Compact Nuclear Rockets

by James R. Powell

Someday, in exploring the outer planets of our solar system, humankind will want to do more than send diminutive probes that merely fly rapidly by them. In time, we will want to send spacecraft that go into orbit around these gaseous giants, land robots on their moons and even return rock and soil samples back to Earth. Eventually, we will want to send astronauts to their intriguing moons, on at least a couple of which liquid water—the fundamental requirement for life as we know it—is believed to be abundant.

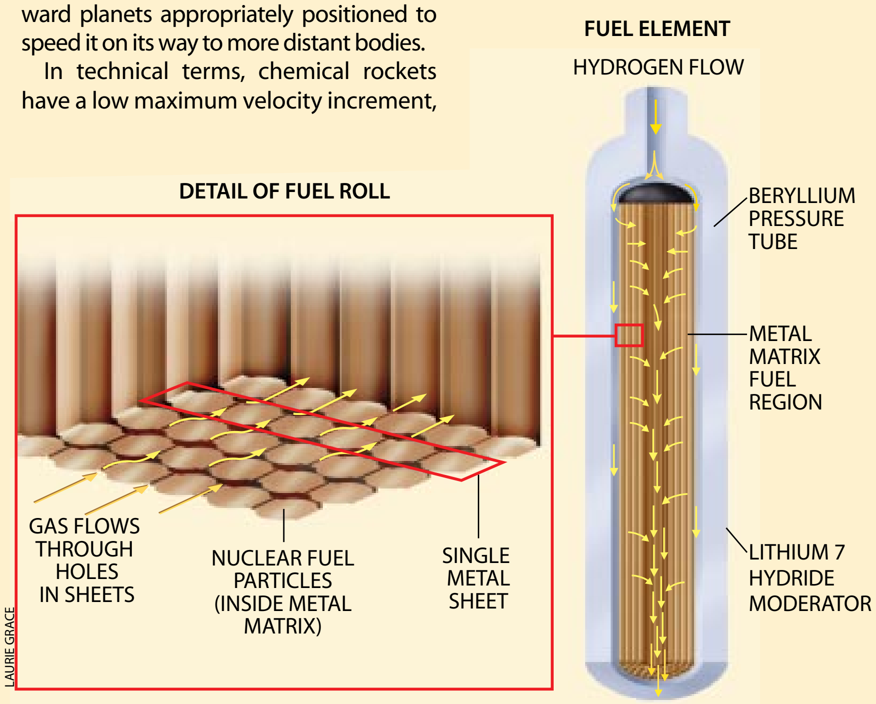
For missions such as these, we will need rockets powered by nuclear fission rather than chemical combustion. Chemical rockets have served us well. But the relatively low amount of energy that they can deliver for a given mass of fuel imposes severe restrictions on spacecraft. To reach the outer planets, for example, a chemically powered space vehicle must have very limited mass and make extensive use of planetary gravitational "assists," in which the craft maneuvers close enough to a planet for the planet's gravitational field to act like a slingshot, boosting the speed of the craft. To take advantage of these assists, mission planners must wait for "windows"—short periods within which a craft can be launched toward planets appropriately positioned to speed it on its way to more distant bodies.

In technical terms, chemical rockets have a low maximum velocity increment, which means that their exhaust velocities are not high enough to impart very high speeds to the rocket. The best chemical rockets, which are based on the reaction between hydrogen and oxygen, impart a maximum velocity increment of about 10 kilometers (six miles) a second to spacecraft departing from Earth orbit.

Nuclear rockets, in contrast, could impart a maximum velocity increment of up to about 22 kilometers a second. Such a high value would make possible a direct path to, say, Saturn, reducing travel time from about seven years to as little as three. A nuclear rocket such as this would be inherently safe and environmentally benign: contrary to popular belief, a nuclear rocket need not be strongly radioactive when launched. The spacecraft, with its nuclear thrusters, would be launched as a payload atop a conventional chemical rocket. Then, once the payload was in high-Earth orbit, above about 800 kilometers, the nuclear reactor would start up.

The technology required to build a rocket motor powered by nuclear fission is not far beyond current capabilities. In fact, my colleagues and I have designed a compact nuclear rocket engine, which we call Mitee (deriving the letters loosely from the words "miniature reactor engine"), that could be built in about six or seven years at a cost of $600 million to $800 million—actually quite modest in the context of space launches. In fact, the costs of developing the engine would be offset by savings in future launch costs. The reason is that nuclear spacecraft powered by the engine would not need to haul along a large mass of chemical propellant, meaning that launching it would not require a Titan IV vehicle costing $250 million to $325 million. Instead a lower-priced rocket, such as a Delta or an Atlas in the range of $50 million to $125 million, could be used.

In our design, the reactor's nuclear fuel would be in the form of perforated metal sheets in an annular roll, in a configuration similar to a jelly roll with a hollow center [*see illustration below*]. A jacket of lithium 7 hydride around the outside of the fuel roll would act as a moderator, reducing the speed of the neutrons emitted by the nuclear fission occurring inside the fuel. The coolant—liquid hydrogen—would flow from the outside of the roll inward, quickly turning into a gas as it heated up and flowed toward the center. The superheated gas, at about 2,700 degrees Celsius (4,900 degrees Fahrenheit), would flow at a high velocity along a channel at the center axis of the roll and then out through a small nozzle at the end.



FUEL ELEMENT would be one of 37 in a compact nuclear rocket engine. Liquid hydrogen flowing into the element would convert to a gas and flow through the nuclear fuel roll (*light brown*). Five of the roll's metal matrix sheet layers are shown in the detail at the left. The superheated gas would then shoot down a center channel and out the bottom of the element, providing thrust.

A key attraction of nuclear propulsion is that its propellant—hydrogen—is widely available in gaseous form in the giant planets of the outer solar system and in the water ice of distant moons and planets. Thus, because the nuclear fuel would be relatively long-lasting, a nuclear-powered craft could in theory tour the outer solar system for 10 or 15 years, replenishing its hydrogen propellant as necessary. A vehicle could fly for months in the atmospheres of Jupiter, Saturn, Uranus and Neptune, gathering detailed data on their composition, weather patterns and other characteristics. Alternatively, a craft could fly to Europa, Pluto or Titan to collect rock samples and also accumulate hydrogen, by electrolyzing water from melted ice, for the trip back to Earth.

Because its reactor would start up well away from Earth, a nuclear-powered spacecraft could actually be made safer than some deep-space probes that are powered by chemical thrusters. In the outer reaches of the solar system, the sun's rays are too feeble to provide energy for a spacecraft's instruments. So they generally run on plutonium 238 power sources, which are highly radioactive even during launch. In a probe with nuclear thrusters, on the other hand, the instruments would be run off the same reactor that provides thrust. Moreover, the amount of radioactive waste produced would be negligible—amounting to about a gram of fission products for a deep-space mission—and in any event the material would never come back to Earth.

Nuclear rockets are not new. Among the U.S. Department of Defense's projects in this area was the Space Nuclear Thermal Propulsion program in the late 1980s. Its goal was to develop a compact, lightweight nuclear engine for defense applications, such as launching heavy payloads into high-Earth orbit. The cornerstone of the design was a particle bed reactor (PBR), in which the fuel consisted of small, packed particles of uranium carbide coated with zirconium carbide. Although the PBR work ended before a full-scale nuclear engine was built, engineers did successfully build and operate low-power reactors based on the concept and demonstrated that high-power densities could be achieved.

Indeed, our Mitee engine owes much to the PBR effort, on which my colleagues and I worked for nearly a decade at Brookhaven National Laboratory. In addition to the same basic annular configuration of fuel elements, the Mitee also would use lightweight, thermally stable lithium 7 hydride as a moderator. To be conservative, however, we designed the Mitee's fuel assembly to have a power density of about 10 megawatts per liter instead of the PBR's 30.

It is an easily provable fact that with only chemical rockets, our ability to explore the outer planets and their moons is meager. In the near term, only nuclear rockets could give us the kind of power, reliability and flexibility that we would need to improve dramatically our understanding of the still largely mysterious worlds at the far edges of our solar system.

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make long-term exploratory missions to Uranus and Neptune that would return far more data than the simple flybys that Voyager 2 made in the 1980s, according to James S. Sovey of the NASA Lewis Research Center.

Other Thrusters

Ion engines are not the only futuristic space drive being considered for solar system exploration. Hall thrusters also accelerate ions, but without grids. They employ radial magnetic fields, in part, to direct the ions, and they can deliver larger thrusts: a 50-kilowatt version has been tested, and research models are as propellant-efficient as an ion engine, according to Robert S. Jankovsky of the NASA Lewis center. The devices are attractive for now mainly for near-Earth space applications, although that could change if performance improves. The U.S. government has already flown one on a classified payload, and Teledesic, which plans to offer a broadband, global telecommunications service, will use Hall thrusters on its fleet of satellites.

Photovoltaic cells are now used to power almost all satellites in near-Earth orbit. And their performance is expected to improve: NASA has developed advanced designs that incorporate myriad small lenses that focus sunlight on the photovoltaic material. Deep Space 1 is now testing this type.

But solar power can be used to provide thrust more directly. The U.S. Air Force has committed $48 million to a four-year program to develop a solar-powered final rocket stage that would move satellites from low-Earth orbit to geostationary orbit at a fraction of the cost of chemical rockets. The Solar Orbit Transfer Vehicle uses a lightweight mirror to direct the sun's light onto a graphite block, which reaches 2,100 degrees Celsius (3,800 degrees Fahrenheit) and vaporizes stored liquid hydrogen. The expanding gas provides the thrust.

An operational version would take three to eight weeks to boost a typical payload to geostationary orbit, but its light weight means that a satellite will be able to go on a smaller rocket than it would otherwise. The savings amount to tens of millions of dollars for each launch, notes deputy program manager Thomas L. Kessler of Boeing.

The sun, however, can only do so much, and it is difficult to exploit solar power for journeys to planets more distant than Jupiter. The Galileo mission to Jupiter and the Cassini mission to Saturn both employed radioisotope thermal generators, which utilize the heat generated by the decay of plutonium 238 to generate modest amounts of electricity. But this technique

Space Access		
	Approximate launch year:	2003
	Approximate cost:	$4 billion to $6 billion
	Power source:	Air-breathing engines, rockets

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HEAVY SPACE PLANE is being developed by Space Access in Palmdale, Calif. The craft will utilize innovative ejector ramjet engines to accelerate to Mach 6, then switch to rocket engines. Separated stages will individually fly back to the launch strip.