Evolving SP-100 Powerplants via Electric Propulsion to GEO and Lunar Orbit

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As they contemplate sending personnel on long-term missions to the Moon and Mars, technologists and mission planners are responsible for delineating the costs and risks involved, and for formulating program plans reducing these costs and risks. In this planning, a crucial aspect is program continuity, i.e., the continuing application of a given technology over a long period so that experience will accumulate from extended testing here on Earth and from a diversity of application in space. An integrated view is needed of the missions to be carried out under the space exploration initiative (SEI), near-term as well as far-term, and of the ways in which these missions can mutually support one another. Near-term programs should be constituted to provide both the enabling technologies and the accumulation of experience needed for long-term missions. In achieving this, nuclear-electric propulsion (NEP) missions in Earth orbit should both evolve and demonstrate the technologies crucial to permanent residence on the lunar surface, and the program for the lunar laboratories should evolve and demonstrate the enabling technologies for both exploring the surface of Mars and for flights of human beings to Mars and back.

Introduction

IN response to President Bush's request, the ways to establish permanent operational bases and astronomical laboratories on the lunar surface, and later to dispatch inhabited spacecraft to Mars and back, are being studied. Both the financial costs and the financial risks of carrying out these ventures loom large. New technologies (nuclear-thermal and NEP, in particular) are frequently cited as the means for reducing both the costs and risks of these missions, but the new technologies themselves introduce additional costs and risks. How do we balance these costs and risks? How do we exploit advancing technologies in order to reduce both program costs and risks to personnel while simultaneously limiting the costs and risks of the advancing technologies themselves? This article addresses that important issue, taking a broad, overall view of the entire SEI program while focusing on NEP. In shaping that program, we should choose each new technology or operational capability for its contribution to the entire program, pruning from the program those elements of limited utility. For example, we should not return to the Moon for merely a brief daytime visit, repeating Apollo; instead, we should take program steps constructively leading to permanent residence on the lunar surface. For power generation or propulsion, we should select, develop, and employ concepts spanning applications extending from low Earth orbit (LEO) to low lunar orbit (LLO), to the surfaces of the Moon and Mars, and to transportation to Mars and back.

From a unified view of SEI missions in the near-term and far-term, and from that, building on a successful past in order to guarantee the future, we can reduce the risks and costs of these future missions. We would also likely save a few lives in the process. And, if we wisely choose the technologies we support, we will still be able to realize performances close to the best achievable. This article delineates just such a programmatic path for power generation and electric propulsion.

The keys to successful exploitation of new technologies for this propulsion and power are the following:

1) After assessing the potential of a concept for improved performance and wide application, introduce margins in design in order to reduce programmatic risks. This should reduce the time and the money as well as the risks.

2) Exploit the concept in a variety of early applications, showing through actual service in space, the concept's performance, durability, and reliability.

3) In a succession of applications in space, evolve the concept toward its performance potential through successive reduction in the design margins introduced at the program's start.

A program extending from a modest beginning to a grand and glorious future can have low cost and low risk if it consists of a succession of steps, each of moderate risk and cost. Such a program must be, to some degree, monolithic and conceived with vision.

Apart from studies of the TOPAZ thermionic reactor, development of SP-100 is the only significant effort on nuclear-space power in the U.S. This development will require the total expenditure of perhaps 1–5 billion dollars, and about 20 yr from the program initiation in 1981 to its first useful application early in the next century. Evolution of SP-100 will therefore be emphasized herein.

Missions

In what follows, missions leading to continuous residence on the lunar surface will be emphasized, the potential benefits to the Martian missions being merely inferred and stated in general terms. Neither the missions themselves, nor the manners in which they will be carried out, are clear at present. Instead, the missions will likely be the principal topics of study after study, iteration after iteration, in order to delineate the best ways to carry them out. For example, what should be the power level of a nuclear powerplant for NEP to make best use of a given launch vehicle? Alternatively, what new class of launch vehicle should be developed to most effectively mesh with NEP for transport of cargo and personnel to the Moon and to Mars? Most of the answers to these questions lie in the future.

On the other hand, it is already clear that continuous support of operational bases on the lunar surface depends upon

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economical transportation of supplies and equipment to the Moon. In low-risk, incremental evolution of such future capabilities, early reliance on NEP for payload-boosting from LEO to geosynchronous Earth orbit (GEO) is a valuable precursor of both transport of cargo to LLO and of continuous occupation of laboratories on the lunar surface. For transport of cargo to either GEO or LLO by way of NEP, the time of transport is an important measure of merit, along with payload mass fraction. Both time of transport and payload mass fraction will therefore receive equal emphasis herein. Two modes of transport of cargo are evident: 1) one-way trips and 2) round-trips (RT). Both will be considered.

SP-100

In this nuclear powerplant, the nuclear reactor produces 2500 thermal kW to heat a pumped stream of molten lithium to 1350 K, thereby heating a thermoelectric power generator to 1300 K. Studies of alternative generators have chiefly focused on the turbogenerating Brayton cycle[1] and the reciprocating Stirling engine,[2] but other possible concepts would use potassium-vapor Rankine cycle[3] or alkali-metal thermoelectric energy converter (AMTEC).[4] A virtue of the SP-100 reactor is its suitability for use with this variety of power generators, a significant programmatic advantage over thermionic reactors (e.g., Ref. 5). With its overall efficiency of 4%, SP-100's thermoelectric generator will produce 100 kWe from this 2500 kW. A representative mass breakdown of the SP-100 powerplant from the design review in May 1988 is given in Table 1.[6]

The corresponding specific mass of this 100-kWe powerplant is thus 54.22 kg/kWe. The first four components (totaling 3049 kg) comprise the nuclear heat source, and the last four components (totaling 2373 kg) are associated with the thermoelectric power generator. The estimates of total mass for the SP-100 powerplant have risen and fallen over the intervening period, ranging from 4460 to 5531 kg.[7] Because of that, the masses of the powerplant and its nuclear heat source are still a bit uncertain. In what follows, 3049 kg is taken as the mass of SP-100's nuclear heat source and 5422 kg for the complete powerplant. Its specified output is 200 volts direct-current (VDC) and 500 A. Although a voltage that high is technologically difficult for the thermoelectric generator, it is so low that massive power conditioning is needed for use in electric propulsion. A previous study by the Jet Propulsion Laboratory (JPL)[8] reflects the severity of the problem, power conditioning for electric propulsion there adding 70% to specific mass of that powerplant. For SP-100, 5 kg/kWe was optimistically taken as the specific mass of thrusters and power conditioning, the total then being 59.22 kg/kWe. For various values of specific impulse, efficiency of ion thrusters was taken from Ref. 9.

Because this 100-kWe nuclear powerplant will most likely be used in near-term applications, boosting payloads on one-way trips from LEO (arbitrarily, at a 1000-km altitude) to GEO is emphasized. In shifting the orbit plane by 28.5 deg, the thrust vector was slued as a function of azimuth angle during the ascent from LEO to GEO, total delta-V being 5585 m/s. For each given time for transit from LEO to GEO,

Table 1   Component masses for SP-100

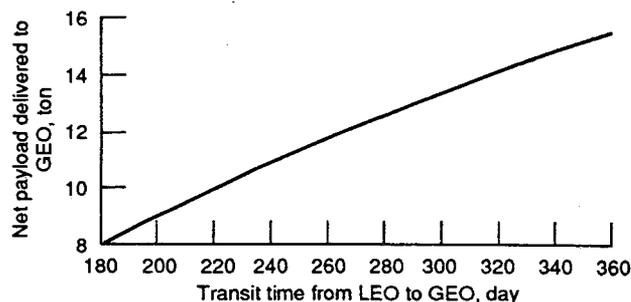| Component	Mass, kg
Reactor	803
Shield	1255
Primary heat transport	632
Reactor's instruments and control	359
Power generation	409
Heat rejection	1027
Power conditioning	399
Mechanical/structure	538
Total mass, kg	5422

Fig. 1   One-way to GEO by way of the SP-100 powerplant. 1300 K; reactor + shield = 3049 kg.

one value of specific impulse delivers the largest payload fraction, herein referred to as "the optimum specific impulse." As shown by Fig. 1, 8–16 metric tons of net payload can be boosted to GEO by SP-100 in 180–360 days, and optimum specific impulse ranges from 2500 to 4000 s. Inasmuch as SP-100 itself would also be delivered, some fraction of its mass (the fraction of its 100 kWe useful to the payload) could be added to this net payload. Larger payloads are possible, but only if longer transit times are accepted. In Fig. 1, each net payload delivered also corresponds to a specific initial mass in low Earth orbit (IMLEO), and these values of IMLEO vary from 17.5 to 24.8 tons. If IMLEO were fixed, the results would generally lie below and to the right of the curve shown, the two curves being tangent at a single point. Figure 1 shows the best that SP-100 can achieve, the imposition of constraints, such as fixed IMLEO, somewhat impairing its performance.

Brayton + 2500-kW Reactor

The low efficiency of SP-100 has a dominating influence on its specific mass, for at 100 kWe, the specific mass of the nuclear heat source alone is 30.49 kg/kWe. Also, each kilowatt of electric power is valuable in its own right. With its overall efficiency of the order of 30% already demonstrated, the Brayton cycle offers the potential for about 750 kWe from the SP-100 reactor, and thereby to cut specific mass. Gas turbines are widely used here on Earth at about 1500 K to generate powers up to 200 MWe and to propel aircraft. In a space-technology program, this terrestrial technology was sharply scaled down to the level of 10 kWe in combination with the peak cycle temperature of 1150 K. A 10-kWe powerplant, tested for over 38,000 h, achieved the overall efficiency of 29%; modification and retest of its components show that it has the potential for overall efficiency of 32% (Ref. 10, p. 13).

The Stirling engine also has the potential for comparable efficiencies of power generation at moderate powers, but its state of technology is more rudimentary than Brayton's, and its capacity to grow to hundreds of kilowatts of electrical power is limited by rising specific mass and falling efficiency.[11] Neither the potassium-Rankine cycle nor AMTEC has shown the potential for efficiencies approaching those of Brayton, and their potential for power generation from this SP-100 reactor is therefore more limited than Brayton's. In addition, the Brayton cycle, not being tied to any given temperature for phase change (as from liquid to vapor) has great potential to evolve in a succession of modest increments in operating temperature. The Brayton cycle is therefore emphasized as the principal alternative to thermoelectric power generation. To provide margin in the SP-100 reactor program, reactor-outlet temperature is cut by 150 K and subsequently restored to its current value of 1350 K. Concurrently, turbine-inlet temperature will evolve from 1150 to 1300 K.

1150 K Brayton

For those powerplants, the nuclear heat source mass is 3049 kg and output 2500 kW, as before. Other components are scaled from Ref. 1, a study of 400-kWe reactor-Brayton pow-

erplants directed by JPL. In directing this study,[1] JPL specified that the Brayton components be designed for 120,000 h of operation at full power (about double the life JPL required of competing thermoelectric powerplants) and that power generation incorporate 100% redundancy. Because redundancy is mass-extravagant, modular construction of the powerplant is assumed herein in combination with a mission strategy that accepts some loss of power (see the following discussion). The mass of the waste-heat radiator was taken as 6 kg/m², a representative value.

For a heat input of 2500 kW and turbine-inlet temperature of 1150 K, the attainable power and specific mass are shown by Fig. 2. Each point plotted is a possible design point and represents a specific combination of independent variables, chiefly compressor pressure ratio and compressor-inlet temperature. In Fig. 2, the recuperator effectiveness E of 0.9 yields minimum specific mass at the power level of 700 kWe. Despite the 150 K reduction in reactor-outlet temperature, substitution of Brayton for thermoelectric power generation raises useful power from 100 to 700 kWe, and powerplant specific mass decreases from 54 to 17 kg/kWe.

For ion propulsion with a dynamic power system, the synchronous alternator can match the voltage of the thruster's principal load, only rectification and filtering being needed. Even for secondary loads, power conditioning would be efficient and of low mass because of the high voltage generated. For these reasons, the combined specific mass of the thrusters and their power conditioning was taken as 2 kg/kWe, notwithstanding that a specific mass this low has not yet been demonstrated for the complete thrust subsystem. The total specific mass of powerplant, power conditioning, and thrusters was 19 kg/kWe.

On one-way trips from LEO to GEO (Fig. 3), this 700-kWe powerplant can deliver 63 tons of net payload in 180 days, roughly eight times what SP-100 can deliver. Alternatively, 39 tons could be delivered in 100 days, performance
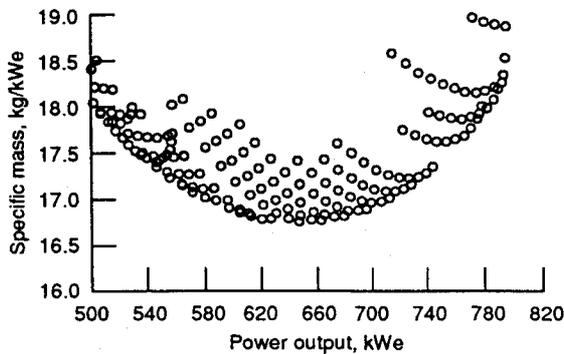
beyond the capacity of SP-100. Optimum specific impulse ranges from 2600 to 5400 s. For the payloads of 39 and 63 tons, the corresponding values of IMLEO are 65 and 88 tons, respectively. If IMLEO were instead constrained to some fixed value, this constraint would impair performance, just as for SP-100. On the other hand, modular construction of the Brayton powerplant (perhaps seven 100-kWe modules) would aid adaptation of the powerplant to this constraint, an approach permitting payload fractions close to the optimum for selected transit times. (See the section entitled "One-way Trips from LEO to LLO.")

The essential point to be drawn from this comparison of high-temperature thermoelectric (1300 K) and low-temperature Brayton (1150 K) power generation is that very large performance gains are achievable in a program of lower risk, and thereby, most likely of lower cost. The reduction in reactor-outlet temperature from 1350 to 1200 K would reduce the risk in operating the reactor successfully, and therefore, likely permit the reactor to be brought into useful service in a briefer time and at lower cost. Generation of 700 kWe from 2500 kW requires an overall efficiency of 28%, less than the 29% already demonstrated.[10] That 150 K reduction in reactor-outlet temperature could be treated as pure margin in the reactor-Brayton program, permitting early benefits from its early completion, but the performance potential need not be forgone. After a period of successful testing at 1200 K, reactor-outlet temperature might be raised in successive increments to the rated 1350 K. This evolutionary approach reduces the costs, risks, and time to bring a new technology into useful application without sacrificing, over the long term, any of the performance of which the concept is capable.

1300 K Brayton

With reactor outlet at 1350 K, turbine-inlet temperature could be raised to 1300 K (Fig. 4) by using the same structural alloy (PWC-11) as SP-100. With emphasis on high-power output, recuperator effectiveness of 0.92 was chosen in order to minimize specific mass at the power output of 850 kWe, specific mass being 13.6 kg/kWe and overall efficiency 34%. At the increased operating temperature, power output increases and specific mass decreases.

For boosting payloads to GEO, an NEP truck utilizing this Brayton powerplant could operate on either one-way or RT, only RT being shown, for brevity, in Fig. 5. Inasmuch as these RTs will bring a "hot" nuclear reactor with its accumulation of fission products back to LEO, they present new operational problems and constraints. Chief among these constraints will be the minimum LEO altitude to which such a reactor might be brought, perhaps 1000–2000 km. A crucial question is whether or not the truck might inadvertently descend out of control to altitudes below those judged safe. Fortunately, any NEP craft en route from GEO to LEO will descend slowly, the transit from GEO to LEO taking several weeks. Progress of the spacecraft could be continuously monitored during this

Fig. 2 SP-100 reactor + Brayton cycle for 2500 kW and 1150 K. Cycle temperature = 1150 K; reactor + shield = 3049 kg; E = 0.90.

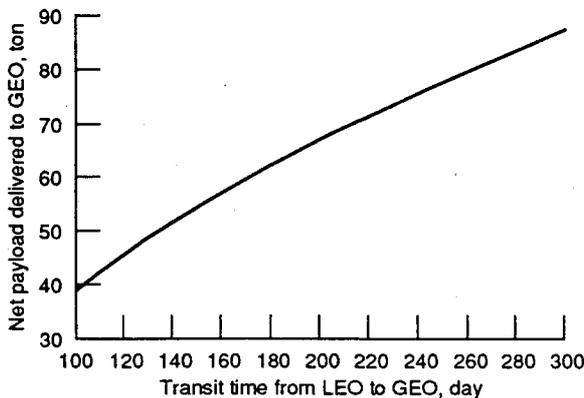**Fig. 3 One-way to GEO by way of the SP-100 reactor + Brayton power generation. 1150 K; reactor + shield = 3049 kg.**
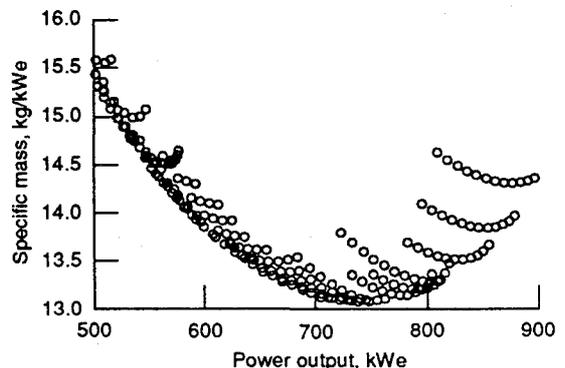
Fig. 4 SP-100 reactor + Brayton cycle for 2500 kW and 1300 K. Cycle temperature = 1300 K; reactor + shield = 3049 kg; E = 0.92.
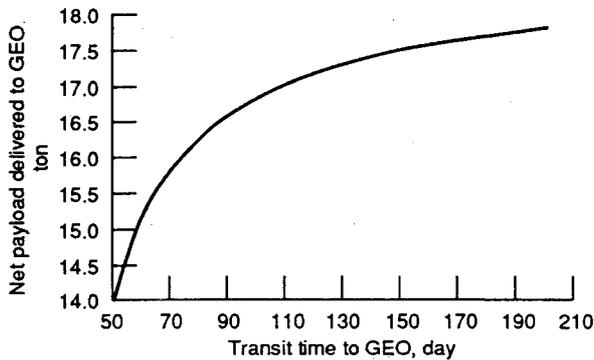
Fig. 5　Optimum roundtrips, LEO to GEO. Powerplant: 850 kWe at 15.6 kg/kWe.
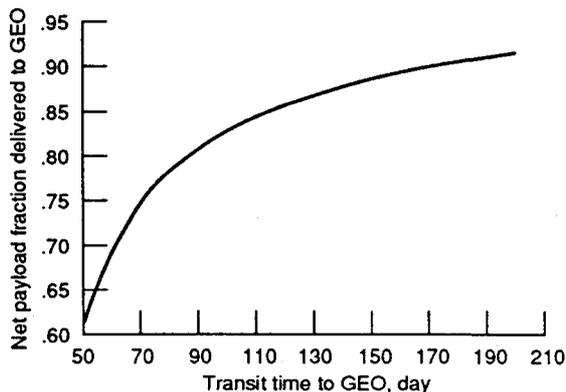

Fig. 6　Optimum roundtrips, LEO to GEO. Powerplant: 850 kWe at 15.6 kg/kWe.

transit. If the vehicle's path were to depart from nominal, the thrusters could be commanded to turn off and the powerplant to shut down, the spacecraft then following a highly predictable and reliable ballistic path. Failing that, further drastic action might be taken. A firm delineation of what is practical here has yet to be worked out.

On the first flight of such an NEP truck, the truck itself must be launched along with the payload, plus propellant sufficient for a RT. The increase in propellant for a RT will slightly diminish this first payload below that for a one-way trip. However, for subsequent trips, only the payload, plus the propellant sufficient for a RT, need be launched into LEO. Figure 5 focuses on RTs after the first. The total specific mass of 15.6 kg/kWe includes 2 kg/kWe for power processing and ion thrusters, as before. Payloads deliverable to GEO range from 17 to 18 tons for transit times from 100 to 200 days; the corresponding masses boosted to LEO range from 20 to 21 tons, and the payloads delivered to GEO exceed 80% of the mass boosted to LEO (Fig. 6). This large payload fraction is a distinct advantage of NEP on RTs. Optimum specific impulse ranges from 7400 to 15,000 s, values pushing the state of the art even for ion thrusters.

Let's next consider power loss from failure of a Brayton power module and its impact on mission capability. Consider, for example, that we have eight Brayton modules boosting a 17-ton payload in 100 days (Fig. 5). Loss of the output of one module would decrease power to $\frac{7}{8}$ its rated value, and thereby stretch propulsion time to $\frac{8}{7}$ the planned time. The 17-ton payload would still be delivered to GEO, but in 115 days instead of 100. The performance penalty from partial loss in power is therefore quite modest for those missions for which some power loss is contemplated and planned for.

Use of as many as eight Brayton power modules would likely add to powerplant mass in comparison with, e.g., just 1 or 2 larger power modules. In general, design and development of power modules specifically for the power required

on a given flight would likely produce the lowest powerplant mass, but that new development would increase program cost and risk. Highest reliability could be realized through the use of multiple highly-developed, proven power modules in combination with a mission strategy that accepts partial loss of power.

Power for the Moon and Mars

Nuclear powerplants developed and applied in these ways can also be installed on the Moon and Mars in order to supply power to laboratories or other installations there. Long periods of successful operation in NEP trucks shuttling between LEO and GEO (as in Fig. 5) would assure us of the potential for long-term operation on the lunar surface and on Mars. Modular construction makes the powerplant tolerant of failure and provides program flexibility in meeting smaller demands for power. On the surface of either the Moon or Mars, the refractory-metal alloys in the SP-100 reactor and its power modules require an enclosure to protect them from environmental contamination. In either case, atmospheric pressure is so low that the mass of the enclosure can be quite small, the enclosure for the Moon likely being suitable on Mars as well.

The NEP truck using the SP-100 reactor and evolved for boosting payloads from LEO to GEO (Figs. 3 and 5) would be suitable for detailed mapping of the Moon, Mars, and its satellites before selection of the landing sites. For an astronomical observatory on the Moon's far side, continuous communication with Earth will require a relay in lines-of-sight from both the Earth and the lunar observatory. The same NEP spacecraft used for hauling payloads from LEO to GEO could transport that communication relay to its stationary point, power its communication receiver and transmitter, and provide the low-thrust propulsion needed for stationkeeping and for attitude control. Personnel on the Martian surface will require a comparable communication relay, and NEP trucks could similarly transport and power those relays. The near-term applications of NEP trucks can therefore provide extensive support for various phases of the SEI missions.

Nuclear-Electric Propulsion to Low Lunar Orbit

One-Way Trips from Low Earth Orbit to Low Lunar Orbit

If lower recuperator effectiveness in Fig. 4 is lowered to 0.83, then the Brayton cycle can produce 700 kWe from the SP-100 reactor's 2500 kW; the total mass of the powerplant is about 9118 kg, 3049 kg for the nuclear heat source and 867 kg apiece for seven 100-kWe Brayton modules. Varying the number of modules readily adapts the powerplant to a wide range of launch masses, payloads, and delivery times. Two to seven of those power modules permit boosting the following payloads on one-way trips to LLO in 120 days; the corresponding values of IMLEO are also given (Table 2).

Reducing Transportation Costs

Permanent residence on the Moon will eventually make such one-way trips uneconomical, for that one-time use of an NEP truck requires the manufacture and launching of a new truck for each flight. Although RTs between LEO and LLO would reduce transportation costs, the higher powers for that service require development of a new, larger powerplant. That new powerplant would, of course, also be valuable for transport of cargo to Mars and perhaps of people as well, and its repeated use between LEO and LLO would make us con-

Table 2　NEP from LEO to LLO in 120 days, using the SP-100 nuclear heat source and 100-kWe Brayton power modules

Total power, kWe	200	400	600	700
Payload, ton	5.8	15	24	28
IMLEO, ton	14	27	41	48

fident of its durability for the Martian missions. Because the 2.5-MW output of the SP-100 reactor is inadequate for these higher powers, reactor redesign[12] for outputs of 10 and 50 MW was studied, interpolation among the 2.5-, 10-, and 50-MW reactor designs providing herein the heat-source masses for various levels of thermal power.

Performance might also be improved through replacing SP-100's niobium alloys by tantalum alloys. For ASTAR-811C (Ta-8W-1Re-0.7Hf-0.025C), 98 individual creep tests spanned temperatures of 1144–1972 K, stresses of 3.45–344 MPa, and test duration of 314,140 h (35.8 yr).[13] Correlation of these test data shows that this alloy will creep 1% in 10 yr (not rupture) at 1) 28 MPa and 1500 K or 2) at 9 MPa and 1700 K,[14] an allowance of two standard deviations being included. Limited testing of other, stronger Ta alloys shows that temperatures 200 K higher might also be practical.[15] Reactor fuel pins using uranium-nitrate (UN) fuel and Ta-alloy clad have been tested for a total of 342,000 h, of which 19,000 h were at clad temperatures of 1600 K or above, and 31,000 h at 1550 K or above.[16,17] Because of the high density of the Ta alloys, 10% was added to the estimated masses of the nuclear heat sources in Ref. 12. Under these conditions, the mass of a 40-MW nuclear heat source is estimated to be 16 tons.

1500 K Brayton

From this 40-MW nuclear heat source, a 1500 K Brayton powerplant with recuperator effectiveness of 0.85 can generate 12 MWe (Fig. 7), its overall efficiency being 30%. Minimum specific mass is 6.2 kg/kWe, and radiator area is 0.4 m²/kWe. Specific mass of the radiator is 2.4 kg/kWe, mass per unit area being taken as 6 kg/m². In general, a Rankine-cycle powerplant having the same turbine-inlet temperature can reduce radiator area to about one-third that size. However, the high temperature of the Rankine radiator will restrict its materials to those of high density and will impair the effectiveness of extended surfaces (fins). In turn, the specific mass (kg/kWe) of a competitive potassium-vapor Rankine powerplant will be only marginally lower than Brayton's. If we generate megawatts of power by any of these approaches, the waste-heat radiators will be so large that compaction for launching and either erection or assembly in space are required. The comparatively small radiators for the Rankine cycle will continue to be a distinct advantage in this respect. The means for compacting any of these radiators for launching and for either erecting or assembling them in space have yet to be evolved.

Roundtrips Between Low Earth Orbit and Low Lunar Orbit

To the 6.2 kg/kWe for the powerplant (Fig. 7), 2 kg/kWe for power conditioning and thrusters was added, as before. For a resupply mass of 150 tons in LEO, 125 tons of payload can be placed in LLO in 100 days (Fig. 8), payload fraction being 0.83 and optimum specific impulse 10,500 s. Return to LEO takes 42 days, the RT time of 142 days fitting comfortably within a 6-month resupply period. For this class of launch vehicle and NEP truck, very large payloads can therefore be placed in LLO in time periods acceptable for transportation
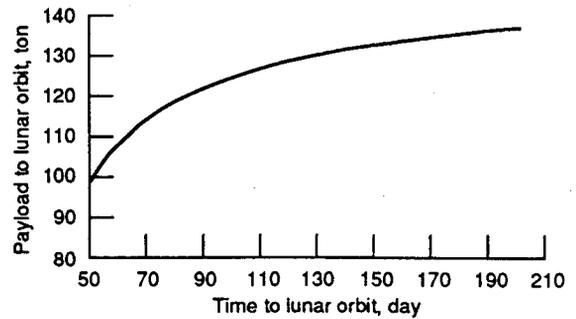

Fig. 8 Optimum lunar roundtrips, LEO to LLO. Resupply mass in LEO, 150 tons.

of cargo. For transit times ranging from 100 to 200 days, optimum specific impulse varies from 10,500 to 22,000 s, extending beyond the range of experience even with ion thrusters. Throughout this range, ion thrusters have substantial advantages over magnetoplasmadynamic (MPD) thrusters, not only in both efficiency and thrust, but also in state of technology.[18,19]

Preparing for Missions to Mars

Before actually sending people to Mars, we need to gain confidence in all the means required for doing that. Even in the near term, we can begin programs that are not only useful in their own right, but will also contribute to the confidence requisite for the flight of people to Mars. In a properly chosen succession of program steps, each of modest cost and modest risk, the knowledge and experience gained from each step could give us confidence in the succeeding step. By this approach, a venturesome future could progressively build on a successful past. NEP of payloads to GEO, LLO, and related destinations has already been discussed at considerable length herein. Such an NEP truck would also enable difficult scientific missions to the outer planets (e.g., Neptune or Pluto[20]) to comet and asteroid rendezvous, and out of the ecliptic plane. Choosing to execute these future missions in ways consistent with attaining the goals of SEI could add to our confidence of safely reaching these goals.

But we need a basis for that choice; the broad plan for carrying out the SEI program needs to be delineated. In turn, this formulation of a broad, comprehensive plan for SEI would reciprocally strengthen SEI through the contributions of these subordinate, correlative efforts. At each step, candidate technologies, system developments, and missions could be evaluated for their contributions to achieving the principal goals of SEI. Those steps that are digressions or dead-ends could be pruned from the program. A good example is photovoltaic power for use on the lunar surface; for continuous delivery of hundreds of kilowatts of electric power, the mass of energy storage alone for such a powerplant is prohibitive (over 200 kg/kWe, perhaps 10 times the value for reactor-Brayton). In contrast with successive development of both photovoltaic and nuclear powerplants, focusing all those resources onto the essential, nuclear powerplant would yield a more highly developed, and thus, more reliable nuclear powerplant.

One might also ask how current, existing programs, as well as future ones, can contribute to our preparations for permanent residence on the Moon and for the ultimate flights of personnel to Mars. In particular, how might we utilize the Space Station Freedom to investigate important aspects of nuclear-power generation? Also, emphasis on what class of electric thruster would most contribute to attaining the ultimate goals of SEI?

Solar-Brayton power generation has already been proposed for the Space Station. In storing heat for use in the Earth's shadow, molten lithium, with its large sensible heat, would halve the mass of the fusible salt previously considered.[21] Such a solar-Brayton powerplant would be a valuable precursor of
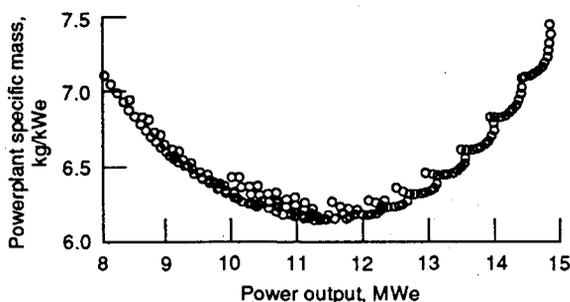

Fig. 7 Brayton power generation plus 40-MW SP-100 reactor. Temperature = 1500 K; reactor + shield = 16 tons; E = 0.85.

Table 3 Thruster specific impulse for selected missions to GEO and LLO

Peak temperature, K	Power, kWe	Trip	Transit time, day	Payload, ton	Specific impulse, s
1,150	700	1-way to GEO	100	39	2,700
1,300	850	RT to GEO	100	17	7,400
1,500	12,000	RT to LLO	100	125	10,500

reactor-Brayton, both using molten lithium to supply heat to the Brayton power generator. In this way, solar-power generation aboard the Station could increase confidence in the nuclear-power program.

The results also provide a perspective on the electric thrusters needed for this program. Consider, for example, optimum specific impulse in Table 3 for the following missions selected from Figs. 3, 5, and 8.

Although we might debate selection of either ion or MPD thrusters for the earliest mission listed, the selection for the more attractive missions is clear: for the range of specific impulse that these missions require (5000 s and above), the current technology for the MPD thrusters is simply not competitive with the efficiency and the values of thrust/power of the ion thrusters.[18,19] If, as herein proposed for power generation, the SEI program were to emphasize, even for the earliest missions, the thruster concept having the greatest long-term benefit to the SEI missions, then we should exploit the ion thrusters for all three of these applications. Through, once again, such repeated application of a single concept for propulsion, we could gain for the thrusters the same confidence in their performance and durability as we would for the power generating systems.

Concluding Remarks

1) As NASA contemplates sending personnel on long-term missions to the Moon and to Mars, technologists and mission planners are jointly responsible for delineating the costs and risks involved and for formulating program plans that will reduce these costs and risks. In planning for reduced costs and risks, a crucial aspect is program continuity, i.e., continuing application of a given technology over a period so that experience will accumulate from extended testing here on Earth and from a diversity of applications in space.

2) Nuclear power in space differs in kind from chemical and solar power, not just in degree. Its distinctive features include design life of 10 yr or more, compactness, and, most important, the capacity to produce power in either sunlight or darkness. The concern for nuclear safety must, of course, also be encompassed by the program.

3) Because of the long durations of space missions for which nuclear power is contemplated, development of nuclear power takes a long time (10 yr or more). The most trustworthy demonstration of long-term performance and endurance of a given powerplant concept would be through its actual utilization in space. For these reasons, there is great value in a programmatic approach to nuclear power that utilizes a single concept for power generation in widespread applications.

4) In general, design of a nuclear powerplant for its first application should include considerable design margin, an approach not only decreasing the time for development of the powerplant, but also diminishing the cost and risk in its initial development and application. That approach would also permit later evolution of the powerplant concept in a succession of modest steps, each of low cost and low risk and with future gains building on past successes. In this approach, the powerplant would evolve to its ultimate potential without any sacrifice in the performance to be ultimately achieved.

5) A lithium-cooled nuclear reactor, such as SP-100's, is compact and suitable for use with several types of power generators. Among these, the Brayton cycle, with its high efficiency and long life already demonstrated, can produce the most power from this nuclear heat source, and can thereby

extend the reactor's range of application and increase its value. Inasmuch as the Brayton's working gas is not tied to a given boiling temperature, a given Brayton powerplant can operate over a considerable range of turbine-inlet temperature, a feature permitting the incremental, evolutionary approach proposed herein for the reactor and its power generator.

6) From the 2500-kW SP-100 nuclear reactor currently planned, the Brayton-cycle powerplant concept can generate 700 or 800 kWe rather than 100 kWe from the thermoelectric power generator, can reduce powerplant specific mass by $\frac{2}{3}$, and can simultaneously reduce program risk by lowering reactor-outlet temperature from 1350 to 1200 K, the 150 K reduction being pure design margin. In its early application to NEP, this Brayton powerplant can boost 39-ton payloads on one-way trips from LEO to GEO in 100 days, far beyond what thermoelectric power generation can achieve. In contrast, thermoelectric generation is dead-ended in its power output from that reactor.

7) Through use of an available refractory-metal alloy (AS-TAR-811C), the reactor-Brayton concept appears capable of operation at higher powers (12 MWe) and higher temperatures (1550 K), enabling its application in an NEP truck hauling cargo on RTs between LEO and LLO. From 150 tons boosted to LEO, that NEP truck could deliver 125-ton payloads to LLO in 100 days.

8) That same 12-MWe powerplant and its ion thrusters are a promising candidate for exploration of Mars, for transportation of cargo from LEO to orbit about Mars, and for return of materials from Mars to Earth. The same concept also merits further study for transportation of personnel to Mars and return.

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