II
Space Transportation:
Launch Systems, Propulsion, and Power

The committee concurs with NASA's view and the general consensus that robust and reliable transport to LEO and beyond is essential to the success of HEI. Further, it believes that the currently available launch systems and their derivatives will not meet these criteria in the future. Improved capabilities are required for transport of humans and high-value cargo to and from LEO; transport of large unmanned components, propellants, and expendables to LEO; and orbital transfer to the Moon and Mars.

For reasons of cost and reliability, the transport of humans and other precious cargo will require a different launch system than those for the transport of more ordinary or bulk cargo. Because operations of the space shuttle will continue to be labor-intensive and expensive, because the system is not robust, and because the system probably will reach the end of its useful life sometime between 2000 and 2010, the committee believes that a successor to the shuttle eventually will be necessary for human transport to orbit. For at least the next 10 years, however, the nation will necessarily rely upon the shuttle for this role, and it is essential that the existing shuttle fleet be maintained in a fully operable state. As indicated in the NRC report, *Post Challenger Assessment of Space Shuttle Flight Rates and Utilization*, at least one additional replacement orbiter is likely to be required every 5 to 10 years to offset inevitable attrition of the present fleet. But orbiter replacements should not impede the emergence of a new capability for launch to LEO. Eventually, a plan for a graceful phasing out of the shuttle system should be prepared.
An important aspect of reducing costs, when considering the design of new launch systems, should be the efficiency of activities on the ground that are required to prepare vehicles and payloads for launch.

HUMAN TRANSPORTATION TO AND FROM ORBIT

The space shuttle system now appears to be operating satisfactorily, and there is reason to believe that with continued scrupulous adherence to proper manufacturing, maintenance, and operating procedures, it can continue to do so. It does, however, have a limited design life, like any high-performance system. It requires continuing refurbishment and in due course it will require major replenishment, or it will have to be supplanted. Continued access of humans to space will require that planning begin soon for a new human transportation system that will first supplement and then assume the shuttle's role in human transport to and from orbit, sometime between 2000 and 2010. The best available technologies should be used to produce a system that is robust, highly reliable, reasonably cost-effective, and that has minimum requirements for ground support and preparation for launch.

At present, the most likely configuration of the required system is a two-stage rocket powered vehicle, with a fly-back first stage, an orbiter with substantial cross range capability, and a thermal protection system or hot structure that allows reuse without major refurbishment. It may be that some of the technologies being developed in the National Aerospace Plane Program (NASP) will find application in this system.

UNMANNED LAUNCH SYSTEMS

In light of the evident requirements for lifting mass to LEO, a modern launch system with heavy lift capability will be essential. It does not exist in this country at this time. Therefore, a family of launch systems based perhaps on the interagency Advanced Launch System (ALS) or similar technologies should be defined and committed to development. The design of these systems, although not requiring a safety rating for humans, should still emphasize reliability and robustness over performance, as measured, for example, by the ratio of payload weight to gross weight. The level of reusability should be selected similarly to optimize the reliability and robustness of the systems and to minimize cost on the basis of realistic utilization rates. More reliable technologies can be used, at a given overall cost, if some of the critical components are recovered. It is the committee's view that if these criteria are met, substantial improvements in launch cost will accrue, relative to those for current systems.

The family of launch systems envisioned is likely to accommodate the
upper range of payload masses projected by the Department of Defense, as well as the heavy lift requirements of the HEI. This can be done by clustering modular liquid propulsion systems with staging appropriate to the particular launch requirement. Key features of the required new launch systems will be the use of modern materials and technologies. The engines probably will operate at chamber pressures below those of the space shuttle main engine and will be manufactured using advanced technologies, such as precision casting, which lower costs while improving quality. Guidance and control will take advantage of modern electronic technology to provide fault tolerance and largely eliminate single point failures. Even with these improvements, it will be desirable to configure the vehicles so that missions can be completed after loss of one engine early in a launch. With the higher performance that will be available, such robustness should be affordable.

The committee favors this approach for three reasons: First, if developed to the criteria outlined, such liquid bipropellant systems will have a higher level of reliability than do the solid boosters utilized on the shuttle. The engines can be test fired prior to launch, an engine-out capability is feasible, and engine shutdown in flight is possible if a fault is detected. Second, pollution of the atmosphere by chlorides, as occurs with solid propellants, would be eliminated. This is likely to become an increasingly serious issue as launch rates rise in the buildup of the HEI. Finally, the committee believes liquid bipropellant systems have the potential for significantly lower recurring costs compared to solids. Thus, for the long term, the committee anticipates reliance on liquid rockets.

There are several alternatives to the above strategy. One considered by the committee is a flexible family of launchers that would use existing fully-developed solid propellant motors in clustered arrangements, providing up to four stages and a wide range of payloads to LEO or to higher orbits. Such launchers are certainly feasible. Their development costs would be lower than those of the ALS-class systems discussed above, and their recurring costs would probably be lower than the Titan, shuttle, or Shuttle-C. The committee has three concerns about this concept: First, with a large number of solid motors, this system is not likely to be as reliable as those using liquid rocket technology. Second, the recurring costs are likely to be substantially higher than for an all-liquid system, and, finally, the solid upper stages would present environmental problems with injection of chlorides at very high altitudes.

The committee notes, however, that the universal launch system complex being designed for this family of launchers, based on oil platform technology, has very attractive features such as modular construction of assembly buildings and a launch platform that can be elevated. An elevatable launch platform avoids the construction of flame ducts and can serve a variety of launch vehicles. These should be considered carefully if a new
launch complex is needed. This concept could be applicable to manned or unmanned systems and could reduce costs for the entire launch complex.

Another alternative is single-stage-to-orbit rocket launch systems, which have been proposed many times. This option has been raised again in the present context in a configuration that conceptually would offer engine-out capability, a safe abort at any point in the launch, and full recoverability. The committee's brief review of this concept has led to the conclusion that it is founded on unrealizable assumptions regarding structural weight and propulsion system weight. Dramatic advances in single-stage structural technologies and in materials, even beyond those anticipated in current programs such as NASP, would be required to make this a viable concept.

A sea-launched, two-stage, fully recoverable system with pressure-fed engines has also been suggested, with the projection that the components could be reused up to 25 times. In any launch system, optimistic reuse projections can lead to attractive, but unrealistic, estimates of costs, and in the committee's judgment, such extensive reuse is improbable due to the effects of the marine environment. Ocean operations can pose more of a problem than an aid. Very large pressure-fed systems are also difficult to deal with and require very large nozzles. Further, this concept currently lacks a credible plan for recovery of the second stage, which would reach full orbital speed.

NUCLEAR THERMAL PROPULSION

Although the reference approaches in the NASA 90-Day Study rely on chemical propulsion, NASA has included nuclear thermal propulsion as an option to be considered for orbital transfer to Mars. Several possibilities have been mentioned within this general class of systems, all of which offer higher specific impulse than chemical rockets and employ hydrogen as the propellant.

The alternative nuclear propulsion technologies differ in the temperature to which the hydrogen is heated by the fissioning nuclear fuel; the pressure level in the thrust chamber (which along with the temperature determines the extent of dissociation of the hydrogen to atomic form); and the power density assumed to be achievable in the reactor. The temperature and pressure determine the specific impulse, while the power density largely determines the thrust-to-weight ratio of the propulsion system.

The baseline capability is taken to be the NERVA class technology, the technical feasibility of which was demonstrated in the late 1960s. In the NERVA program, a reactor was tested on the ground for periods longer than required for operation, at power densities that would yield thrust-to-weight ratios on the order of five, and at temperatures giving
specific impulse as high as 850 seconds. This technology is available for full-scale development. It should be evaluated for injection to Mars in competition with hydrogen-oxygen chemical systems. The higher specific impulse of the nuclear rocket results in a smaller propellant expenditure for a given total impulse, but the propulsion system weight is higher, so that its attractiveness depends on the velocity change needed, and whether the system is reused. A major advantage of nuclear propulsion is its ability to enable transfer between Earth and Mars in one-half to one-third the time required with single-stage chemical propulsion systems. This advantage could be critical, pending the outcome of research on human performance in space for long periods. The use of nuclear technology in space faces formidable barriers of public acceptance, however, especially if employed in Earth orbit. Therefore, issues of safety are paramount in research and development.

An advanced reactor design has been partially evaluated experimentally that offers much higher power densities, hence much higher thrust-to-weight ratios, than the NERVA class technology. If proven feasible, this class of technology will make the nuclear rocket more attractive relative to chemical propellants. The risk involved in this technology development appear very high at present, but the committee urges a feasibility test be carried out to determine what thrust-to-weight ratio is practically achievable. It also recommends that the potential of the technology be reviewed by a senior group experienced in nuclear rocket technology.

The 90-Day Study mentions gaseous-core nuclear rockets as offering much higher specific impulse levels. A number of gaseous-core reactor concepts were carefully evaluated in the years between 1959 and 1970, but none was found to be technically feasible. Unless a new idea has appeared, which is always a possibility, the committee believes the gaseous-core nuclear rocket technology is too speculative at this time and should be dismissed as a possibility.

If careful systems studies, using thrust-to-weight ratios and specific impulse known to be feasible, show a significant advantage for nuclear rockets in trip time or in weight to orbit, an in-space demonstration of this technology should be done as soon as possible—taking into account requirements for crew, ground personnel, and public safety covering all phases of launch and flight, including mission abort. It will not be feasible to select the nuclear rocket as a baseline in a system architecture until such a demonstration has been conducted.

NUCLEAR ELECTRIC POWER

The committee believes that nuclear power eventually will be essential
for lunar and Mars bases. The NASA reference approaches incorporate nuclear power; The Great Exploration does not.

At present, the only active technology program applicable to this need is the SP-100 thermoelectric space reactor, which has been pursued under a tri-agency program for several years. SP-100 was initiated in the absence of a definite mission requirement as a general purpose space power source. This program should be redefined in light of the requirements of the HEI and committed to development; nuclear thermionic research should continue to be pursued as well.

Consideration should be given to demonstration of the nuclear electric power system as the power source for an electric propulsion system, which may have application to science missions with large launch velocity requirements. (In fact, a number of outer planet missions have been suggested, including a Jovian system grand tour, that will require such advanced power sources.) Here, as with the nuclear rocket, considerations of safety must be incorporated into research, development, and demonstrations and factored into assessments of overall systems performance. The nuclear electric system might be demonstrated within these constraints by a mission in which the system is launched to a high orbit, say 600 miles, before it is operated. The orbit could then be raised by nuclear-electric propulsion to geosynchronous orbit or beyond.

If safety concerns can be successfully addressed, and feasibility demonstrated, the committee believes that use of nuclear power and propulsion can meet many needs in the human exploration of space.