

The NSS Roadmap to Space Settlement (Revised 2/28/00)

The NSS Roadmap to Space Settlement depicts the path currently viewed as leading to realization of our vision. It displays an evolutionary path consisting of major program and policy initiatives, with certain alternatives, and major barriers to proceeding on the path. The rate of progress is dictated by removal of the barriers, resources available to the international space development community, commercial space development, technical progress, and political will. NSS recognizes the significance of the barriers to progress on our roadmap, and is dedicated to removing them in the interests of humanity's long-term future.

Each of the initiatives and barriers is discussed below. Here we describe the roadmap as a whole.

The overall concept of the roadmap is to begin or continue activities that can be started now or are ongoing, to give priority to the barriers, which deter near-term progress, and then to move towards long-term goals in an orderly manner.

Most of the near-term activities are related to technology development, legislation, and studies. (The developing space tourism industry, for example, is deeply involved in all three.) Two related space mission activities stand out: acquisition of knowledge specific to human missions and settlement through robotic missions. The knowledge sought will tell us where to go with human missions and how to deal with possible biological risks.

These knowledge acquisition objectives could in part be built into currently planned missions. However, although it is not widely known, current U.S. space policy places human missions beyond Earth orbit (other than possible tourism) in the indefinite/far future and does not allow expenditure of NASA resources to obtain data specific to these missions. Reversing or limiting this policy is an urgent NSS objective since we cannot begin to reach for our goals until this is done.

Space tourism is an important step in the direction of making space travel accessible to ordinary people, and NSS advocates removing policy barriers, as well as establishing a pro-active legislation and policy basis, which encourages rather than discourages commercial development of space tourism.

Certain studies are important: particularly to define space transportation and mission architectures appropriate to settlement, and to define how early missions can best achieve technology advancements and demonstrations of settlement self-sufficiency. Space transportation and mission architectures specifically aimed at settlement will be different than those intended mainly for scientific exploration. The most important differences are (1) settlement architectures must drive recurring costs to the lowest practical levels, and (2) self-sufficiency needed for settlement goes far beyond the usual assumption of propellant production, and must be demonstrated to be stable and adequately productive over long periods of time.

Economic feasibility of settlement demands low-cost space transportation (by present standards; a settler who had to pay the ticket price would not think it "low" even if as low as theoretically achievable!). Launch costs need to come down a long way. Commercial launch costs are coming down due to competition in the marketplace, and growth of the commercial market for launches of communications satellites. A rigorous policy that NASA should purchase launch services for human exploration missions to the extent possible (rather than develop a "custom" heavy-lift vehicle) would increase the market for launches in the heavy-lift class (served initially by Atlas V, Delta IV, and future versions of Ariane V), stimulate development of improved heavy-lifters and help to drive prices down. In fact, government agreement to purchase launches is likely to be essential to the development of such heavy-lift vehicles. Until a suitable commercial vehicle becomes available for carrying people, the NASA shuttle would necessarily continue to fill that role, but NASA should announce a policy to purchase human trips commercially when a suitable launch service becomes available.

The "goal" in-space transportation system will surely be fully reusable and employ advanced technology. There are several alternatives, and it is important to select one or more for development early, so that long-range plans can be laid and technology advancement begun. Further, until studies and technology demonstration show costs commensurate with settlement are reachable, we cannot affirm a policy goal of settlement as other than an ideal.

Let us re-emphasize: While a government-supported scientific base could exist for a very long time on public funds if the prices were right, true settlements require self-sufficiency. We cannot expect governments to accept a perpetual claim on public funds for a space settlements program. This means that settlements, in the long run, must achieve survival and growth almost entirely on indigenous resources, relying on imports only to the extent these are paid for by settlement exports. The underlying technology and operations must be demonstrated as fully capable before human populations beyond Earth are permitted to grow to the point that there is no reasonable way to turn back.

Settlement begins with human missions beyond Earth orbit. While settlement must await great cost reductions in space transportation, the initial missions need not necessarily do so. However, even initial missions need cost reduction, and increase of availability of the transport resource, to be able to fit into an overall space

program serving recognized needs. Timing of ambitious missions such as these is driven by budget, including competing demands for resources, and political considerations. Since these cannot be forecast accurately, our roadmap does not have a specific timetable.

The road map does not stop at Mars. The space frontier offers an endless set of more and more challenging goals. Two of these are noted, constructed habitats and travel to the stars.

The capacity of the Moon and Mars to support people is limited. Presently, these capacities are unknown. People have speculated that one billion or so settlers could probably live on Mars without overstressing resources there, assuming enough water is present. The number that could live on the Moon is a good deal less. One of the reasons O'Neill so strongly favored the idea of constructed habitats was that available resources in the solar system, i.e. in the asteroid belts, could permit construction of enough habitats to support many times Earth's present population.

The eventual goal of space exploration and development is to leave the solar system and travel to the stars. This is by far the most challenging goal on the road map. We cannot today put any sort of schedule to it. For the purposes of the present plan it is sufficient to recognize it as the ultimate goal.

Where and When ... Those elements of the road map that are first steps can begin now or as soon as certain barriers are removed. However, human missions beyond Earth orbit cannot go everywhere at once. Choices must be made where to go first, why, and when. It is tempting to adopt an unwavering position on the subject. However, NSS has avoided doing so.

We recognize that motivations are different for the Moon and for Mars. Planetary science and the search for existing or former extraterrestrial life clearly favor Mars. Industrial development and use as an astrophysics platform clearly favor the Moon. Settlement is a legitimate objective for either, and if successful, greatly reduces the cost to the sponsoring governments for mission accomplishment at either location. Proper choice of the "goal" in-space transportation infrastructure makes both accessible.

Determining which motivation takes precedence is a political decision. The entire question of where to go first really arises because of the perception that the costs are so extreme that there is no possibility of more than one destination. NSS believes that if this roadmap is, in general, followed, the costs and benefits of settling the Moon and Mars are such that both can be done more or less in parallel, although a choice must be made for the first new human mission beyond Earth orbit.

Timing is a question of cost reduction by introduction of technology and resource availability.

Our expectation is that a return to the Moon is a prudent first step on the road to Mars. A commitment to go directly to a Mars mission, with a stay on Mars' surface of a year or more is most likely to be viewed as placing people and their "can't test them too much" machines on a very unforgiving mission profile. A return must await opening of a low-energy window and then requires many months. By comparison, a return from the Moon can occur almost any time and requires only a few days. Testing other than in the relevant environment and under actual operational conditions is incomplete. An unexpected failure (which might not even be a hardware failure, but an overlooked operational necessity or a human failure) would likely be fatal on Mars but recoverable on the Moon.

The final decision, however, is not for NSS to make. It must be made by the scientists, engineers, mission planners, and sponsors of the missions.

Description of Milestones

Robotic Missions . Initial human missions must be preceded by robotic missions to gather key scientific and engineering information relevant to design of the human missions. The robotic mission activities envisioned would develop a clear understanding of ice resources on the Moon and obtain information leading to an assessment of the biological risks associated with human missions to Mars.

NASA's Prospector mission to the Moon detected the presence of hydrogen in the lunar regolith in the vicinity of the lunar poles. It is widely assumed that this means water is present, but it is not assured; the hydrogen could be in some other form. Even if it is water, the nature and extent of water deposits is important to their utility for propellant production and support of human habitation. The nature of the deposits also affects their scientific value and would lead to decisions on how to preserve scientific value while obtaining practical benefit from the resource. Finally, the extent of the resource will affect planning for its use. If deposits are very large use as rocket propellant may be practical while if they are modest it may be preferable to conserve them for life support uses.

Questions of nature and extent can only be answered by direct inspection and sampling. Missions have been proposed to NASA in recent years to do just that, but without a definite prospect for future space initiatives, which could use lunar water deposits. This mission must compete entirely on its somewhat uncertain scientific merit. Depending on the nature of the deposits they may have little or great scientific value.

NSS believes one or more lunar ice robot missions should be conducted based on the merit of assaying a

potential resource which, if present in reasonable quantity, has great value for future human uses of the Moon.

NASA is presently conducting a focused series of Mars robotic missions aimed at garnering scientific knowledge of Mars. These missions are presently being planned and designed without significant consideration of human missions.

Issues have been raised regarding the biological risks of human missions, (1) the return of possible harmful biological agents from Mars, and (2) contamination of Mars and risk to possible Mars biota by human missions and the inevitable release of Earth organisms into the Mars environment by leakage from human-occupied systems. While NSS believes these risks are low, they cannot be entirely disregarded. Further, human missions will need to use resources on Mars and operate in the Mars environment in ways not important for modest robotic missions. Examples include production of propellant and construction and/or equipment emplacement operations on Mars surface. Note that propellant production is also relevant to a robotic Mars sample return mission.

NSS believes the Mars robotic exploration program should be adjusted to experiments leading to propellant production, greater/ broader assessment of Mars' biological environment (already a high priority), and specific evaluation of the biological risks by the scientific community.

Low Launch Costs

To achieve low launch costs, the private sector needs (in addition to adequate market size) continued advancements in technology enabling efficient vehicles with turnaround time one day or less. NASA and other government-funded space agencies should continue their role in developing space transportation technology through flight test demonstrations such as the X-33 and X-34. These activities place the technology "on the shelf" for industrial/commercial uses. Technology developed with government funding must be immediately placed in the public domain. It is a government role that has proved very beneficial in the aviation industry. This is an appropriate area for continued and expanding government technology investment. Investment in aviation technology by NASA's predecessor NACA, beginning in 1915 and continuing over a long period of time, played a major role in U.S. aviation development.

Most of the launch requirement for exploration missions, to the Moon or to Mars, is in-space transportation hardware and propellant. These requirements could be met today by commercial launch if the commercial providers could satisfy the launch rate needs. While exploration mission designers find it "inconvenient" to design their systems to be compatible with current and mid-term commercial launch capacities (they would prefer to have a super Saturn V), it is only inconvenient and not impossible. The total cost of an exploration mission using commercial launch will come down, because custom launchers developed and operated by the government have historically been, and will continue to be, very expensive.

Expendable launch systems need to get down to about \$ 1000 per pound to enable human return to the moon and humans to Mars. Ultimate costs for reusable systems are expected to reach below \$100 a pound to enable large-scale settlement. Achieving such low values will require a large volume of traffic demand, very rapid turnaround enabling up to 200 uses per year per vehicle, and vehicle life exceeding 1000 trips to orbit.

No mechanism for cost reduction is as effective as free market competition, given an adequate market. For this reason the NSS Roadmap envisions that NASA continue to move in the direction of purchasing launch services from the commercial sector, including human trips to orbit. When commercial entities could competitively enter this market arena the current shuttle fleet would be retired.

There are several regulatory issues to deal with. We highlight the issue of liability legislation; it is appropriate for the government to provide liability limits to the industry. It is also appropriate for governments to maintain current regulatory and licensing roles protecting public safety in space flight operations, as government also does in the aviation industry.

Legal Protection of Property Rights

It is difficult to conceive of successful settlements in space if the settlers are not permitted to own real as well as personal property, and if business enterprises cannot own and run the facilities necessary to operate their businesses in extraterrestrial locations. NSS believes that private individuals and groups who are considering investing their own resources to settle and develop the frontier will need to know in advance that, if they succeed, they will be rewarded by legally enforceable recognition of their claims of private ownership. Accordingly, NSS strongly endorses the establishment and recognition of such rights.

Current treaties among the nations of Earth prohibit national claims of sovereignty over bodies in space (although some nations have claimed ownership of the portions of the geosynchronous orbit arc over their territory). Therefore, it may be that nations or other terrestrial entities cannot grant ownership of property in space. However, even in the absence of modifications to such treaties, it is possible to expect that a legal regime could be established wherein reasonable claims, based on beneficial occupancy and development, could be recognized by terrestrial entities.

A legal regime for property rights in space would need to incorporate the usual protections for individuals, businesses and the natural environment, and fair competition. These protections include prevention of monopolistic ownership of scarce and valuable resources, and sensible zoning. The legal regime should take a minimalist approach, not creating volumes of regulation prematurely, before future space settlers are able to determine, based on actual knowledge and experience, what is reasonable. It should strive for the creation of economic incentives for human expansion into space, access to space for all, protection of settlers' rights, and protection of space resources.

It should be noted that no individual or company currently has the power to issue "titles" to uninhabited extraterrestrial real estate. NSS regards any past and contemporary offers of "title" to such lands -- as opposed to solicitations clearly denoted as symbolic and unofficial -- as unethical and deceptive, if not outright illegal.

Land Grants or Other Economic Incentives

Economic incentives need to be found to encourage off-Earth settlements.

To increase the potential for private investment in affordable space transportation, facilities, or settlements, claims of off-Earth land recognized on the basis of beneficial occupancy and development could plausibly be broadened to include additional tracts large enough to make feasible subdivision and re-sale to such extent as may be necessary to make a settlement economically profitable.

Of ideas currently proposed, such extraterrestrial "land grants" appear to be the most likely way to foster privately funded space settlements. Accordingly, efforts to develop an acceptable method of offering land grants as an incentive for such settlements should be given a very high priority by the U.S. Congress and the space community.

Self-Sufficiency

The main issue for self-sufficiency is to achieve adequate human productivity, and diversity of production and service capabilities, with a small population on an undeveloped planetary surface so that the colony is not dependent on resupply for critical resources (e.g. air, water, power, shelter, basic foodstuffs, etc.) This implies a broad spectrum of advanced manufacturing servicing, maintenance and repair technologies with an underlying structure of advanced automation and robotics.

An indication of the problem can be given by the example of construction of a current-technology space station habitat. The cost of such a habitat is on the order of \$100 million, which implies a labor content exceeding 500 man-years. The finished habitat would, approximately, support a typical family unit of four people. A habitat on the surface of the Earth (i.e. a house) requires less than one-man year labor content to produce. It is clear that the human labor content for producing habitat space for a family unit on the Moon or Mars (or in space) needs to approach to one-man year for it to be feasible for space settlers to construct their own habitation, as well as habitation for new settlers and population growth.

Our understanding and capabilities in this area are extremely rudimentary. We have some ideas how to recycle air and water and produce food in a space habitat, but attempts to create an artificial closed ecology in earthbound experiments have been failures. Even when these succeed, self-sufficiency must go much further, to the level of producing daily needs such as energy, clothing, daily living amenities, and shelter (i.e. habitats) from local resources. NASA has no consequential technology efforts in this important area. Indeed they cannot as long as the policy barrier against such research exists; NSS must seek to change that. Once it is changed it will still be necessary to press for meaningful funding in this research area. NSS believes NASA and other organizations should give high priority to developing the foundations for self-sufficiency technology and that future human missions to the Moon and Mars should focus on demonstrating how these technologies can work in the space environment.

Affordable "Goal" In-Space Transportation

Analyses of cost drivers for in-space transportation indicate that with substantial reduction in launch costs, the lowest cost systems are fully reusable as is true for launch systems. Most current Mars mission architectures and some lunar mission architectures employ expendable or partially expendable systems in order to reduce initial mass in Earth orbit. In order to have reasonable initial mass for a fully reusable in-space transportation system, the system must either have very high propulsion performance such as an advanced solar-electric system, an advanced nuclear propulsion system, or must obtain propellant for the return trip at the destination.

Typical architectures with these features use lunar oxygen or lunar water for return from the Moon, solar electric or nuclear propulsion and/or destination refueling for transfer between Earth and Mars, and use propellant derived from Mars atmosphere for ascent from Mars as well as the return trip to Earth. They may

also use propellant obtained from Phobos or asteroids resources for return to Earth from Mars orbit or Mars-Sun L1.

These advanced architectures need evolutionary paths or "start-up modes" to avoiding relying on the advanced features for initial trips. Lunar architectures will be partially expendable until lunar surface propellant -production can be implemented. Advanced solar-electric propulsion could be developed relatively quickly with a focused technology effort since the level of technology required presently exists on a laboratory scale. Similarly, Mars lander/ascent vehicles will be expendable until Mars surface propellant can be put into production. Chemical interplanetary transfer propulsion systems may be adequate if destination resources are use for the return trip. These will be at least partially expendable until propellant production can be implemented for their refueling.

It is important to select one or more advanced technology approaches towards an affordable "goal" in-space transportation system so that "start-up" architectures and technology programs can be designed for efficient evolution to these eventual systems.

Set Mission Goals for First Mars Mission

Current NASA study activities on Mars missions do not emphasize settlement. Early human Mars missions will not be settlements and must precede a program decision to create a settlement since one of their mission goals will be to conduct engineering tests to verify the self-sufficiency technologies to enable settlement. In order to get off on the right track, even the first human Mars mission must have settlement-derived mission goals and these need to be decided before detailed mission design begins.

As an observation, this need also exists for return to the Moon but is less of an issue, since we have already achieved the goal of reaching the Moon with humans. A return mission will clearly focus on practical uses of the Moon including settlement, since the goal of simply proving that humans can go to the Moon and return no longer exists.

Lunar Facility

A lunar facility for testing planet surface operations is in principle no different than one, which is the beginning of a lunar base. NSS views these as the same, and expects that any facility put on the Moon be designed for long-term use. It must be almost all the way there to serve as a test bed, so wise investment policy would to build it with the option of serving a long-term future.

This facility, suitable for initial developmental use, and test, checkout and training for Mars missions, would be very similar to a small space station on the Moon. In fact, space station modules could be used with little modification if desired. One can imagine such a facility with a habitat module and a laboratory and operations module. If regenerative food growth were desired a third module would be necessary.

On the Moon it is essential to provide radiation shielding. (This is a lesser but still important need on Mars.) Several concepts are available using lunar regolith. The habitat and laboratory modules would require support of thermal control and electrical power generation systems. Additional mission equipment would be required depending on particular mission purposes. The mission equipment might be prototypes of equipment planned for use on Mars.

Location of the facility near one of the lunar poles offers a more benign thermal environment, locations for solar electric power systems, which would probably be sunlit most of the time, and access to lunar water and other volatiles detected by the Prospector spacecraft.

Trips to and from the lunar poles are most easily implemented by a transportation architecture in which the entire return vehicle lands on the surface of the Moon. These architectures are also best suited for use of lunar surface propellant for return to Earth.

The lunar transportation system would be designed to operate between low Earth orbit and the lunar surface. Avoidance of extensive assembly operations on the Moon requires a delivery capability about 20 tons.

The requirement to land the entire return system on the Moon is satisfied with a similar capability. Since the ratio: mass in earth orbit to lunar delivery payload is on the order of 5 this implies a departure mass about a hundred tons. With launch systems capability in the range 20 to 40 tons, a few to several trips to Earth orbit are required for each trip to the Moon. The lunar transportation vehicle would require some assembly in orbit, much simpler than that required for the international space station (or for that matter the Mir). Once constructed, the lunar transportation system would operate in reusable mode between Earth orbit and the lunar surface and would have an expected life of dozens of trips.

Government-Industry Base

This is a multipurpose facility in the spirit of the International Space Station, with programmatic features that encourage early industry investment and involvement, as described below. Its timing re the first

Mars mission is flexible. The lunar facility described above could directly evolve to a government-industry base with delivery of a few more modules and installation of additional infrastructure equipment. The transportation system for the initial facility would also serve the government-industry base. The timing of such a base depends upon funding available, resources required for other missions such as humans to Mars, industry interest, and definition of technology initiatives, which could make a small lunar settlement economically self-sufficient.

Human Explorers to Mars

NSS views the first mission to Mars as a precursor to a settlement. The human trip is preceded by infrastructure emplacement so that the initial visit can stay on Mars for over a year, and take advantage of the relatively low-energy conjunction profile. The first mission need not necessarily achieve the affordable "goal" in-space transportation system, but should to the extent possible use systems, which are on the evolutionary path to the "goal" system. For example, if the "goal" system uses solar-electric transfer propulsion and a Mars lander/ascent system fueled by Mars propellant, the initial system should at least use some solar-electric assist, and would also use Mars propellant for ascent from the surface. The first mission to Mars, like all missions in NSS' view, should obtain Earth launch services by purchase from the commercial sector. The first mission, in addition to science, would conduct experiments on self-sufficiency technology.

Several architectures have been defined for the first mission to Mars. Selection of architecture depends on selection of the "goal" in-space transportation architecture discussed above. Candidates include a solar electric propulsion system, nuclear propulsion, the Mars Direct architecture or some variation of it, and cryogenic aero-braking architectures intended to evolve to use of Phobos or asteroid propellants. Given a shakedown cruise on the Moon to test equipment, operations, and crew performance, the first mission to Mars should use the conjunction profile and stay on the surface of Mars for about a year and a half.

In order to reduce projected cost of the first Mars mission, there has been a tendency to skimp on estimates of Mars surface mission equipment and systems to be emplaced prior to the first human trip. It is important to provide an adequate infrastructure on Mars surface, especially for the first mission, to reduce risk and enhance mission productivity.

Evolution to Settlements

Continuing missions to Mars would continue on the evolutionary path to the "goal" in-space transportation system and would perform enough demonstration of self-sufficiency to enable a decision to begin establishment of a settlement proper.

One distinguishing characteristic of a settlement is that settlers emigrate without clear and specific plans for a return. The evolution would begin when self-sufficiency on basic life support needs including food growth has been demonstrated, and it becomes practical to construct human habitation facilities and supporting infrastructure from lunar or Mars resources.

True settlement cannot begin until assurance has been demonstrated that indigenous food growth can be productive and stable over long periods of time. Attempts to create artificial closed ecological systems here on Earth have so far been failures. Before we can commit to sending people to a space settlement without firm and definite plans to return them, we must know that long-term survival and quality of life is assured. Therefore NSS visualizes that continuously occupied bases on the Moon and/or Mars must operate for 10 to 20 years, reaching higher and higher levels of self-sufficiency, until enough confidence is gained to begin the true settlement process.

Another major issue for true settlement is who will pay the way for the settlers. Historically, in most cases, settlers have paid their own way. Transportation costs to space to settlements will probably (at least in the beginning) be too high for settling families to pay their own way. Therefore it is essential to develop an approach, which can raise enough funds to pay for settlers to emigrate without placing a large burden on public tax revenues.

Exploration of Asteroids

Asteroids may prove to be practical sources of resources including metals, nonmetals and volatiles. Exploration of specific asteroids that are reasonably accessible from Earth or Mars is needed to develop a catalog of resource availability and mission timing. This exploration could be entirely robotic. The robot spacecraft would land on the asteroids and perform resource exploration and assays. These robots could be launched directly from Earth and probably could be compact enough for direct launch by a contemporary ELV.

Space Tourism

Tourism is critical for creating the market for space settlement. People will likely not want to settle on

the Moon or Mars or elsewhere until many have visited those places. Tourism is also essential for providing incentives to reduce launch costs and make reusable launch vehicles more reliable.

NSS anticipates that space tourism will begin in the near future with sub orbital flights to altitudes exceeding 100 kilometers, enabling passengers to briefly view Earth from space and earn astronaut-passenger wings. The next step would be orbit-capable vehicles carrying passengers to orbital trips lasting one to two days in micro gravity. Investors and corporations have already discussed construction of hotels, resorts and casinos in orbit around Earth and the Moon. Tourist travel to the Moon itself would follow, and at some later time tourists might travel to the Mars and other destinations.

Constructed Habitats

In 1974 Dr. Gerard O'Neill proposed the construction of large pressurized habitats in space from resources obtained from the Moon. These habitats would be something like giant space stations, but large enough that the interior could be treated as real-estate land on which crops could be grown and houses constructed. People would live in a manner similar to a region of small villages and cities. The habitats would be cylindrical, rotating around their cylinder axis so that the inner surface would experience centrifugal acceleration similar to the gravity force on the surface of the Earth.

Design and operations concepts for these habitats have been widely published. Suffice it to say that construction of these represents an enormous space industry enterprise similar to building a city. For this to be feasible a high level of automation and robotics is needed, from raw resource acquisition through complete construction and outfitting of the habitats. It is difficult to project when space engineering and construction technique will make such projects feasible in a practical sense. It is, however, probably very safe to say it will be feasible long before interstellar travel becomes feasible. Therefore NSS recognizes construction of O'Neill-style habitats as an evolutionary step in humanity's development, growth and expansion into the universe.

"New Physics" Propulsion

Human travel much beyond Mars will not be practical with propulsion technologies now in use or now in development. Solar-electric systems quickly run out of sunlight beyond Mars orbit and chemical propulsion systems have too low specific impulse. Some sort of advanced approach involving nuclear energy or off-board energy sources is clearly required.

Nuclear fission systems like the old solid-core reactor systems also do not have enough specific impulse to reach beyond Mars. There has been speculation about gas-core nuclear fission rockets but the crucial experiments demonstrating a feasible concept have not been performed. Further, testing of fission propulsion technologies is highly problematic given the importance of environmental protection here on Earth.

NASA currently has a modest program seeking scientific breakthroughs in propulsion physics, concepts such as compact efficient fusion, antimatter, and even gravitational effects. These are not necessarily needed for settlement of the Moon and Mars, or for exploitation of asteroid resources, or even for construction of O'Neill-style habitats from lunar or asteroidal resources. However, they are needed to open up the Mars transportation windows so that travel to and from Mars becomes possible other than during low-energy opportunities every 2.2 years. They are certainly needed for our eventual ambitions of travel to the stars. This NASA program should be expanded, to conduct tech-nicely significant experiments where analysis shows a potential for progress.

Nuclear fusion, especially if a neutron-free reaction could be produced, would provide enough specific impulse to reach throughout the solar system. Whether nuclear fusion technology can produce an acceptable thrust-to-weight ratio remains to be seen.

Current fusion reactor designs are unsuited for neutron-free reactions and are very unlikely to reach useful thrust-to-weight ratios. More advanced techniques such as antimatter and catalyzed nuclear reactions offer eventual promise of much higher performance and possibly attractive thrust-to-weight ratios but are in their infancy. Even beyond these technologies are notions of affecting gravity or influencing the structure of space-time itself (which is probably the same thing).

These propulsion technologies are an important aspect of NASA's long-range research. It is essential to focus most of the effort on concepts well enough understood to have some promise of success, and for which success can be characterized as adequate specific impulse and thrust-to-weight performance to represent a quantum step forward beyond what can be achieved with current and developmental technologies.

To the Stars

Travel to the stars is a challenge more difficult by orders of magnitude than any other on our roadmap. This can be quickly seen by comparing distances. A trip to Mars typically covers 2×10^8 kilometers. The nearest stars are four light years away, and a reasonable star-travel capability should be able to reach out at least

10 light years. A light year is 10^{13} kilometers; 10 light years is of course 10^{14} kilometers, 500,000 times farther than Mars. A spaceship with speed able to reach Mars in 90 days would require over 100,000 years to travel 10 light years. If such a journey were launched and if interest in interstellar travel continued, such a slow ship surely would be overtaken by a faster one in not too many years.

Well, no one is serious about sending a Mars spacecraft on an interstellar journey. We will have to develop better propulsion, fusion or antimatter or some such. It's a common belief that fusion, for example, could get a ship up to about a tenth the speed of light. Then a 10-light-year trip would only take a hundred years. Or would it?

Let's imagine we have a device that converts mass into energy (as any energy source does) with high enough performance that we can have more or less any specific impulse (jet velocity) we want, up to the speed of light. Let's further suppose, which is reasonable, that its efficiency is not perfect, that some of the energy released is deposited in the equipment, while most of it may very well be deposited in the jet. The energy deposited in the equipment we must get rid of by radiating it to space.

Liquid propellant rockets and nuclear thermal rockets solve this problem nicely by absorbing the unwanted energy in the propellant before it goes through the engine, thus carrying the unwanted energy with the jet away from the ship. Studies of higher-performance nuclear rocket concepts, in particular the gas-core fission rocket, indicate this isn't going to work at specific impulse more than about 2000 seconds (four times that of a chemical rocket); there isn't enough propellant flow to carry away the heat.

If we are extremely optimistic, we might imagine we could radiate away the heat at 2000K. The corresponding radiator power is given by the Stefan-Boltzmann law as 900 kW per square meter. One might also optimistically presume such a high-temperature radiator and heat rejection system could weigh as little as 5 kg per square meter. Neglecting other masses, our energy production system can produce 180 kW of unwanted energy per kg of mass.

Now let's further assume the machine is 90% efficient, that only 10% of its energy is unwanted, the other 90% appears as jet velocity. Then we can produce 1620 kW per kg of machine mass. (This is about four orders of magnitude better than present-day space power plants.) Let's further assume that our ship is 1/3 energy conversion machine, 1/3 payload (passengers, their habitation and support systems), and 1/3 propellant. To reach 10% of the velocity of light, we will need a jet velocity about 20% the velocity of light, 60 million meters per second. We know that power is jet velocity times thrust divided by 2. Then we can solve for thrust over mass (thrust-to-mass ratio) as 2 times power divided by jet velocity. The power available is 1.62 million watts per kg of machine; the result is about 0.05 newtons per kg of energy production machine, less than 0.02 newtons per kg of ship mass. The acceleration is about two thousandths of a g. At this acceleration we will need 50 years to reach 10% of the speed of light. Oops! We forgot to provide propellant to slow down! Well, if we did provide it we would cover about 2 light years accelerating, a little less than 2 slowing down, and need 60 more years to cover the 6 light years of coast time. So we are really thinking of more like 150 years.

This is a characteristic of power-limited machines, limited either by the mass of energy conversion machinery, as are current space power plants, or ultimately limited by the mass of equipment needed to reject unwanted heat. As you raise the jet velocity, i.e. specific impulse, the available thrust goes down and one must select a compromise between too much machinery mass and too much propellant mass. The compromise often ends up 1/3 power plant, 1/3 propellant and 1/3 payload, which is why we divided things up that way.

As shown, we can just barely imagine machines energetic enough to permit interstellar travel over periods of a century or so. Are there any ways around this dilemma? Not that we can really imagine, but perhaps a machine 99+% efficient could be built. Perhaps we could use an external power source; Bob Forward has suggested (on a small scale for scientific probes!) a laser or microwave beam reflected by a large mirror or antenna on the ship, so that the ship is accelerated by "light pressure". Such a device could reach the 99+% efficiency goal (for the ship; the energy machine is stationary and is not accelerated.) The thrust available is between 1 and 2 lb force per billion watts of laser or microwave power. If the entire U.S. electrical generating capacity were hooked up to such a laser, even with 100% efficiency (most lasers are very inefficient) we could produce about 500 lb of thrust. A 500-lb-thrust chemical rocket engine you can pick up with one hand.

Perhaps there is some strange way we could manipulate space-time itself so that we don't really have to cover the enormous distance to get from here to there. A common theme of science fiction; real physics tends to say one would need huge concentrations of mass-energy something like a black hole. Not a near-term propulsion technology. As far as we know there are no natural black holes anywhere near the solar system (let's hope not!)

Travel faster than light is another common theme of science fiction. Relativity says (more or less) no. All the tests of relativity so far conducted indicate it is a correct model of space-time. Again, by manipulations of space-time it might be possible to be traveling locally at less than light speed, while to a remote observer, i.e.

the distant stars, be traveling at greater than light speed. These manipulations may in fact amount to about the same thing.

The only scheme for interstellar travel we could rally put on our road map is to build a huge O'Neill-style habitat capable of supporting a population for a few centuries, equipping it with a huge fusion or anti-matter engine, and setting forth on a journey of lifetimes. Who would pay for such a mission? If human economies continue to prosper, we will most likely be able to figure that out before we figure out the propulsion system.

Meantime, scientists continue their quests for "breakthrough physics". Don't hold your breath, but we haven't had a really radical revolution in physics since relativity and quantum mechanics, and their origins are almost a hundred years in the past.