooled suit was developed by Burton and Collier in 1962 at the Royal Aircraft Establishment (RAE), Farnborough, England. Although primarily concerned with the protection of crewmen in hot aircraft cockpits, they immediately realized that practical personal cooling systems would have many possible applications. The original British water cooled garment was made with 40 small plastic tubes threaded into a suit of cotton underwear. Cooling water was piped to the ankles and wrists, then back over the limbs and trunk of the body. The head and neck were not cooled.

Systems analysis showed that the high heat capacity of water should provide excellent cooling with lower pumping power, less system weight, and a much less bulky garment than the air ventilated suits. Practical testing was required to answer questions about the efficiency of heat transfer from human skin to the circulating coolant; and whether tubes touching only a small percentage of the body surface could provide thermal neutrality without sensations of local chilling. The first tests of the prototype garment showed excellent thermal coupling between the body and the cooling water. John Billingham, one of the first test subjects, reported that the suit was comfortable, even with high heat loads that required low water temperatures. Subsequent improvements in suit design over the next few years led eventually to the current Royal Air Force liquid-cooled suit.

At the start of the Apollo program, life-support system contractors were seeking a more effective way to cool the lunar astronauts. Hamilton Standard Division of United Aircraft joined with Webb Associates who had been concerned with personal cooling suits for several years. They knew about the experiments at Farnborough, and devised their own prototype suit with which the effectiveness of liquid cooling was confirmed.

The British prototype liquid cooled garment was demonstrated to NASA in 1964 at the Manned Spacecraft Center. The subject wore both the LCG and a full pressure suit while exercising at a rate that produced 1,350 Btu/hr. In an attempt to insure a heat balance, the test used circulating ice-water so that the garment removed heat at 3,400 Btu/hr. The subject complained of being too cold, and would soon have been severely chilled. This trial showed both the power of the technique and the need to learn how to control cooling. The liquid cooling concept was incorporated into the Apollo suit design and Hamilton-Standard was selected as the development contractor. Early prototype water cooled garments were fabricated by B. Welson & Co., and the flight garments were designed and manufactured by ILC Industries as a basic part of the Apollo space suit.

Physiological evaluation promptly showed several basic facts:

- . Liquid cooled garments provided a powerful means of removing heat from the body; so effective, that one can easily remove all the heat brought to the skin, even during hard work. The technique could readily handle the 2,000 Btu/hr work rate anticipated for lunar surface exploration.
- . Cooling virtually eliminated sweating for any work rate. Subjects found that the unique sensation of working hard without sweating was a particularly pleasant condition.

- . The zone of skin temperature between the shivering threshold and the onset of sweating was narrower than expected. To keep active subjects comfortable, the skin temperature had to be moved progressively lower as work rate increased.
- . Compared directly with gas ventilated suits, the LCG was far more effective in reducing signs of heat stress--whether the heat came from a hot environment, or from high work rates.
- . A surprisingly wide range of water flow rate and temperature combinations could be used effectively.

D. Ventilated Garments

Design and improvement of modern air-ventilated cooling garments took place over about the same time span (1958-1966), and involved many of the same investigators who contributed to the advancement of liquid cooled garment technology. At the Royal Aircraft Establishment in 1957, John Billingham and P.J.R. Phizackerley undertook the development and evaluation of an air ventilated suit for the RAF. The limited cooling capacity of conventional ventilated garments apparently impressed both investigators sufficiently that each independently undertook to improve the system.

Phizackerley endeavored to increase the cooling effect by utilizing radial air flow normal to the body, a concept which he called "dynamic insulation." Although radial flow was first employed to direct warm air flow against the skin to protect pilots from cold exposure, this dynamic insulation concept later formed the basis for Crockford's cooling suits for steel workers.

Through 1961, Billingham continued to work on personal cooling and protection of pilots in high performance aircraft. Dr. Billingham then joined the Apollo team at Manned Spacecraft Center, and after several years there, transferred to direct the Biotechnology Division at Ames Research Center.

A critical problem in the iron and steel industry is the protection of workers who must repair furnaces and steel hearths as soon as possible after shut-down. From 1960 through 1964, at the University of London, G. W. Crockford undertook the development of insulated and ventilated hot suits for steel workers. This work was sponsored by the British Iron and Steel Research Association, and involved many practical tests of experimental ventilated suits. Using the radial air flow concept, Crockford was able to protect furnace rebuilders from environments ranging up to 400°F. Heat stress on the workers was reduced, and the length of time they could spend repairing the furnaces was more than doubled.

In the United States during the early 1960's, the Gemini program evolved using the ventilated space suit developed by the David Clark Company. In this ventilated suit, gas flow was directed to the body's extremities, flowing back over the body and head. For extravehicular activity, it would have been desirable to select an oxygen flow rate sufficient to maintain the astronaut in a "no sweat" condition by using only the sensible (non-evaporative) cooling power of the gas stream. However, the oxygen flow rate necessary to achieve sufficient sensible cooling at high metabolic rates required uncomfortably high air velocities and high noise levels. Thermal tests of the Gemini suit that were performed in simulation chambers did not anticipate the strenuous work loads that would be encountered by the Gemini astronauts when working under weightless conditions during space walks.

During the development of the prototype Apollo suit, the thermal inadequacy of an oxygen-ventilated suit became abundantly clear. Heat removal was limited to approximately 800 to 1,000 Btu/hr. Strenuous activity, such as walking in loose sand, sent the metabolic rate to 4,000 Btu/hour for short periods. Nearly all of this heat would be stored in the body because it could not escape from the space suit. Even at moderate work rates, sweat ran into the astronaut's eyes, and caused skin irritation. These studies played a critical part in the development of liquid cooled clothing because they so dramatically illustrated the upper limits of cooling by conventional ventilated garments.

E. Vortex-Tube Cooling

The vortex-tube conceived more than 30 years earlier, provided the next improvement in ventilated suit cooling. The vortex-tube was invented in 1931 by Ranque, a French metallurgist. The German physicist, Hilsch, further developed the device, and published design and performance data on it in 1946. For over a decade, the Hilsch tube was regarded as a laboratory curiosity. A stream of compressed air fed into one end of the Hilsch tube is divided into two streams: one loses heat, emerging as cold air; while the other stream absorbs heat and is exhausted as hot air. Although a patent was granted in 1958 covering the use of a vortex-tube for a pilot's cooling suit, virtually no attention was paid to the device until the early 1960's. Webb and Blockley in 1961 described the performance of the vortex cooler; and several improved forms of the Ranque-Hilsch tube appeared on the market. The novelty of a refrigeration device that had no moving parts captured the imagination of workers throughout the world, and for several years, many attempts were made to perfect the device for use in heat protective garments.

Starting in June 1962, Linehard tested vortex-tube cooled hot suits to protect workers at a Kaiser Aluminum plant in Louisiana. At the Savannah River atomic energy plant, Croley modified commercially available vortex-tubes to improve the cooling of suited atomic workers. ALCOA and Mine Safety Appliance worked together to develop cooling clothing for furnace operators and potmen in aluminum plants.

While the vortex-tube cooler did increase the cooling effectiveness of ventilated garments, there were many problems with the early vortex units. Care had to be exercised to prevent the wearer from being burned by the hot end of the tube, which could easily reach 250°F. The noise from an unmuffled vortex-tube caused headache, ear ringing, and nausea in less than 2 hours. Numerous improvements were gradually made in the systems, and today, commercially available vortex-tube protective garments are proving useful in specialized industrial applications.

III. Space Requirements and Contributions

Manned space exploration certainly extended and improved the technology of cooling garments--more importantly, it also altered the goals of personal cooling. When attention shifted from cooling designed to protect seated aircraft pilots, to an objective of maintaining thermal balance for mobile, working astronauts, many new requirements emerged. In the course of satisfying these requirements, much new knowledge was generated concerning thermal physiology, and a host of improvements and innovations were added to liquid cooling technology.

Much of what was learned in Gemini, Apollo, and post-Apollo programs, stemmed from two important differences that set these space programs apart from earlier work on personal cooling:

- * For the first time, the biothermal processes of the wearer, and his physiological responses, became an integral part of the total cooling system. It was essential to design a cooling system that would work in harmony with the thermoregulatory processes of the human body. Instead of providing an artificial "microclimate" to which the wearer must adjust, the objective was to maintain thermal neutrality between the body and the environment.
- * Because extravehicular activities presented a variable work load, liquid cooled garments could not be designed to provide any fixed level of cooling. Rates of heat removal must be adjusted over a wide range. Further, man was found to be an exceedingly poor judge of his own thermal condition, especially when busy with tasks requiring close attention. The need for thermal control strategies, and for automatic control techniques, became increasingly important.

The major space requirements for personal cooling are shown in Table 2, together with specific contributions developed in various space programs in the course of satisfying these mission requirements.

TABLE 2

SPACE REQUIREMENTS AND CONTRIBUTIONS

<u>Space Requirement</u>	<u>Programs</u>	<u>Contributions</u>
Remove Humidity Gas Cooling	Gemini Apollo Prototype	Practical limits defined Zero-G workloads determined Dehydration, weight loss Metabolic cost of work in suits
High Heat Removal	Apollo Advanced Suits	Apollo LCG; work without sweat Thermally conductive pads Dynamic cooling
Long Duration Comfort Maintain Thermal Balance Avoid Overcooling	Apollo Skylab IMLSS*	Comfort zone defined O ₂ uptake, heat loss delay Thermal time constants Biothermal models
Small, Lightweight Low Power Reliability	Apollo PLSS Advanced suits Lifting body flights	Walking beam pump Expendibles control Passive control techniques Phase change materials
Monitor Heat Stress	Apollo Post Apollo	LCG heat removal correlated with stress levels Real-time heat balance
Controlled Cooling	Apollo Advanced Suits IMLSS*	Manual control Feedback control strategies Control signals from VO ₂ , skin temperature, sweat rate, humidity Fluidic controller Temperature rise over muscles Tubing distribution
Balanced Regional Cooling	Apollo Advanced Suits	Head and neck cooling Heat partition Cooling patches

* IMLSS = Integrated Maneuvering and Life Support System.

Between the time the first prototype LCG was devised in 1962, and the first lunar landing in 1969, personal cooling was studied intensively and in great detail. The Manned Spacecraft Center and NASA contractors including AiResearch, Hamilton Standard, ILC Industries, Lovelace Foundation, Honeywell, Litton Industries, Webb Associates, the John B. Pierce Foundation, McDonnell Douglas, and other groups contributed significantly with fundamental research, as well as improvements in the design, fabrication and use of liquid cooled garments.

The successful development and use of the LCG and associated life support equipment was apparent to everyone who watched the Apollo astronauts explore the lunar surface. However, the importance of many physiological findings that came from the LCG development is less widely recognized. Because what was learned in the process of assuring reliable crew support for astronauts has subsequently been applied to a number of earthly problems, some of the major findings will be briefly summarized.

Skin Temperature and Subjective Comfort. Maintaining skin temperatures within desired ranges permitted long exposure to hot environments with minimum reduction in mental and physical performance. The LCG permitted real-time thermal monitoring of work loads by measuring water temperatures at inlet and outlet points. Metabolic heat output was found to be an excellent measure of physiological cost of work, and could be directly correlated with other indicators of load and stress--such as heart rate, oxygen consumption and body core temperature. Better indexes of heat strain were developed permitting accurate assessment of the effect of heat stress.

The "comfort zone" between shivering and sweating was found to be narrower than expected. For any particular rate of metabolic work, the skin temperature at the sweating threshold was only a few degrees above that of the shivering threshold. These critical values have been rigorously defined over a wide range of work loads and environments, leading to new criteria for defining "comfort." Man is a poor judge of his own thermal state, and often reacts too late or too strongly to the sensation of warmth from working. Keeping the body thermally neutral in the physical sense was shown to be a more reliable way to maintain comfort than depending on subjective evaluation.

Space studies determined, for working subjects, the precise rates at which cooling occurred via convection, evaporation, radiation and conduction, individually and in combination. Thermal response characteristics for different parts of the body were determined, and cooling rate data for different environmental conditions were specified. Particular conditions evoking different thermoregulatory responses were then related to subjective sensations of comfort, and to impairment of human performance.

Dynamic and Regional Thermal Regulation. The dynamics of body cooling processes were analyzed. The behavior of the body as a whole or any selected region was found to depend on surface area, local heat production, tissue insulation, vascularity, and thermal exchange processes.

The striking importance of head cooling in maintaining human comfort and effective performance under heat stress conditions was "rediscovered," and accurately measured; and has now become more widely appreciated as an essential part of providing a desirable thermal environment. New details concerning the effects of local or regional cooling on many other parts of the body were compiled.

Biothermal models of man were developed using analog computer simulations. These routines permit exploration of various metabolic and thermal processes in the body. Dynamic simulation is particularly useful in reducing the amount of human experimentation required. Thermal extremes that would be hazardous for human subjects can be investigated, and the effectiveness of different emergency treatments can be compared.

Automatic Control of Human Heat Balance. The time delays and actual rates for thermal processes in the body were determined for the first time. The rates of muscle heat production at the onset of work, rise in blood temperature, skin temperature, rise in body core temperature due to heat storage, and rejection of metabolic heat through the skin and respiratory system, were all found to be nonlinear functions. Each step of the dynamic thermal process can be accurately represented as an exponent in the thermal balance equation. This development made practical the application of control theory to human temperature regulation.

Manual control, requiring each astronaut to select the cooling level needed was used on all Apollo flights. Automatic control may be desirable for advanced missions. Liquid cooled undergarments were found to be capable of overwhelming normal thermoregulation, and producing abnormal responses. The lower limit of cooling was established for resting subjects. During prolonged periods of rest, a small error in cooling rate can gradually produce extremely uncomfortable heating or cooling effects. Overcooling of this kind was experienced during the astronauts' stay in the Apollo 11 Lunar Module.

Automatic control has been applied to water cooled garments to maintain prescribed conditions of thermal comfort for the wearer throughout the entire range of metabolic heat production rates and work profiles. Various modes of control--simple proportional regulation, as well as more accurate feedback control techniques--have been demonstrated. Four electronic controllers and one fluidic control unit were developed, based upon control signals derived from skin temperatures, skin resistivity, or respiratory measurements.

Automatic controllers that permit cooling to follow the body's need for heat dissipation, keep the subject in a state of continuous comfort, never overcooled, yet always able to dissipate his metabolic heat at minimal physiological cost. Persons wearing cooling garments gladly tolerate automatic control while asleep, at rest, or working, and for many hours.

Special Cooling Techniques. Methods for the passive control of suit temperature and humidity were explored. Heat pipes, thermal switches, and diodes were found to provide effective cooling for special situations. Advanced, evaporative cooling systems, and phase-change materials for self-contained cooling garments were developed and evaluated.

IV. Subsequent Applications--Their Requirements

Applications of the liquid cooling technique to non-space problems began almost immediately after the effectiveness of the LCG was shown by NASA, and by the Royal Aircraft Establishment (RAE). As would be expected, the earliest uses typically were for transferring large amounts of heat to or from the body at high rates. Most of these applications sought solutions to long recognized problems of thermal stress.

Furnace Repair. Performing routine maintenance and repair of glass furnaces and steel hearths requires fairly heavy work in surroundings at nearly 400°F. Pilkington Brothers, originators of the float-glass process, developed a liquid cooled garment of their own design for use in these extreme environments. In the past, repair work had been done by using a number of workers in succession, each able to work for only a few minutes at a time. They wore insulated clothing covered by aluminized asbestos outer garments, together with a polished aluminum helmet, to give short-term protection from the radiant environment. The effectiveness of the LCG was first tested by having an operator work close to an opening into the furnace, lifting and placing fire bricks in a radiant environment of several hundred degrees. The normal working-time limit under these conditions was 4 minutes; with the addition of the water cooled suit, the shift-time could be extended to 25 minutes.

Next, Dr. Hill of Pilkington Glass, performed careful tests using both workers who were experienced in hot furnace repair work, as well as inexperienced laborers. Working in an environmental globe-temperature of 383°F, the maximum possible exposure time without the water cooled suit was 13 minutes. The pulse rate of these workmen rose to 165 beats per minute, body temperature increased 1.82°F, and the average sweat rate was 3.25 liters per hour (roughly 7 pounds per hour). With the use of the water cooled garment, even inexperienced workmen could perform moderate to heavy work in this environment for at least 60 minutes, while other men worked as long as 153 minutes. Based on these experiments, it was planned that future hot maintenance and repair work be performed using a working shift of 2 hours, consisting of five working periods of 20 minutes with four 5-minute rest periods.

A portable cooling unit rugged enough for heavy industrial use, was also designed by Pilkington engineers and is now manufactured by Beaufort. A cylindrical block of dry ice inside a water-jacketed pressure tank, acts as the coolant. The gas evolved from the dry ice is used to power a diaphragm pump which circulates the suit liquid. Thus, the unit is self-contained and needs no batteries or other connections. It provides a cooling rate of 1,200 Btu per hour, gradually declining to half that value after 3 hours.

Surgery. The British liquid cooled suit has been used to cool surgeons while performing operations. The purpose here was to reduce the risk of sweat contamination rather than to reduce thermal stress, since air temperatures in the operating room are normally comfortable, although there is considerable radiant heat from the overhead lighting. A surgeon, at the Royal Orthopedic Hospital, successfully carried out a 2-hour long operation for a fractured femur while wearing a liquid cooled suit. Sweat suppression eliminated the need to sponge the surgeon's forehead, and minimized sweating of his hands inside the surgical gloves.

Automobile Racing. One of the first applications of LCG technology involved stock car race drivers at tracks throughout the southern United States. Transfer of technology was promoted in this instance by two factors:

- (a) Several Hamilton Standard engineers working on the LCG also served on Society of Automotive Engineers technical committees dealing with human factors and safety equipment. These groups maintained frequent contact with professional racing teams, and told about the effectiveness of liquid cooling.
- (b) For years, stock car drivers had practiced a primitive form of "liquid cooling," at pit stops during a hot race, one of the crew would toss a bucketful of cool water through the driver's window to douse his clothing!

For the Firecracker 400, the traditional Fourth of July race at Charlotte, North Carolina, "Fireball" Roberts was the first driver to wear a liquid cooled garment. Following a 400-mile drive at record setting speeds, Roberts emerged from the 140°F seat of his enclosed car appearing cool and alert, while other drivers showed the strain of sweat and fatigue. Roberts had obtained his LCG and cooling equipment from one of the space contractors, and this system provided a margin of safety and comfort throughout many blistering races.

Many other racing drivers adopted the idea. Often, homemade cooling garments and circulating systems were used, and some drivers discovered the hazards of using the basic technology without complete knowledge concerning proper application and control. Too much cooling was often applied to the

torso, and not enough to the head, legs and arms; and some drivers became chilled and thoroughly uncomfortable. In Europe, the Porsche racing team was more successful. They tested a suit and ice unit supplied by Normalair-Garret, and Beaufort, the manufacturers of the RAF suit. The reduction in stress and driver fatigue was so clearly evident that Porsche ordered a number of sets for use by the full team.

Warm-Suits for Divers. Divers in frigid waters have found that the LCG principle can also be used with warm water to provide highly effective protection from chilling. Systems have been developed to circulate warm water through rubber wet-suits worn by free swimming divers, or LCG's can be worn under conventional diving suits. Several manufacturers, including Westinghouse and Sanders Associates, have developed commercial warm suits for divers that can be used with portable radioisotope heat sources. The U.S. Navy is currently testing several types of liquid warming garments to increase the duration and depth of saturation diving.

Hot Industrial Environments. Several U.S. firms offered commercial versions of the LCG, redesigned for industrial use. The Model 20 Cool Suit introduced by Welton, for example, offered about 1,200 Btu/hr of cooling, and was designed for the convenience of the wearer as an elastic fabric, hip-length vest. This cool suit was used successfully by test pilots, by crop dusters who had to wear impervious protective clothing, and by research technicians who gathered data while working in 125°F laboratories. ILC Industries, Webb Associates, and a few other organizations attempted to interest industry in using the LCG to avoid thermal stress and increase the productivity of workers in hot environments. Some trials were conducted using cooling garments for hammer-forge operators, steel mill workers, and men applying vitreous enamel to plumbing fixtures.

Acceptance of the idea was limited, and relatively few cooling garment systems were marketed. Part of the problem was cost--because the early suits were custom made and fairly expensive. Cultural resistance to change was an even more formidable barrier. Neither labor nor management perceived this new technology as a desirable and useful advance. Workmen were reluctant to wear the unfamiliar garb which might not be convenient or comfortable. The extra pay or special status associated with certain hot jobs might be lost. Management often maintained that there was no problem with heat stress, or that workmen soon got used to the heat. There was doubt that increased work output would offset the cost of personal cooling. Unions sometimes objected because the number of men needed per shift to perform work in hot areas could be reduced.

The whole idea of individual cooling to minimize stress on the working man ran counter to centuries of tradition: labor is exhausting; discomfort, sweat and fatigue are part of the job. Thus, in the late 1960's, the concept of using liquid cooling for workers in hot environments had not yet arrived.

About 1969, work with liquid cooled garments entered a new phase. Unlike applications of the LCG in which effectiveness depended mainly upon high heat transfer rates, newer uses were more sophisticated, and took advantage of other properties of the LCG. Subsequent development and use of liquid cooled garments followed two major trends:

- (1) Applications depending upon accurate thermal control, precise temperature measurements, and automatic regulation characteristics.
- (2) Development of smaller garments having improved thermal coupling, simplified design, greater convenience for the user, and lower cost.

Typical of those applications that depend upon the accuracy and repeatability of thermal measurements made with the aid of liquid cooled garments are the growing number of uses of the LCG as a tool in physiological research. The use of automatic controllers for the LCG has made possible experimental applications in clinical medicine, surgery, and diagnostic procedures.

Cardiovascular Research. The Manned Spacecraft Center provided an Apollo LCG to heart and circulatory research workers at the University of Washington. The thermal garment has been used in a continuing series of cardiovascular and metabolic investigations.

Initially, the LCG was used to produce rapid changes in the skin temperature of men who were exercising at different rates, so that muscle efficiency and metabolic response could be determined. In further studies, the response of the heart and circulatory system was monitored while the skin temperature was driven rapidly to high levels and maintained at the upper level of the subjects tolerance. Detailed study of how the body reacts throws new light on the mechanisms of heat tolerance and heat stroke. Other experiments determined the rate of redistribution of blood flow when subjects were rapidly heated using the LCG. It was found that all of the extra blood pumped by the heart goes directly to the skin and working muscle, rather than to other vascular beds within the body. Thermal garments have now become an accepted technique in experimental physiology, both for the control of thermal conditions, and for monitoring the body's response.

Direct Calorimetry. For the first time, direct whole body calorimetry on actively working subjects was made possible through use of the LCG. Similar to procedures used to obtain a real-time heat balance for the lunar astronauts, this application takes advantage of the fast response time and great accuracy of the thermal measurements made with the LCG. Direct measurements of the heat output from the body can be made with an accuracy of better

than 1 percent. The suit is comfortable to wear for long periods of time, and can be used to study diurnal temperature cycles in the body, metabolic disorders, fever, and dietary factors such as specific dynamic action of various foods.

A study for the U. S. Navy on the rewarming of divers was recently conducted by Webb Associates who first developed this technique. It is important to know how long it takes for the body to recover thermal equilibrium after divers become so chilled that they must leave the water. Diving officers need some reliable way to tell when rewarming is completed before permitting the men to dive again. Somewhat surprisingly, results show that the divers themselves consistently misjudged the rewarming process. They feel completely recovered soon after shivering ceases, when the rewarming process is only half completed. Nor can any set of body temperature measurements be used to determine that rewarming is complete and thermal equilibrium has been restored. At the present time, the safest procedure is to rewarm the men until the skin begins to sweat. This sweat response signals that rewarming has gone further than needed, and the men will have to lose some stored heat in order to regain neutrality.

Medical Applications. The use of thermal garments in clinical medicine and diagnosis is still experimental but rapidly gaining acceptance. Liquid cooled boots have been used for several years to provide refrigeration anesthesia prior to the amputation of limbs above or below the knee.

Versions of the LCG with automatic temperature controls are being used to aid patients who lack normal body temperature regulating mechanisms. Some persons are born without the ability to sweat. In other cases, damage to the spine sometimes renders paraplegic patients unable to sense whether they are hot or cold, and can also impair the ability of the body to compensate. For patients who have lost thermal sensation or regulation, liquid cooled garments are providing increased safety and comfort.

Both the University of Oklahoma, and the National Cancer Institute are exploring the use of liquid cooled garments for the early detection of breast cancer. Special cooling garments and controls developed at Ames Research Center, are used to cool the skin and tissues prior to obtaining an infra-red image of the breast area. Because this procedure insures uniform temperatures and precise, repeatable control over skin and tissue temperatures, the physician can obtain increased contrast between normal tissue and the hot-spots that may denote tumor growth. Smaller tumors can be detected at earlier stages where the prospects for treatment are better.

Improved and Simplified Thermal Garments. The second major line of LCG development has been to make the garments more effective, smaller, more convenient to use, and less costly. Some of these improvements have come directly from further studies on astronaut cooling; other improvements represent attempts to simplify the personal cooling concept for more widespread use.

Abbreviated garments such as jackets or ponchos covering only part of the body are easy to put on and do not restrict movement as much as full body suits. But, would partial garments provide adequate cooling, and where should cooling be applied? For over 40 years it had been known that resting subjects could be kept from sweating by immersing one hand in ice water, but little research had been done on local cooling of actively working subjects. Different regions of the body show distinct thermoregulatory characteristics that need to be considered in designing a cooling garment. The Apollo LCG, for example, used tubing distributed uniformly over the body, and kept the wearer comfortable while at rest; but during walking, with high total cooling rates, the torso felt chilly, while the legs were persistently hot. Subjects who could select separate cooling rates for different body regions, chose the greatest cooling for their legs and head, with lower rates for the arms and torso.

Gold and Zornitzer, of the Negev Institute for Arid Zone Research, tested the effect of partial body cooling with a garment covering roughly 60% of the body--the chest, upper arms and the upper thighs. They found that the strain on men exercising in the heat was effectively reduced. A few years later, Schwartz continued this work, comparing the cooling provided by a hood covering only the head and neck, with that obtained by using both the partial suit and the hood. After walking for 2 hours in a temperature of 122°F, subjects without cooling showed signs of exhaustion or dizziness. Wearing both the hood and the partial body suit virtually eliminated thermal stress; while the hood alone, covering only 12 percent of the body, gave about half the protection afforded by both garments.

Starting about the same time (1968) Stephan Konz and others at Kansas State University systematically studied the performance of water cooled hoods covering the head and neck. Both comfort and efficient heat removal were found to depend critically upon the fit of the head covering and the degree of thermal contact maintained. Nunnely, of Webb Associates, performed physiological studies that underscored the importance of head cooling in reducing stress from heavy work and from external heat.

Various workers between 1968 and 1972 investigated local cooling or warming of different regions of the body--the legs, the torso, the arms, and the carotid artery at the base of the neck. Garments tested ranged from heavy leather "chaussables," to lightweight nylon ponchos. Spot cooling, applied over pulse points, removed significant heat from less than 1 percent of skin surface. Cooling the legs of aircraft pilots minimized pooling of blood in the limbs during acceleration, thus protecting the pilot from "grey-out" or loss of peripheral vision.

Together, these studies eventually pointed up two opposing facts:

- (1) The torso and shoulders provide the most convenient body region on which to mount various cooling systems.
- (2) The head and neck area is the most desirable region to cool; but difficult to fit with conductive cooling units.

The head and neck region represents roughly 12 percent of the body surface, yet a substantial portion of metabolic heat is normally dissipated by the head. This region has the highest skin temperatures, and is well perfused with a rich flow of blood. Unlike other regions of the body, the head shows little vasoconstriction in response to cold, so that effective cooling can be maintained without the body trying to reduce heat transfer. Because of clothing, the head is normally accustomed to being cooler than the rest of the body, and cooling the head and neck contributes markedly to subjective feelings of comfort. Mobility can be almost unrestrained if the arms, legs and torso are not encased by cooling garments. Finally, small hoods or helmets are easy to put on, and only a few sizes would be needed to fit most people.

However, the plastic tubing used in most cooling garments was poorly suited for shaping to conform to the head and neck region. If effective head cooling was to become practical, some other form of conductive cooling unit was needed. Improvements of this type eventually resulted from the need to provide more efficient cooling systems for space use.

Advanced Astronaut Cooling Garments. For post-Apollo missions of long duration, there were requirements to increase the cooling capacity, make the garment lighter and more comfortable to wear, and increase the cooling time provided from the available battery pack and expendable cooling supplies. The Biotechnology division at Ames Research Center directed attention toward several goals:

* Achieving better thermal contact between the garment and the skin. Covering a larger fraction of total skin area where desirable; or covering only selected regions of the body where cooling is most effective.

* Developing coolant passageways having higher thermal conductivity than the plastic tubing generally used. Better conductivity would permit equivalent cooling with less temperature difference between the skin and the coolant.

* Increasing the practicality of wearing LCG's for long periods by making the garments lighter, thinner, more comfortable, and suitable for manufacture on a large scale.

First, soft, flexible plastics were modified to have relatively high thermal conductivity, and molded or cast into coolant circulating pads. These modules fit snugly against the skin, providing good thermal contact over selected areas. Because these "patches" allowed more heat to be removed from a given area, considerable attention was given to finding the best distribution over the body. Detailed studies of the transient thermal behavior of living tissues were conducted by Shitzer and Chato at the University of Illinois, in support of the Ames development program. The molded patches were an improvement over vinyl tubing, but thinner and lighter cooling modules would be still better.

The key innovation was achieved by NASA workers in the process of solving a military problem. Helicopter pilots of the "Huey" Cobra gunships often encounter extreme temperature and humidity in the cockpit even when outside temperatures are moderate. They frequently return from missions showing definite symptoms of heat strain, typically with complaints of dizziness, stomach cramps and prolonged fatigue.

A series of flexible, form-fitting cooling patches was developed in 1972, by Accurex Corporation and Ames Research Center, expressly for the purpose of cooling the head. The first cooling modules were made of neoprene, and were thin enough to be fitted as the helmet liner of the Army 8ph-4 helicopter aircrew helmet. The latest version, dubbed Flexitherm, is made of polyurethane, and is only .006 inches thick--about equivalent to one layer of fabric.

The thermal conductivity of these new coolant modules is vastly superior to that of the small vinyl tubing used in the Apollo LCG. At a typical flow rate, the Apollo LCG could transfer 43.6 Btu/hr/°F, while the newly developed modules will handle more than 250 Btu/hr/°F. In practical terms, this means that the coolant inlet temperature can be much closer to the desired skin temperature, and still remove the required heat. Table 3 shows the coolant temperatures required to transfer various metabolic loads using the Apollo LCG versus the new Ames cooling garment. For use in space, this also means that a smaller heat exchanger and radiator system can be used.

The effectiveness of the Ames cooling helmet in reducing heat strain on pilots was shown in a series of investigations by Williams (ARC) and Dr. Avraham Shitzer (postdoctoral fellow from the Technion, Haifa, Israel). Forseeing applications beyond space and military needs, the Aerotherm Division of Accurex Corporation was formed to market commercial versions of both cooling helmets and garments. The thin coolant circulating patches are laminated inside Spandex garments for general cooling uses, and inside foam wet-suits to keep divers warm.

TABLE 3

COMPARISON OF APOLLO LCG AND AMES LCG

<u>Metabolic Heat Load</u>	<u>Desired Skin Temperature</u>	<u>Inlet Water Temperatures Required At Typical Heat Loads</u>	
		<u>Apollo</u>	<u>ARC</u>
1,000 Btu/hr	90°F	67.2°F	86°F
	85°	62.0°	81°
	80°	57.0°	76°
2,000 Btu/hr	90°	44.0°	82°
	85°	39.0°	77°
	80°	34.0°	72°

Once again, racing drivers were quick to recognize the desirability of personal cooling. Stock car driver, Richard Petty, had his racing helmet fitted with patches by Aerotherm, and tested the unit in an environmental chamber at Ames. While in the heat chamber, Petty operated a complex mechanism to measure his ability to perform tasks requiring alertness and coordination (Figure 2). Half a pint of cool water circulated through the helmet reduced the rise in pulse rate by 75 percent, and cut body temperature rise and perspiration by half. Pleased with the results, Petty left to race at Riverside using the cooling helmet. Accustomed to high temperatures while sitting behind a hot engine throughout 4-hour races, Petty is concerned most with sweating. "Heat doesn't bother me," he explained, "but if you sweat, you lose energy." Having previously tried carrying an ice bag on his chest during hot races, he observed, "You can still make it okay, but you could be a little sharper. A lot of times that's all it takes to win."

Chemotherapy. Doctors who learned about the effective head cooling provided by these new cooling modules suggested an application that was far from obvious--an aid in chemotherapy. Some of the most potent antitumor drugs are designed to attack cancer cells which have abnormally high rates of metabolism, growth and cell division. These hyperactive cells absorb the drugs preferentially, and cell division is arrested, or the tumor cells are destroyed.

Oddly enough, hair follicles also show unusually high metabolic activity. Prolonged treatment with doses of agents sufficient to destroy malignant cells often kill the hair follicles causing rapid and permanent loss of hair. This undesirable side effect may limit use of certain kinds of cancer therapy. In addition, the agent absorbed by the healthy cells, reduces the drug concentration available to combat malignant cells.

Today in cancer hospitals, liquid cooling techniques are being evaluated for their ability to cool the head and neck, thereby slowing down the metabolism of the cooled tissues. This technique minimizes damage to skin and hair, permitting full effectiveness against malignant cells.

Simplified Cooling Systems. During the past 5 years, a number of investigators have designed and tested greatly simplified personal cooling systems. Some did away with external heat sinks, ice chests, or cooling units. Others eliminated the use of a circulating heat transfer fluid. Most of these recent developments also attempted to reduce the bulk, weight, cost and complexity of individual cooling garments.

More than a dozen different portable cooling systems were considered and evaluated for use in future space exploration. Evaporation, sublimation and the use of phase-change materials generally offer the greatest cooling capacity per unit weight. The use of dry ice to cool the circulating liquid was developed by the U.S. Navy. At NASA's Flight Research Center in the California



Figure 2 - Richard Petty Evaluating the
Liquid Cooled Helmet at Ames Research Center

Photograph Courtesy W. Williams, NASA ARC

desert, "lifting body" test pilots require protection from cockpit heat. However, it is not possible to provide cooling systems in most experimental craft. A compact, self-contained cooling vest was developed to solve this problem. To permit the complete cooling system to be worn under regulation flying suits, this vest uses a prefrozen ice shell shaped to fit the pilot's back. Coolant solution is circulated through the vest by a battery powered pump, keeping the pilot comfortable for up to 40 minutes.

Hamilton-Standard engineers have developed new and improved types of regenerable ice-pack heat sinks for astronaut cooling. After the initial ice has melted, water is evaporated thereby continuing to remove heat from the cooling garment.

The simplest system for personal cooling uses ice held in plastic pockets throughout the garment. Plastic waistcoats of this type were recently introduced for miners in deep, hot, gold mines of South Africa. The jacket holds 10 pounds of water in 28 separate pouches. The water is prefrozen by placing the whole garment in a deep freeze before being donned by the workmen over a woolen vest.

While the prefrozen vest is not as effective as liquid cooled jackets, it does provide substantial protection. For men working moderately hard at 90°F wet-bulb air temperature, heart rates and rectal temperatures were no higher than for comfortable (70°F) conditions. Without the ice-vest, only 2 hours of hard work could be completed, but with somewhat higher than normal body core temperatures.

The psychological benefits were even more dramatic than the physiological ones. The men were highly cooperative and in good humor at the end of the work period when they wore individual cooling systems. Their reaction contrasted with the exhaustion and bad temper of the men at the end of work without the garments. Trials in hot mines indicate that miners can be protected completely against the danger of heat stroke, and at the same time productivity can be substantially increased.

A series of ice and dry-ice cooled garments have been developed at Kansas State University. The dry-ice version is illustrated in Figure 3. Slabs of dry ice are inserted in six or twelve felt pockets sewn onto a net undershirt. Each pocket is insulated by a layer of flexible urethane foam, plus a layer of plastic bubble film. An insulating jacket over the dry-ice vest helps minimize cooling of external air. The garment delivers about 75 percent of total available cooling to the man.

Resting subjects in an environmental chamber at 110°F received about 315 Btu/hr of cooling benefit. The proposed federal hot environment standard suggests 100.4°F as the maximum permitted body temperature. This limit would have been exceeded in just over 1 hour without effective cooling. With the vest, the subject was able to remain for 4 hours, and had a body core temperature of only 98.9°F at the end of the test. A commercial version of the dry-ice vest is now being marketed under the trade name "Cool Poncho."

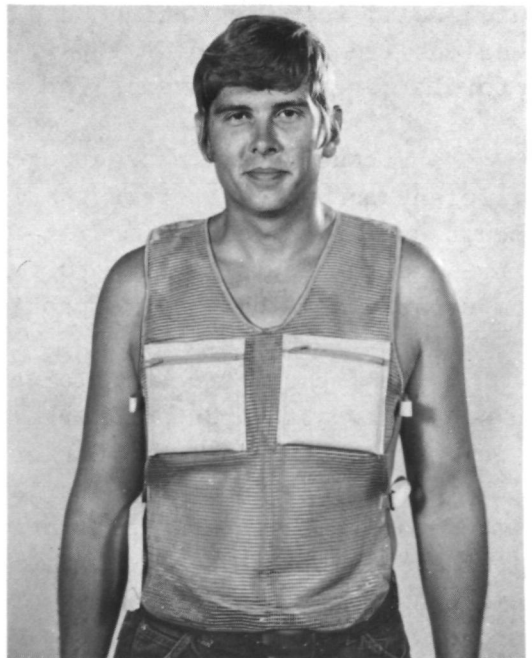
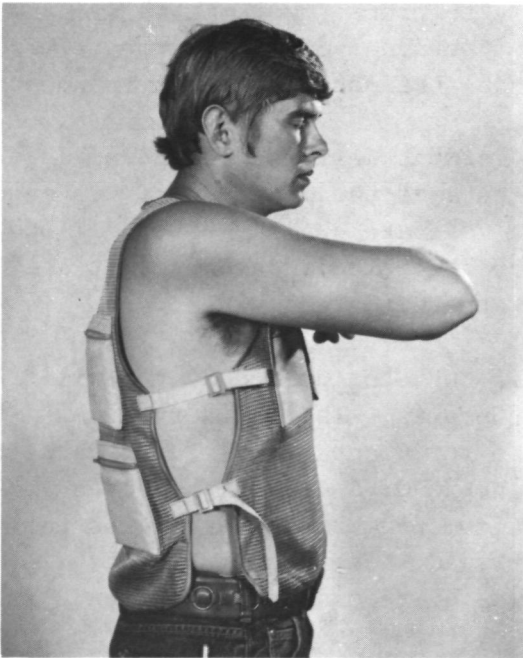
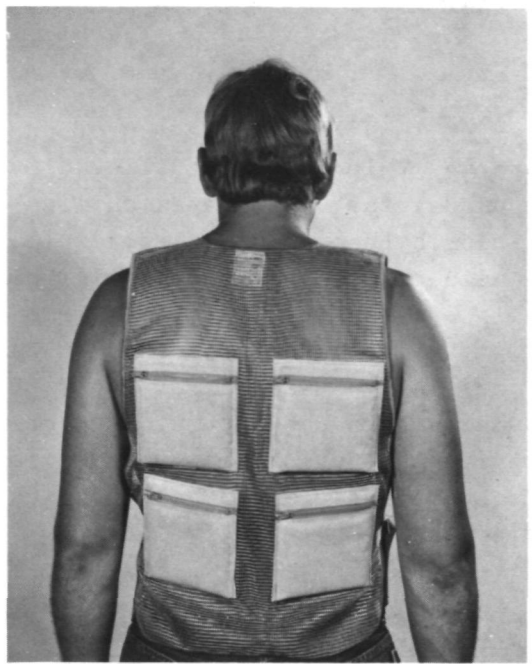
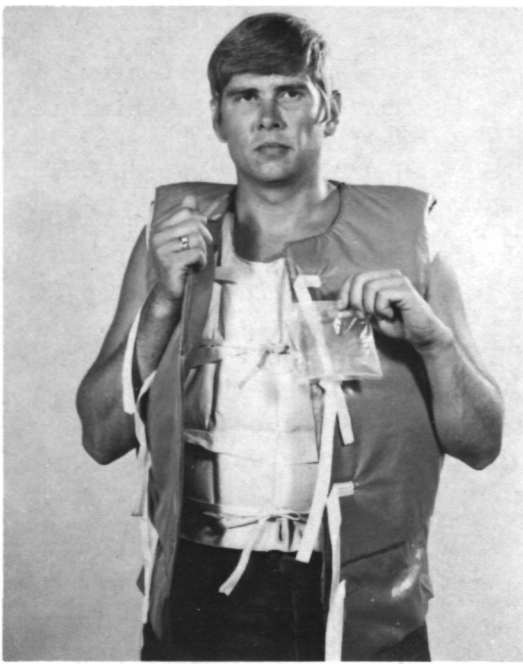


Figure 3 - Dry Ice Cooled Jacket

Photo Courtesy Stephan Konz Kansas State University

The latest redesign of the Apollo cooling garment is shown in Figure 4. This cool suit offered by ILC-Dover is a totally portable unit (12 pounds) that circulates chilled water through a network of channels. Providing both head and torso cooling, the unit permits the wearer to maintain high performance with a minimum of fatigue.

Disney World, in Florida was one of the first customers for the ILC-cool suit. Hundreds of these personal cooling units are worn by the costumed actors who portray all the world famous Disney cartoon characters. Formerly, the job of simply strolling in the Florida sunshine while wearing the costume and plastic head of Donald Duck, or Pinocchio, could soon become intolerable.

V. Application Impact/Significance

In the 10 years since liquid cooling techniques were first demonstrated for use in space, the applications of this technology have been significant--but hardly what the developers originally envisioned. Although liquid cooled suits are being used industrially to protect workmen in special situations (such as furnace repair), the use of personal cooling garments has yet to win general acceptance for workers in hot, but not extreme environments.

Virtually all of the recent cooling garment designs are intended for a different purpose than were the cooling garments of the mid-1960's. Today's garments usually have been modified to provide moderate cooling--500 to 1,000 Btu/hr--and to permit workmen to remain comfortable in environments that are uncomfortably hot, but not to protect from an otherwise deadly heat.

An important reason for this trend is that the United States will soon adopt new standards for work in hot environments. The advisory committee on heat stress of the National Institute for Occupational Safety and Health (NIOSH) has submitted standards on which the OSHA industrial codes will be based. These standards define the maximum permissible exposures to various combinations of hot conditions and workload. The new work codes will require that the total heat exposure be reduced for thousands of workmen. As a result, substantially increased use of personal cooling in manufacturing, construction, and mining are now foreseen. In these and similar application areas, there are many situations in which it is not economic to cool the work environment. The alternative of providing personal cooling garments is becoming much more attractive as performance and comfort improve, and costs are being greatly reduced.

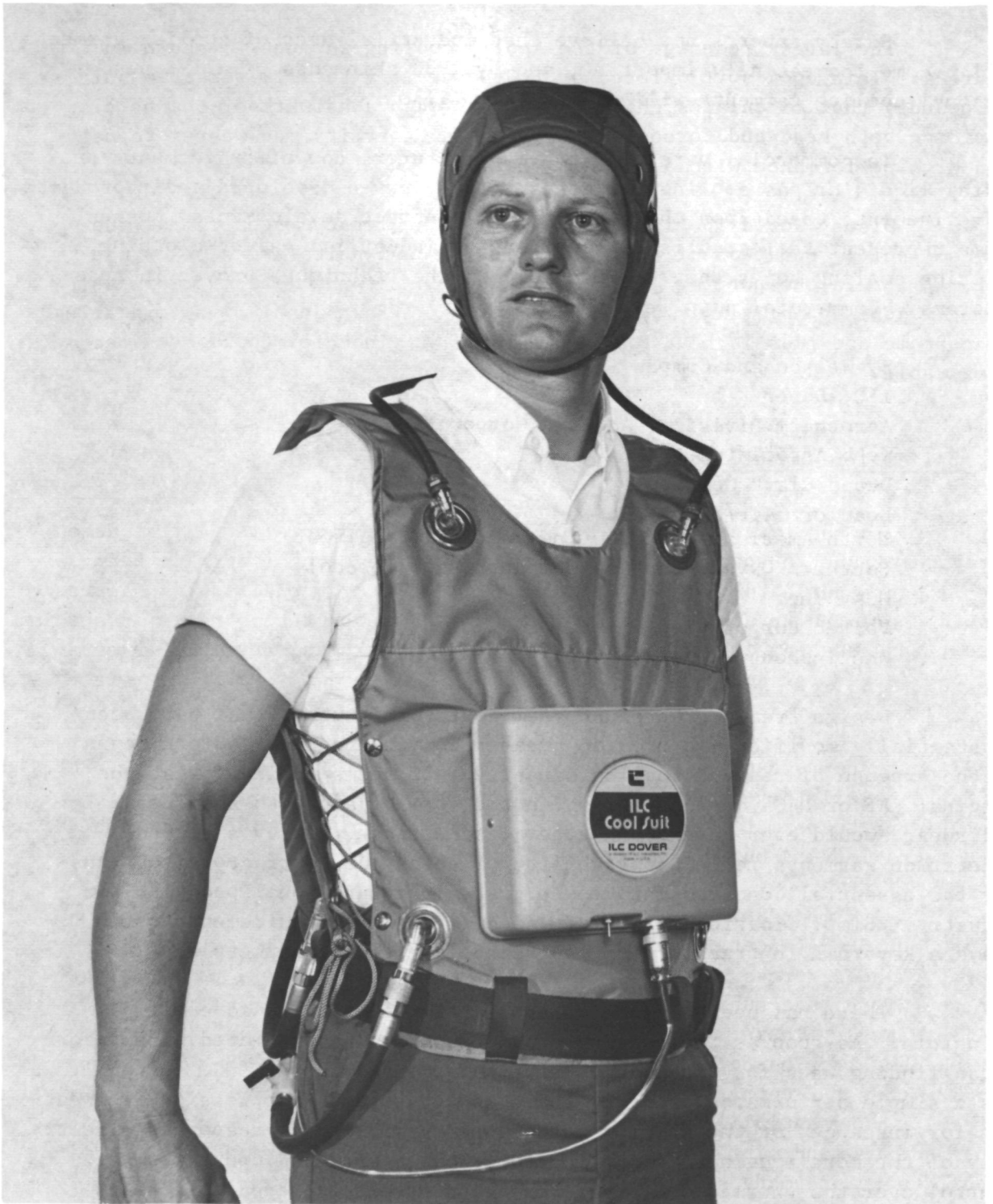


Figure 4 - Self-Contained Cooling Garment
for Industrial Applications

Photograph, ILC--Dover

Safety experts now believe that industrial uses of cooling garments will become increasingly important, and by 1978 shipments of all types of personal cooling garments will exceed \$12 million.

In commercial versions, ten manufacturers now offer garments providing liquid or gas cooling. Of these firms, seven developed their products as refinements based upon their early NASA contract developments. Other firms represent the established suppliers of industrial safety clothing, now offering cooling suits that utilize some of the techniques proven in space programs. Commercial suppliers include:

B. Welson and Company
ILC--Dover
Aerotherm Division, Accurex Corporation
Webb Associates
David Clark Company
Beaufort Air/Sea, Ltd.
North American Distributing Company (Frigivest)
Southern Oxygen Service Company (Cool Poncho)
MSA, Inc.
Vortec Corporation
Westinghouse, Inc. (divers' warm suits)

Design trends at present seem to favor garments that have been substantially modified--to provide greater convenience and comfort, even at the expense of reduced cooling capacity. It seems unlikely that the original RAF or NASA cooling suits, in the form of ankle-to-shoulder underwear, would ever have found general acceptance. Today's second-generation garments reflect the ability of aerospace contractors to transfer the essential concepts into lower cost, more functional products for industry. Simplification to satisfy specific market requirements often plays a key role in transferring new technology to the marketplace.

There has been no lack of application of the liquid cooling principle. As soon as the concept became known and appreciated, innovators began finding uses for the characteristics provided by the LCG. Often it was a simple performance property that was put to use--suppression of sweating for instance, or the ability to measure physiological responses directly. Many of the more imaginative applications have been based upon automatic control over the thermal comfort zone, or on precisely repeatable heat transfer. Thus a growing list of applications is now found in the fields of medicine and physiology. The LCG has permitted great accuracy in studies of human thermal physiology--measurements not readily obtainable until liquid-loop thermal garments were introduced. This is a typical pattern found in technologies still in the growth phase. Knowledge advances are often paced by the availability of accurate instrumentation.

Perhaps of greatest significance, the needs for new technology must evolve along with improvements in the technology itself. Perception of the necessity for personal cooling garments is being altered--by legislative intervention, and by the energy problem. Faced with new requirements, specifying the maximum thermal loads to which workmen may be exposed, the most satisfactory method of protecting workers is being examined with new eyes. Liquid cooling garments have already played a part in defining more accurately the conditions for maximum comfort, and the trade-offs permitting the comfort zone to be maintained at lowest energy cost. Rethinking old problems, in the face of new requirements, plays an important part in technical progress. As one example, automakers and manufacturers of farm tractors and self-propelled combines are now asking questions like: Should air-conditioning require five or more horsepower to cool a car or the enclosed implement cab? The future might even see modified LCG's for automobile passengers rather than energy expensive full car air-conditioning.

Chronology Notes

The complexity of the subject and the close relationship between work on human physiology, and methods of personal cooling makes strict chronological treatment impractical.

Significant contributions to liquid cooling technology have been divided among six topics according to the major emphasis of the information presented:

- . Thermal physiology
- . Development of liquid cooled garments
- . Development and use of ventilated garments.
- . Automatic control of body temperatures
- . Local or limited cooling
- . Special cooling techniques

CHRONOLOGY

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- average metabolic heat load 400 BTU/hr
- maximum heat load 1,000 BTU/hr
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