# 3

# Rocket Problems and Limitations

Although the rockets described in the previous chapter have opened the solar system to preliminary human reconnaissance and exploration, there are severe limitations on rocket performance. This chapter focuses on these limits and what we may ultimately expect from rocket-propelled space travel.

## LIMITS OF THE CHEMICAL ROCKET

A common science fiction theme during the 1950s was the exploration of the Moon by single-stage, reusable chemical rockets. Sadly, this has not come to pass. And because of the fact that the exhaust velocities of even the best chemical rockets may never exceed 5 km/s, this dream may always remain within the realm of fantasy.

During the late 1960s and early 1970s, the United States launched nine crews of three astronauts each to lunar orbit or the Moon's surface. An appreciation of the chemical rocket's severe limitations for large scale application beyond low Earth orbit can be arrived at by consideration of these NASA Apollo expeditions.

Everything about Apollo's Saturn V booster is gargantuan. Standing on its launch pad, this craft was 110.6 m high, taller than the Statue of Liberty. It had a fully fueled prelaunch mass of about 3 million kg. Of this enormous mass, only 118,000 kg reached low Earth orbit and 47,000 kg departed on a translunar trajectory. But the Apollo command modules that safely returned the three-astronaut crews and their cargoes of Moon rocks to Earth had heights of only 3.66 m and diameters of 3.9 m.

The Apollo lunar expeditions were a splendid human and technological achievement. But they did not lead to the economic development or settlement of the Moon. In fact, the economics of lunar travel using chemical rocketry has been compared with a European traveler who wishes to visit the US. Being exceptionally wealthy, she commissions the construction of her own private, full-scale Airbus, for an investment of a billion euros or so. She flies the aircraft to New York, parachutes out above the Empire State Building, and allows the entire aircraft to plunge into the Atlantic Ocean. You could not afford a great many intercontinental visits if that was the only way to go!

G. Vulpetti et al., *Solar Sails,* Springer Praxis Books,
DOI 10.1007/978-1-4939-0941-4_3

By pushing chemical rocket technology and materials science to their limits (perhaps in commercial efforts directed by those promoting space tourism), we may ultimately produce a reusable two-stage or even single-stage Earth-to-orbit shuttlecraft. But payload will be limited. Orbital construction will be required if we wish to venture further afield in the cosmic realm. Chemical rocket costs will severely limit the number of lunar and interplanetary missions fielded by even the wealthiest nations.

## NUCLEAR AND SOLAR THERMAL ROCKETS: AN IMPROVEMENT WITH ISSUES

Let's look at various nonchemical rocket approaches in an attempt to overcome some of these limitations. Two options are the nuclear thermal or solar thermal rocket, in which the energy output of a nuclear reactor or solar collector is used to heat a working fluid (e.g., hydrogen) to a high exhaust velocity (Fig. 3.1). If the working fluid is hydrogen, exhaust velocities of 8–10 km/s are possible, about twice those of the best performing chemical rockets.

During the 1960s, nuclear thermal rockets such as NASA's KIWI (Fig. 3.2) were subject to elaborate ground tests. They are high-thrust devices and are at least as reliable as their chemical brethren. Why haven't we seen the emergence of single-stage-to-orbit nuclear thermal shuttles?

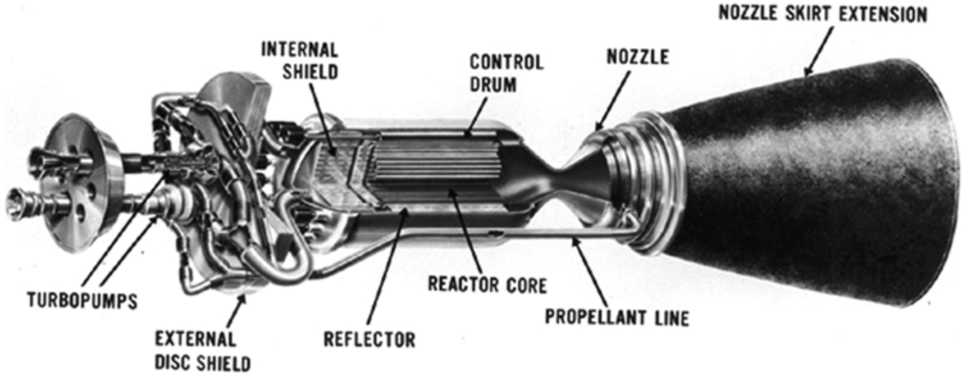
One issue with this technology is environmental pollution. Because of mass limitations, no ground launched economical nuclear rocket could be completely shielded. As a point of fact, a lot of additional mass has to be employed for blocking all nuclear radiations. Invariably, some radioactive fallout will escape to the atmosphere.

Another problem is nuclear proliferation. If many governmental and private space agencies began to employ this technology for dozens of launches per year, what type of security measures might be required to protect the nuclear fuel from terrorists and agents of rogue states?

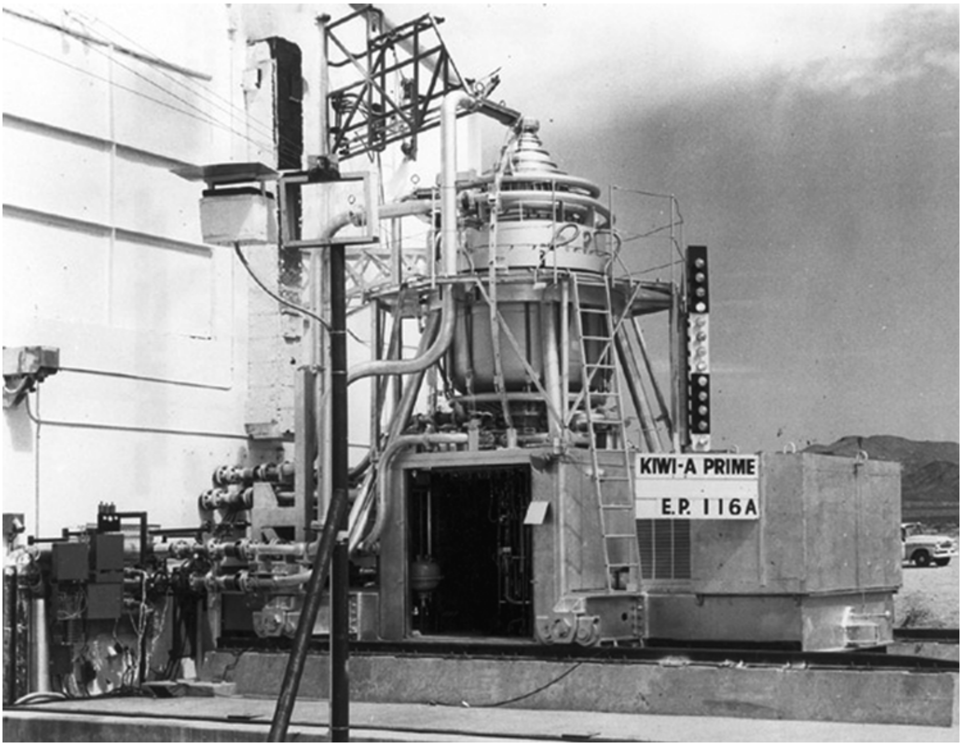
It would be possible to launch the reactor in a safe, inert mode, and turn it on well above Earth's atmosphere. Although this pollution-free option will do little to reduce launch costs, it might have the potential to improve the economics of lunar and interplanetary travel.

There are two problems with this approach. First and foremost is the difficulty of storing the required hydrogen for long durations in the space environment. This low molecular mass gas tends to evaporate rapidly into the space environment unless elaborate (and massive) precautions are taken. Nuclear rocket designers could switch to fuels other than hydrogen. But exhaust velocity decreases with increasing fuel molecular mass, and the advantage of nuclear over chemical would soon vanish.

A second problem involves nuclear fission reactor technology. While it is certainly possible to launch an inert reactor toward space to minimize radioactive pollution from a catastrophic launch accident, it is not possible to turn the reactor off completely once fission has been initiated. A nuclear thermal propelled interplanetary mission would have to contend with the problem of disposing spent nuclear stages in safe solar orbits.



3.1 The NASA NERVA nuclear-thermal rocket concept (Courtesy of NASA)



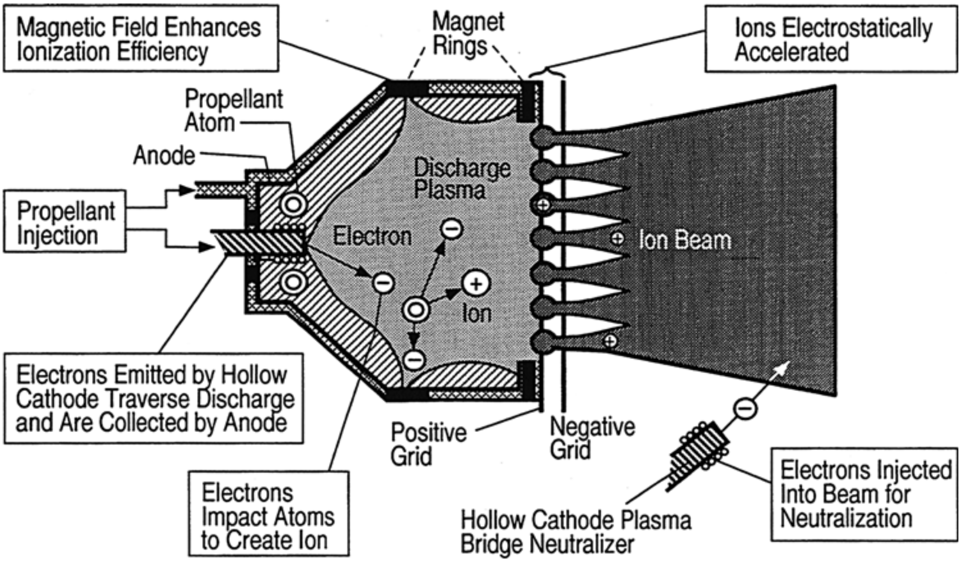
3.2 The NASA KIWI nuclear-thermal rocket reactor on its test stand (Courtesy of NASA)

The solar thermal rocket replaces the reactor with a solar concentrator such as a thin film Fresnel lens. Although exhaust velocities for solar thermal rockets fueled with molecular hydrogen are comparable to those of nuclear thermal hydrogen rockets, the diffuse nature of solar energy renders them low thrust devices. No solar thermal rocket will ever lift itself off the ground. Typical accelerations for these devices, in fact, are of the order of 0.01 Earth surface gravities. Major applications of this technology might be for orbital transfer—like the economical delivery of communications satellites to geosynchronous Earth orbit.

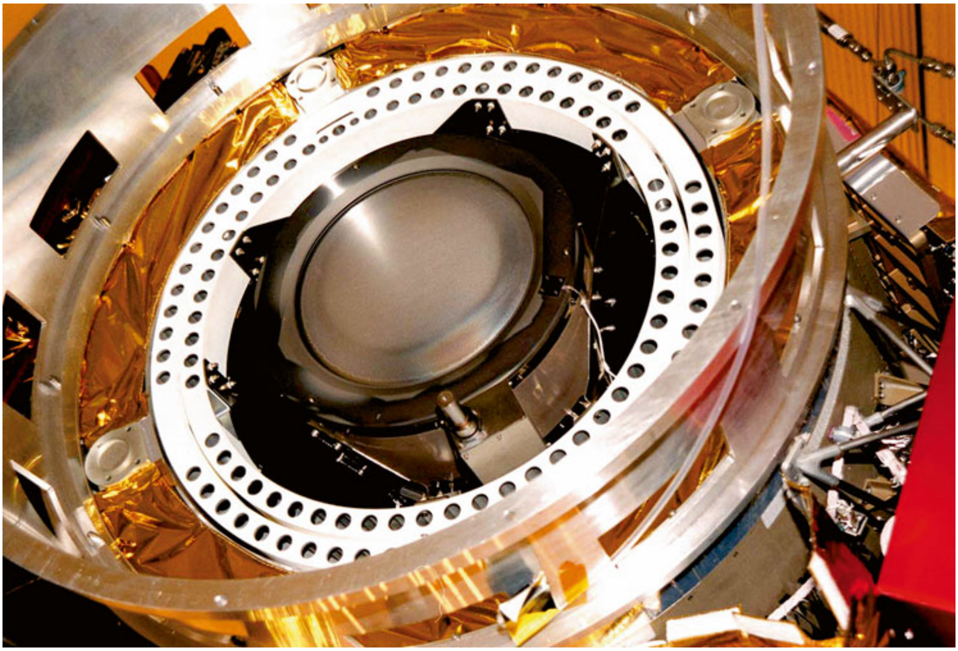
One should note that, strictly speaking, a solar powered rocket is not a rocket because the energy for heating the propellant does not reside in the vehicle. However, such energy is always much, much less than the propellant mass times $c^2$, the square of the speed of light in vacuum. Thus, for the space flights we are considering here, we can continue to consider it as a rocket.

## SOLAR AND NUCLEAR ELECTRIC ROCKETS—THE ION DRIVE

Another nonchemical rocket option is the so-called electric rocket, or ion drive. In the electric rocket (Fig. 3.3), sunlight or nuclear energy is first used to ionize fuel into electrons with negative electric charges and ions with positive electric charges. Solar- or nuclear-derived electricity is then directed to electric thrusters, which are utilized to accelerate fuel ions (and electrons) to exhaust velocities of 30 km/s or higher (Fig. 3.4). Typical accelerations from these low thrust devices are 0.0001 Earth surface gravities, so electric



3.3 Schematic of an Ion drive (Courtesy of NASA)



3.4 An ion thruster on the test stand (Courtesy of NASA)

rockets must be deployed in space and fired for weeks or months to achieve high spacecraft velocities.

Unlike nuclear rockets and solar thermal rockets, solar electric rockets are now operational as prime propulsion for robotic interplanetary probes such as NASA's Deep-Space 1 and SMART-1, the European Space Agency's (ESA) first European mission to the Moon. SMART-1 was equipped with a type of electric propulsive device known as the Hall effect engine, after a plasma phenomenon discovered by American physicist Edwin H. Hall in the nineteenth century. Solar cell panels supplied power to the xenon ion engines, producing a thrust of about 68 mN, but operating for 7 months. The overall flight time to the Moon was about 14 months; during this time only 59 kg of propellant was consumed. The primary goal of this mission was not to reach the Moon, but rather to demonstrate that low thrust, high exhaust, velocity ion thrusters work very well in space as the primary propulsion source. ESA decided to extend the mission by more than 1 year until September 3, 2006, in order to gather more scientific data. Additionally, studies are under way in many countries that may soon increase the effective exhaust velocity of ion thrusters to 50 km/s or higher.

So it may be surprising to the reader that electric rockets have so far been employed only for small robotic missions. Why have these reliable, high exhaust velocity engines not yet been applied to propel larger interplanetary ships carrying humans?

One problem is power. A lot more solar (or ultimately nuclear) power is required to ionize and accelerate the fuel required to accelerate a human-occupied craft massing about

100,000 kg than is required to accelerate a 200 kg robotic probe. But a more fundamental issue is fuel availability.

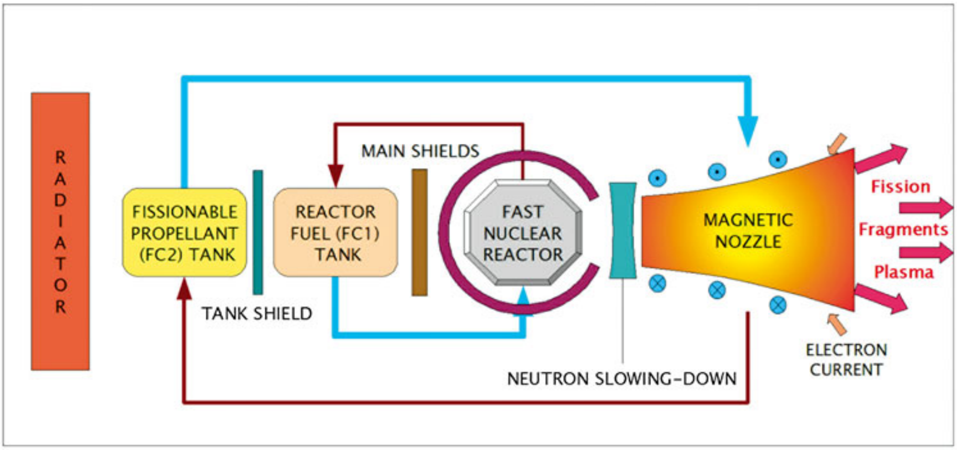
A number of factors influence ion thruster fuel choice. First, you want a material that ionizes easily, so that most of the solar or nuclear energy can be used to accelerate fuel to high exhaust velocities rather than to sunder atomic bonds. Argon, cesium, mercury and xenon are candidate fuel choices satisfying this constraint. But since space mission planners are also subject to environmental constraints, toxic fuels such as mercury and cesium are avoided in contemporary missions. Fuel storage during long interplanetary missions is also an issue—so contemporary electric rockets are fueled with xenon.

But if we propose an interplanetary economy based on large electric thrusters expelling xenon, we must overcome another issue. This noble (nonreactive) gas is very rare on Earth. Most of its commercial inventory is utilized for fluorescent lighting. Even a modest non-robotic interplanetary venture would quickly exhaust the world supplies of this resource.

## NUCLEAR DIRECT: THE NONTHERMAL NUCLEAR ROCKET CONCEPT

Although interstellar missions are not discussed until Chap. 9, in this section we briefly discuss a concept originated for interstellar flight in order to show some additional limitations related to rocket propulsion. In the 1970s, a number of investigators considered either nuclear fission or nuclear fusion for accelerating a spaceship to 0.1 c. The resultant one way trip time of between 40 and 50 years to Alpha Centauri was very appealing from the human lifetime viewpoint (35–40 years still represents a sort of minimum requirement for hoping to get approval for very advanced missions beyond the solar system). Here we comment on a concept (originated by author Vulpetti) that aimed at analyzing a multistage rocket starship exclusively powered by nuclear fission.

Figure 3.5 may help us to figure out the central point of the nuclear direct (ND) propulsion concept. Two types of fissionable elements are necessary in the form of two chemical compounds, say, FC1 and FC2 for simplicity. FC1 may be uranium dioxide or plutonium dioxide, whereas FC2 may be an appropriate compound of plutonium 239. They are stored in special tanks and supply two systems: a (so-called) fast nuclear reactor and a magnetic nozzle. The former one burns FC1 and produces an intense beam of fast neutrons, which are subsequently slowed down at the magnetic nozzle. Here, these neutrons induce fissions in FC2. The fission fragments and the electrons form high energy plasma that is exhausted away through the magnetic field forming the nozzle. Why such a complicated arrangement? The main reason is to utilize the enormous fission energy without passing through the production of heat to be transferred to some inert propellant like hydrogen. In other words, nuclear direct would have avoided the exhaust speed limitations of the nuclear thermal rocket (about 10–20 km/s). As a point of fact, the plasma from ND systems may be exhausted with a speed of 9,000–10,000 km/s. Figure 3.5 presents an oversimplified schematic of the ND concept. Some of the related problems were analyzed quantitatively in the 1970s. Many major difficulties were found to relate to the practical realization of the reactor and the magnetic nozzle. The same concept has not been examined in the light of current knowledge about nuclear reactors, materials science and sources of very strong



3.5 Conceptual scheme of a nuclear-fission engine exhausting the fission products directly, namely, using them as reaction mass (Courtesy of author Vulpetti)

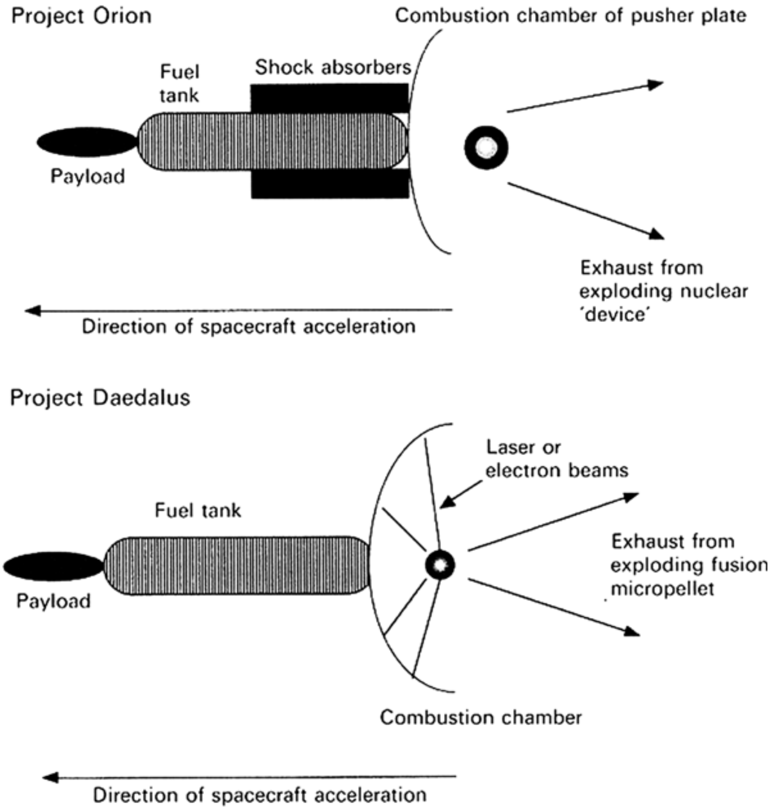
magnetic fields. In any case, even if a multistaged starship of such a type were realizable by future technologies, the amount of fissionable elements to be managed would be so high that even the concept's author would be somewhat perplexed.

One should note that even a small scale version of the ND concept would not be suitable for a human flight to Mars. Simply put, a crewed spaceship to Mars (and back) should have a rocket system capable of a jet speed of 20–40 km/s and an initial acceleration of 0.03 m/s$^2$. If one attempts to use a rocket with a jet speed 300 times higher, but using the same jet power per unit vehicle mass (in this case approximately 0.5 kW/kg), then the initial spaceship acceleration would be about 0.0001 m/s$^2$. Attempting to escape Earth—for a crew—with such an acceleration level would last months in practice and full of risk from radiation. So, one should go back to the nuclear thermal rocket or the ion drive and solve the problems mentioned in the previous sections.

## NUCLEAR PULSE: THE ULTIMATE IN ROCKET DESIGN

Let's say that you're not content with slow accelerations and flights to Mars requiring 6 months or more, and let's also assume that the challenges of a nuclear thermal single-stage-to-orbit do not go away. Instead, you become interested in the ultimate space voyages—across the 40 trillion km gulf separating the Sun and its nearest stellar neighbors, the three stars in the Alpha Centauri system. Are there any rocket technologies capable of interstellar travel?

During the late 1950s and early 1960s, US researchers pondered a remarkable, although environmentally very incorrect, rocket technology that was code named Project Orion (Fig. 3.6). In its earliest incarnations, Orion would have flown as either a single stage or a Saturn V upper stage.



3.6 Two nuclear-pulse concepts. Note the shock absorbers; these would ease the stress on the craft (and its occupants) from the uneven acceleration resulting from the reflection of nuclear debris (From G. Matloff, *Deep-Space Probes,* 2nd ed., Springer-Praxis, Chichester, UK, 2005)

Orion passengers and payload would ride above the fuel tank, as far from the combustion chamber as possible. Fuel would consist of small nuclear fission "charges" that would be ejected and ignited behind the main craft. Remarkably, materials exist that could survive the explosion of a nearby nuclear device.

On paper, Orion would have opened the solar system. Huge payloads could have been orbited by Saturn V with an Orion upper stage; this technology could have been used to perform rapid voyages throughout the solar system.

But Orion does not exist just on paper. Scale models, like the one on display in the Smithsonian Air and Space Museum in Washington, DC, flew through the air on the debris of chemical explosives and then parachuted safely to Earth.

As well as being a high thrust device easily capable of launch from Earth's surface, the exhaust velocity of Orion's highly radioactive fission-product exhaust would have been 200 km/s.

If the small nuclear charges were replaced with hydrogen bombs and if Earth launched Orions were replaced with huge craft manufactured in space, perhaps using extraterrestrial resources, Orion derivatives could serve as true starships. In the unlikely event that the world's nuclear powers donated their arsenals to the cause, super Orions propelled by hydrogen bombs could carry small human communities to the nearest stars on flights with durations measured in centuries.

But sociopolitical Utopia is a long way off. So, in the early 1970s, a band of researchers affiliated with the British Interplanetary Society began a nuclear pulse starship study that was christened Project Daedalus. As shown in Fig. 3.6, a Daedalus craft would replace the nuclear or thermonuclear charges with very much smaller fusion micropellets that would be ignited by focused electron beams or lasers after release from the ship's fuel tank. The Daedalus fusion pulse motor could theoretically propel robotic craft that could reach nearby stellar systems after a flight of a century or less. Larger human occupied "arks" or "world ships" would require centuries to complete their stellar voyages. The proper propellant choice would greatly reduce neutron irradiation that would always be a problem for Orion craft. But major propellant issues soon developed.

The ideal Daedalus fusion fuel mixture was a combination of deuterium (a heavy isotope of hydrogen) and helium-3 (a light isotope of helium). Deuterium is quite abundant on Earth, but helium-3 is vanishingly rare. We might have to venture as far as the atmospheres of the giant planets to locate abundant reserves of this precious material.

## THE LONG-TERM ICARUS DESIGN CONCEPT

In the same manner that Project Orion inspired the engineers and scientists who contributed to Project Daedalus, during the 1970s Daedalus has inspired an ongoing study of interstellar pulsed fusion propulsion called Project Icarus. Like its predecessor, Icarus is conducted by an international team of researchers under the auspices of the British Interplanetary Society.

Like the earlier studies, Icarus is constrained to consider fusion pulse propulsion. However, here is where its similarity to Orion and Daedalus ends. Participants in this study endeavor to expand our knowledge base regarding this type of rocket propulsion.

Issues addressed in Project Icarus include possible starship configurations and staging strategies. Since the main probe is designed to perform an undecelerated fly through of the destination star system, are there efficient technologies (including the solar sail) that can be applied to decelerate sub-probes to allow for longer stay times near the destination star?

Are alternative fusion fuel propellant combinations feasible? Is refueling in the destination star system a possibility? Has technology development since the 1970s offered improved possibilities for laser or electron-beam ignition of fusion micropellets?

Of special interest is analysis of failure modes. Might repeated micropellet ignition in the reaction chamber cause acoustic vibrations resulting in catastrophic failure? If ignition beams miss a micropellet, will these beams damage the reaction chamber?

The primary destination of the Icarus interstellar probe has also replaced the proposed destination of the Project Daedalus spacecraft. In the 1970s, observational data supported the hypothesis that Barnard's Star, a red dwarf star located 6 light years from the Sun and at present our Sun's second-nearest stellar neighbor, had one or more Jupiter-sized planetary companions. Since recent research has not confirmed these early observations, the primary Icarus destination is currently the Alpha/Proxima Centauri triple-star system, which is our Sun's nearest stellar neighbor at a distance of 4.3 light years. Observational data released in 2012 indicates that Alpha Centauri B, the smaller of the two solar-type stars in the Alpha Centauri system, has at least one Earth-sized planet. Although this world is apparently too close to its primary star to have evolved life as we know it, additional planets in or near the habitable zones of Alpha Centauri A and B are not unlikely. Thus, searching for a planet capable of hosting even elementary life is among the primary concerns in the aims of interstellar flight.

The Icarus researchers have somewhat descoped the very ambitious Daedalus design. To achieve a ~60 year flight time to Barnard's Star, Daedalus must be accelerated to about 12 % of the speed of light (or about 36,000 km/s). Even for a fusion pulse ship, the required mass ratio would be enormous. Project Icarus would require much lower mass ratios since the craft could be designed to reach a closer destination in about 100 years.

Project Icarus has itself spawned a number of ongoing projects. Icarus Interstellar, a non-profit spin-off of Project Icarus, commenced operation in 2011 in the United States. This organization, which investigates many aspects of interstellar travel, including beamed energy propulsion as an alternative to fusion, aims to demonstrate an interstellar capability within this century.

In 2012, the Institute for Interstellar Studies was originated in the United Kingdom. The Institute accepts both financial donations and assistance in its research projects to further the development of humanity's interstellar capabilities. Interstellar travel, although perhaps the largest undertaking humanity may attempt, seems no longer to be impossible.

## THE ANTIMATTER PROPULSION CONCEPT

The economies of Daedalus and Icarus would be staggering. But they are nothing compared with the economic difficulties plaguing the ultimate rocket—one propelled by a combination of matter and antimatter.

A concept made popular by the televised science fiction series *Star Trek*, the antimatter rocket is the most energetic reaction engine possible, with exhaust velocities approaching the speed of light. Every particle of ordinary matter has its charge-reversed antimatter twin (see the "antimatter" item in the Glossary). When the two are placed in proximity, they are attracted to each other by their opposite electric charges. And when they meet, the result is astounding. In their interaction, all of their mass is converted into energy—far dwarfing the mass-to-energy conversion fraction of fission and fusion reactions (which never exceed 1 %).

Antimatter storage is problematic. If even one microgram of antimatter fuel were to come in contact with a starship's normal matter fuel tank, the whole complex would be destroyed in a titanic explosion. Tiny amounts of antimatter, however, have been stored for periods of weeks or months, suspended within specially configured electromagnetic fields.

But what really dims the hopes of would-be antimatter rocketeers is the economics of manufacturing the stuff. A few large nuclear accelerators in Europe and the US have been configured as antimatter factories. But an investment of billions of dollars and euros result in a yield of nanograms or picograms per year.

Someday, perhaps, solar powered antimatter factories in space will produce sufficient quantities of this volatile material to propel large spacecraft at relativistic velocities. However, until that far-into-the-future time arrives, we will have to search elsewhere to find propulsion methods for human occupied starships.

Perhaps it is a good thing that cost efficient antimatter manufacture is well beyond our capabilities. Imagine the havoc wrought by terrorists or rogue states if they had access to a nuclear explosive that could be stored in a magnetically configured thimble!

In ending this chapter on rocket's intrinsic limitations, we would like to make two points. The first one is conceptual. When one considers a very high nonchemical energy density source (to be put onboard a space vehicle), there is always a basic difficulty in transferring energy from the source particles to the particles of the rocket working fluid. If one attempts to use the source's energetic particles *directly* as the exhaust beam, then one unavoidably has to deal with significant difficulties: the higher the particle energy, the more difficult it is to build a jet with a sufficiently high thrust.

The second point regards the context of spaceflight, in general, and space transportation systems, in particular. The design and function of small space engines, even though important for a spacecraft, are essentially of a technological nature. Quite different is the problem of a new space transportation technique, which also entails financial problems, safety and security issues, international cooperation (if any), long-term planning and so on. Such problems are most obvious in developing a new launcher, which gives access to orbits close to the Earth. However, some difficulties arise even for in-space transportation systems to distant targets—not only for systematic human flights to other celestial bodies, but also for future scientific and utilitarian space missions, which will invariably increase in both complexity and number.

## FURTHER READING

Many references describe the Apollo lunar expeditions of the late 1960s and early 1970s. For example, you may consult Eric Burgess, *Outpost on Apollo's Moon,* Columbia University Press, NY, 1993. A more technical treatment is found in Martin J. L. Turner, *Rocket and Spacecraft Propulsion,* 2nd ed., Springer-Praxis, Chichester, UK, 2005. Turner's monograph also considers in greater detail many of the rocket varieties examined in this chapter.

Various nuclear approaches to interstellar travel are discussed in a number of sources. For a recent popular treatment, see Paul Gilster, *Centauri Dreams,* Copernicus, NY, 2004. A recent technical monograph is Gregory L. Matloff, *Deep-Space Probes,* 2nd ed., Springer-Praxis, Chichester, UK, 2005.

A photographic sequence showing an Orion prototype in flight is reproduced in Eugene Mallove and Gregory Matloff *The Starflight Hand-book,* Wiley, NY, 1989. The history of Projects Orion and Daedalus are also reviewed in this semipopular source.

Progress made by Project Icarus is described in many scientific and technical articles. Two of these, both published in the *Journal of the British Interplanetary Society (JBIS)*, are:

K. F. Long, R. K. Obousy, A. C. Tziolas, A. Mann, R. Osbourne, A. Presby and M. Fogg, "Project Icarus: Son of Daedalus—Flying Closer to Another Star," *JBIS*, **62**, 403-416 (2009).

R. K. Obousy, A. C. Tziolas, K. F. Long, P. Galea, A. Crowl, I. A. Crawford, R. Swinney, A. Hein, R. Osbourne, and P. Reiss, "Project Icarus: Progress Report on Technical Developments and Design Considerations," *JBIS*, **64**, 358-371 (2011).

The discovery of an Earth-mass planet circling near Alpha Centauri B, was accomplished using the HARPS instrument at the European Southern Observatory (ESO). The ESO press release regarding this discovery can be accessed at http://www.eso.org/public/news/eso1241/