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Multi-Reactor Power System Configurations for Multimegawatt Nuclear Electric Propulsion

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MULTI-REACTOR POWER SYSTEM CONFIGURATIONS FOR MULTIMEGAWATT NUCLEAR ELECTRIC PROPULSION

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ABSTRACT

A modular, multi-reactor power system and vehicle configuration for piloted nuclear electric propulsion (NEP) missions to Mars is presented. Such a design could provide enhanced system and mission reliability, allowing a comfortable safety margin for early manned flights, and would allow a range of piloted and cargo missions to be performed with a single power system design. Early use of common power modules for cargo missions would also provide progressive flight experience and validation of standardized systems for use in later piloted applications. Systems and mission analysis are presented to compare single and multi-reactor configurations for piloted Mars missions. A conceptual design for the "Hydra" modular multi-reactor NEP vehicle is presented.

INTRODUCTION

The ambitious goals of NASA's Space Exploration Initiative, a renewed presence on the Moon leading to manned missions to Mars, will be enhanced, and possibly enabled, by the reductions in vehicle masses and trip times afforded by advanced propulsion systems. Low thrust nuclear electric propulsion (NEP) systems can offer substantial performance increases and mass savings over conventional chemical rockets for lunar and Mars cargo flights and piloted Mars missions. Inherent in this assumption, however, is the use of a highly reliable power supply. Traditional NEP vehicle configurations have tended to rely on power supplies featuring only a single reactor. Although it will presumably be possible to construct highly reliable nuclear power systems, this reliability will be difficult if not impossible to verify without many years of operating experience. Use of a modular, multi-reactor NEP power system and vehicle architecture could provide enhanced system and mission reliability, allowing an increased safety margin for early manned flights, and would allow a range of piloted and cargo missions to be performed with a single power system design. Additionally, early use of common power modules for cargo missions would provide progressive flight experience and validation of standardized systems for use in later piloted applications.

ADVANTAGES AND DISADVANTAGES

Reliability

Modular, multi-reactor power system and vehicle architectures offer the potential for enhanced system and mission reliabilities. The subject of reliability is a very complex one, and it is beyond the scope of this short paper to address this issue quantitatively. However, some qualitative observations can be made.

Two different forms of reliability are of interest. The first, system reliability, represents the probability that power system hardware will provide a designated power output throughout the design system life, and is a function of component failure rates, system configuration, and the number of redundant, or spare subsystems provided. Some failure is acceptable as long as sufficient backup components are available. A multi-reactor system, when designed with redundant reactors, will provide a higher system reliability than is achievable with a single reactor system, given comparable component failure rates. This redundancy may be especially desirable as a safety margin for early flights.

The second, more critical form of reliability is mission reliability. Mission reliabilty represents the probability that a given mission will be able to safely return a crew to Earth, and is a function of the system hardware reliability, contingency propellant, mission design, and the operating characteristics of the propulsion system. A modular multi-reactor system without excess, spare power generation capacity will actually result in a lower system reliability than the single reactor due to the greater number of parts which might fail. However, due to the availability of partial power in the event of a single point failure in one module, mission reliabilty would actually be enhanced. The inherent mission flexibility afforded NEP by high specific impulse and long thrusting times can allow abort modes which would compensate for partial power losses in the unlikely event of a reactor failure [1].

Thus, with or without reactor redundancy, a multi-reactor configuration will provide enhanced mission reliability and crew safety, although at some mass and mission performance penalty.

Modularity

In addition to the potential for higher system and mission reliability, other benefits exist for a multi-reactor configuration. If the multi-reactor system is designed in a modular fashion, each module in itself an autonomous power system with reactor, power conversion and heat rejection elements, the power system and NEP vehicle can be tailored to meet a variety of power levels and mission goals. Combinations of one to four 5 MWe power modules, for example, could perform a range of progressively more demanding objectives from lunar and Mars cargo missions to piloted Mars missions. Flexibility to redeploy power modules at the Moon or Mars would also be allowed, enhanced by the reduced power requirements of lighter returning transfer vehicles.

A modular NEP vehicle will be easier to assemble in Earth orbit than a single large 10-20 MWe system, directly addressing concerns of constructing such large vehicles. The smaller modules, on the order of 5 MWe, could conceivably be made largely or completely self-deploying, greatly reducing manned on-orbit construction requirements. A modular design would also allow ease of repair and refurbishment, aiding turn-around of reusable vehicles. Finally, a modular power system configuration would result in a smaller and lighter launch package per module, reducing minimum launch vehicle requirements from 70-100 MT for a single 10 MWe system to 35-50 MT for a 5 MWe module.

Commonality

Commonality with other propulsion and surface power applications can be achieved for multi-reactor NEP systems through the use of standardized reactor and/or power conversion elements. Programmatic advantages enabled by common systems and technology include reduced development and production cost, as well as potentially reduced lead time for the higher powered systems. More importantly, commonality across power system elements could greatly enhance crew safety. Use of common power modules would also allow progressive flight experience and validation of standardized systems. Early utilization of single power modules in an evolving infrastructure, such as for lunar or Mars cargo missions, would result in well proven subsystem designs for use in later piloted multi-reactor systems. Early unmanned missions would then both fulfill their primary mission of cargo delivery, as well as serve as flight tests for piloted missions. Figure 1 illustrates a family of cargo and piloted NEP vehicles derived from common 5 MWe power modules.

Mass and Performance Penalty

A variety of compelling advantages are seen for going to a multi-reactor power system, but these advantages do not come without cost. Economy of scale would indicate that multiple smaller reactor power systems will be heavier than a single large system of equivalent net power rating. A multi-reactor power system can thus be expected to be heavier than a single reactor system of the same net power rating, although of potentially higher reliability.

Mission performance will also be impacted by selection of a multi-reactor vehicle concept. Mission performance for NEP vehicles is a direct function of the mass of the power and propulsion system for a given power output. A heavier system will require more propellant and an increased transit time. Thus, potential advantages of multi-reactor systems, especially with respect to enhanced crew safety, must be carefully weighed against the mass and mission penalties incurred. Each of these penalties will be examined later in this paper.

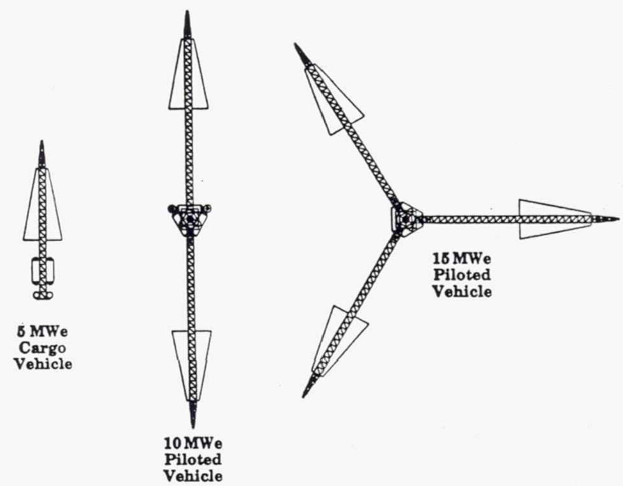

Figure 1: Family of NEP Vehicles

POWER AND PROPULSION SYSTEM DESIGN

System Concept

Two approaches exist for configuring multi-reactor power systems [2]. In the first, a single "integrated" power system would result from integrating multiple reactor subsystems into a single heat source heat exchanger unit, which would in turn feed multiple power conversion loops. This system would differ from a traditional single reactor power system only by the duplication at the reactor subsystem level, and a potentially more complicated heat exchanger design if it is desired to maintain the integrity of the various primary loops. The mass penalty for this concept over the mass of a single reactor concept would then result from the losses in economy of scale for the smaller reactors and primary loops over one large one, and in the potentially heavier heat exchanger design. Duplication at the reactor subsystem level would allow enhanced system reliability with redundancy, and less catastrophic failure modes. A single point failure in one reactor subsystem would not result in total power loss, but rather partial power loss with no built-in reactor redundancy, or no loss if excess capacity is provided. A drawback to this design is that the common heat exchanger still presents a potentially weak link. A failure in this component could still result in total system failure.

A second, "modular" approach for configuring a multi-reactor power system would have each reactor subsystem feeding into its own dedicated heat exchanger, secondary power conversion loops, and heat rejection subsystems. The total power system would thus be made up of completely separate and independent "power modules," each capable of producing power independently from the other units. This duplication at the entire system level would result in a heavier mass penalty over the "integrated" multi-reactor configuration, but would also prevent single point failures within one module from affecting the others. A worst case single point failure in one reactor, primary loop, or heat exchanger would only take out a fraction of the total system rating, rather than leaving the NEP vehicle completely powerless and stranded. The modular system would thus fail more "gracefully" than either the integrated or single reactor systems. Although single point failures in either the primary controls or electronic switching could still be postulated, the total number of potential single point failures should still be greatly reduced. The modular approach to multi-reactor power system design, in particular the "Hydra" multi-reactor configuration, is emphasized in this study [2].

A nomenclature is adopted in this study to distinguish between power systems with varying number of required and spare modules. The nomenclature utilizes the minimum number of power modules required to achieve the full, rated system output, followed by a "+" sign, followed by the number of spare modules, if any. Thus, a "2+1" modular power system would represent two required, and one spare module. Failure of any one module would still allow full power to be achieved with the other two. A "3+0" system would indicate a total of three modules, all of which are required to achieve the full power rating. Failure of one module would result in a 33 percent power loss. A "1+0" configuration would then default to a single reactor system. A single point failure within this module would result in a complete power loss.

System Technology Assumptions

This study assumes the use of "Growth" SP-100 lithium cooled reactors in conjunction with potassium Rankine power conversion. The SP-100-derived reactor subsystems utilize materials and technology currently being developed in the SP-100 program, scaled up from roughly 2.5 MWth to tens of megawatts. A recent study by General Electric supports the suitability of SP-100 reactor technology to thermal outputs of at least 50 MWth [3]. Suggested changes to the base technology include switching to an in-core control rod scheme versus external reflector control, and increasing the fuel burnup limit from 6 percent to 10 percent.

Although employing technology currently under development, a Growth SP-100 reactor will still be a new and larger reactor compared to that of the current program. However, by utilizing materials and technologies of the existing SP-100 space reactor program, while accepting their inherent temperature and performance limitations, programmatic savings in development cost, time, and risk should follow.

High efficiency and rejection temperature make potassium Rankine an attractive power conversion technology for achieving low specific masses in the multimegawatt range. However, technology issues of behavior and management of two-phase fluids in microgravity and turbine blade erosion must be addressed and solved for Rankine to be a viable option. Integration of Brayton power conversion, currently more mature and utilizing a single phase fluid, would likely entail a less expensive and shorter development program. However, a Brayton system with an SP-100-derived reactor would result in an additional 4-5 kg/kWe of specific mass over a comparable Rankine system, largely due to the larger and heavier heat rejection requirements of the Brayton [4]. Although not a large difference for cargo applications, this mass difference may prove an excessive mission performance penalty for piloted applications. Potassium Rankine was selected for this study as having the greater potential when used with the relatively moderate temperatures of SP-100 technology. Brayton power conversion would of course still be a logical candidate for use with more advanced, higher temperature reactor systems.

Ion thrusters utilizing argon propellant are baselined for the electric propulsion system. Ion thrusters are currently the most mature technology for processing megawatt power levels at high efficiency [5]. High efficiencies have already been demonstrated in the 5000-10,000 second specific impulse range, but for relatively small thrusters in the 10 kWe range. Recent performance predictions at LeRC indicate that thrusters in the few megawatt range could be developed, and would have operating lives of 10,000 hr [5].

It should be noted that this paper does not attempt to investigate the entire trade space of potential technologies for space nuclear power and electric propulsion. A collection of relatively modest technologies was assembled for the systems analysis presented in this report in order to leverage the benefits of existing reactor and thruster technology programs. This is not to say that these technologies are currently in hand. More aggressive technologies could be substituted to allow greater system and mission performance. The incremental mission benefit enabled must, however, be carefully weighed against the associated increased programmatic cost and risk.

System Specific Masses

Systems analysis was performed in order to investigate the performance potential of single versus modular multi-reactor power systems utilizing Growth SP-100 reactor technology, potassium Rankine power conversion, and argon ion propulsion. Requirements were for power levels from 5 to 100 MWe, a 10 year full power system life, and man-rated shielding. Effective full power lifetime for redundant modules operating in parallel at reduced power is proportionately reduced, but with enough burnup added to complete a final 2.5 year mission with the minimum number of units operating at increased, full power.

The Growth SP-100 reactor is a fast spectrum lithium-cooled pin type reactor with uranium nitride fuel and niobium refractory alloy cladding and structure. Reactor coolant outlet temperatures on the order of 1350-1375 K are assumed. A layered tungsten/lithium hydride shadow shield is utilized to enable a man-rated shielding requirement of 5 rem/yr at a 40 m diameter dose plane 100 m away. No shielding benefit was assumed from either the boiler or turbomachinery.

Heat transfer from the lithium primary loop to multiple potassium secondary loops occurs through a boiler, which is assumed to generate 1300 K potassium vapor to the turbines. A large 100 percent power conversion loop redundancy is assumed for the piloted 10 year life applications. Each power conversion loop contains a matched pair of counter-rotating turbine-alternator units for balanced angular momentum. Heat rejection utilizes two-sided planar heat pipe radiators. A radiator specific mass of 5.5 kg/m^2 is assumed over the total radiating surface area. Two sets of ion thrusters are carried to allow 20,000 hr of total thrusting time. The specific mass of each set has been estimated at roughly 0.5 kg/kWe, or 1.0 kg/kWe for two sets [5]. Power conditioning, management, and distribution is assumed to be 95 percent efficient, operate at 600 K, and have a specific mass of 2.5 kg/kWe.

Systems analysis was performed using a Lewis Research Center (LeRC) modified version of the ALKASYS system modeling code, and the aforementioned technologies and assumptions [6]. Minimum mass optimization for the 10 MWe single reactor system occurred at a condenser temperature of 900 K, and net thermal to electric efficiency of 20.8 percent. Total NEP power and propulsion system mass for the optimized single reactor 10 MWe system came to 98,700 kg, resulting in a total specific mass of 9.9 kg/kWe.

Figure 2 shows total power and propulsion system specific mass versus electrical power output for a single reactor power system and two different modular multi-reactor systems. Each system, regardless of the number of modules, contains 100 percent internal power conversion redundancy within each module. The standard single reactor system specific mass ranges from 10.7 kg/kWe at 5 MWe, to 8.2 kg/kWe at 100 MWe. Specific masses at 10 and 15 MWe were 9.9 and 9.5 kg/kWe, respectively. Small reductions in specific mass with increasing power are seen due to economy of scale. However, going to very high power levels alone will not result in greatly reduced specific masses. More substantial reductions in specific mass will need to be achieved through higher operating temperatures and more advanced power and propulsion technologies.

Two modular multi-reactor power system configurations were analyzed to investigate the associated mass penalty over a single reactor system. Each system carries three modules, but these modules are utilized in different ways. The "3+0" Hydra multi-reactor system consists of three independent power modules each operating at full rated capacity, with no spare modules. Thus, three 5 MWe units operating in parallel would result in a total power output of 15 MWe. Specific mass for this configuration ranged from 13.7 kg/kWe at 5 MWe total output, to 9.0 kg/kWe at 100 MWe. System specific masses at 10 and 15 MWe were found to be 11.8 and 11.0 kg/kWe. Dividing the standard single reactor system into three independent modules is thus seen to result in a specific mass penalty of roughly 2 kg/kWe at 10 MWe, and 1.5 kg/kWe at 15 MWe. This mass penalty can be attributed to both a reduced economy of scale and a more complex shielding geometry for the smaller power units.

The "2+1" Hydra modular system requires only two modules to achieve full rated capacity, but carriess an additional, redundant power module. This 50 percent module redundancy, in addition to the 100 percent power conversion redundancy within each module, should be expected to allow a very high level of system reliability. System specific masses to achieve this reliability ranged from 15.9 to 11.1 kg/kWe from 5 to 100 MWe. At 10 and 15 MWe respectively, specific mass came to 14.4 and 13.6 kg/kWe. Thus, carrying a complete redundant power module to insure very high levels of reliability will result in system specific mass penalties of 4.5 kg/kWe at 10 MWe, and 4.1 kg/kWe at 15 MWe over the single reactor system.

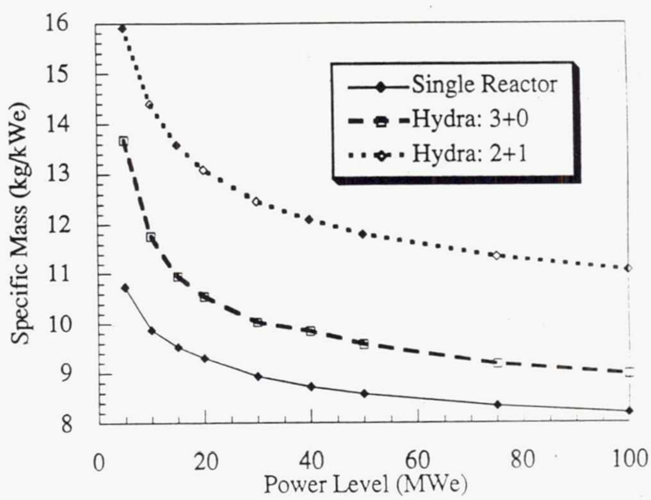

Figure 2: Comparative Single vs. Multi-reactor NEP System Specific Mass

NEP VEHICLE CONCEPT

A conceptual multi-reactor NEP transfer vehicle for a piloted Mars mission is presented in Figure 3. The vehicle utilizes a modular "Hydra" configuration of three 5 MWe power modules operating in parallel for a total system output of 15 MWe [2]. Each module consists of a roughly 25 MWth reactor, shadow shield, potassium Rankine power conversion elements, and primary and secondary two-sided planar heat pipe radiators. A 100 m separation distance between reactor and crew is enabled by a 4 m square self-deploying boom. High voltage alternating current is transmitted along the boom to the power conditioning and propulsion modules at the center of the vehicle. Propulsion in this example is achieved via argon ion thrusters. Each thruster processes 1.25 MWe with

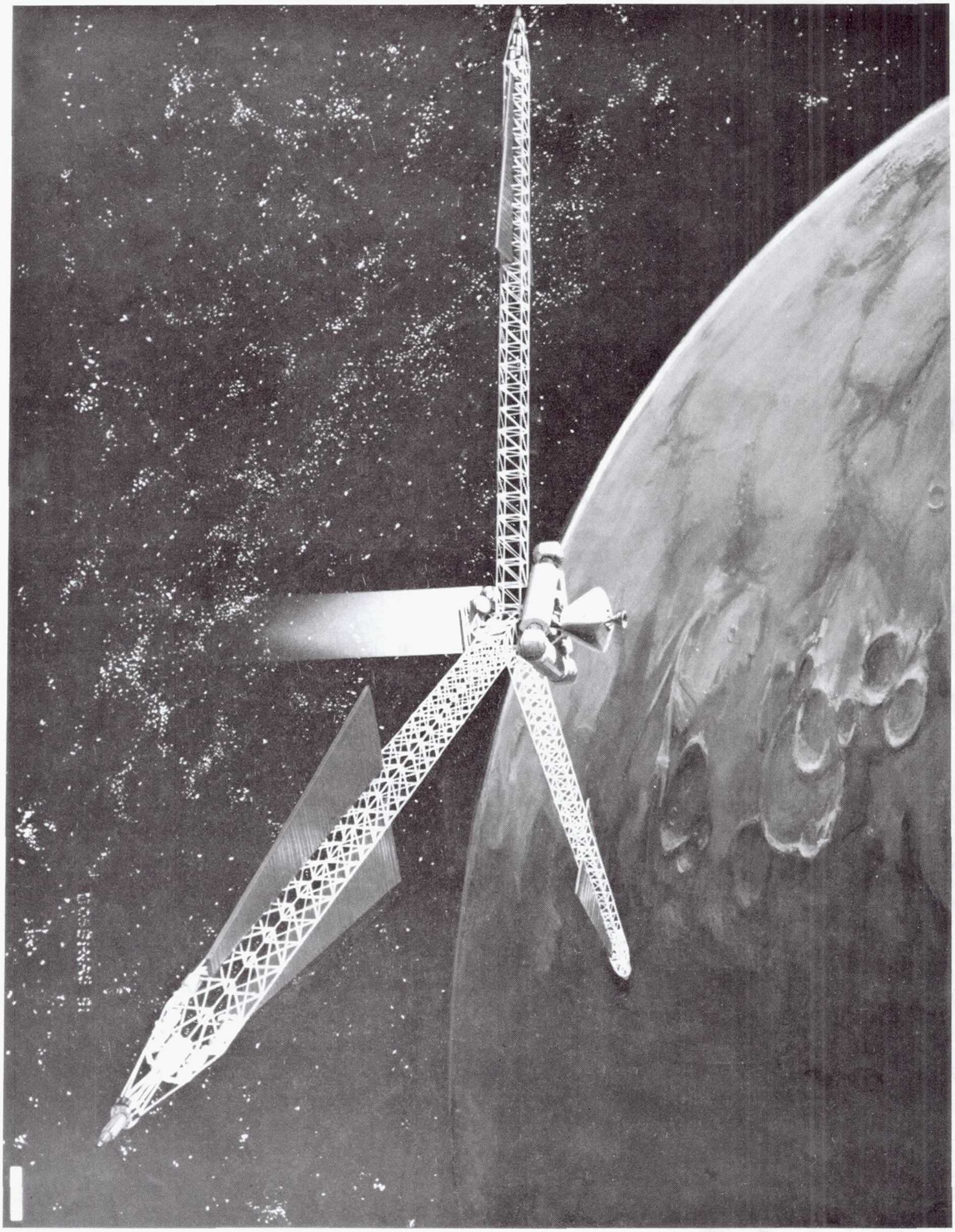

Figure 3: Conceptual Design for a 15 MWe "Hydra" Modular Multi-Reactor Piloted Mars NEP Vehicle.

efficiencies ranging from 70-80 percent at 5000-9000 sec specific impulse [5]. Cryogenic argon propellant storage tanks are located near the thrusters.

The three power modules radiate from a central "hub" module about the central axis. Integration of power modules to the hub assembly would utilize carriages traversing a ringed or tracked assembly about the hub module, allowing various numbers of modules to be rotated and configured symmetrically about the vehicle central axis. Asymmetric boom configurations could be used to counteract an unbalanced payload center of mass. The deployable boom canisters could be mounted directly to these carriages.

Space Station Freedom derived habitat modules, housing a crew of four to six, are illustrated along with a Mars descent/ascent vehicle about the central axis of the vehicle. An airlock would provide access from the habitat modules to the lander. These payload items, as well as the propulsion modules and propellant tanks, would be directly mounted to the central hub module, allowing sufficient clearance for the power modules to be reconfigured if desired.

MISSION PERFORMANCE

Mission analysis results are presented for a reference 2016 opposition-class piloted Mars mission in order to characterize the relative performance of single versus multi-reactor NEP system configurations over a range of power levels. The mission analysis was performed by SAIC under Task Order Contract to LeRC [7]. An "All-Up" mission design was assumed wherein a single vehicle is used to transport both cargo and personnel. The mission departs from, and returns to, a low earth orbit (LEO) of 407.5 km altitude, analogous to Space Station Freedom. Mars staging occurs at Deimos altitude. An outbound payload of 124 MT is carried to Mars, with 40.3 MT returned to LEO. Mars surface stay time is at least 30 days.

The crew is assumed to rendezvous with the NEP transfer vehicle just prior to Earth escape via a high thrust crew "taxi" in order to minimize crew radition exposure to the Earth's charged particle belts. Just after Earth capture on the return leg, the crew will re-rendezvous with the taxi for return to low earth orbit. The mass of this vehicle is not included in the following mission results. Specific impulse, launch date, and leg times were optimized for minimum mass for a range of trip times and power levels. Piloted trip time is defined as the total mission length minus Earth spiral times.

Figure 4 presents Initial Mass in Low Earth Orbit (IMLEO) versus piloted trip time for the single reactor, 3+0, and 2+1 multi-reactor configurations investigated in the above systems analysis section. The three broad curving lines stretching from upper left to lower right represent the "optimal power" curves, or mission boundary envelopes, for each configuration. A given set of technologies configured in a given manner to form an NEP system will possess the characteristic performance represented by its optimal power curve. Achievement of

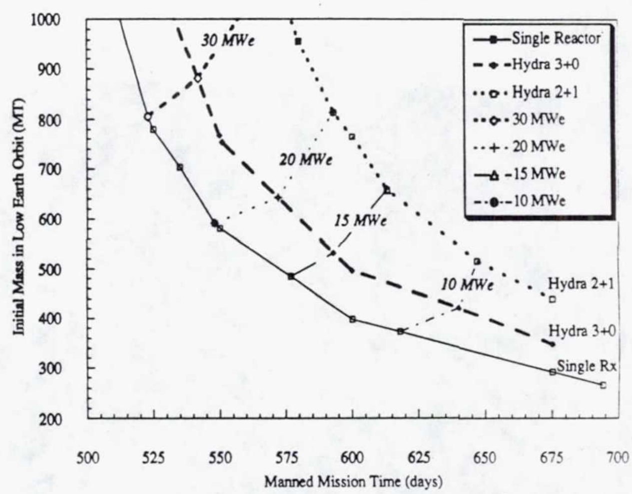

Figure 4: Comparative Piloted Mars Mission Performance.

decreasing trip time along these lines requires increasing IMLEO, increasing system power level, and decreasing specific impulse. Missions to the left of a respective line are not possible for the assumed configuration and technologies. Missions to the right are possible, yet non-optimal.

The optimal power curves are a direct function of the specific mass, and hence technological sophistication, of the NEP system. A more advanced system, with reduced specific mass, will allow faster and/or lighter missions to be flown compared to a less advanced system. Additionally, the slope of each optimal power curve becomes quite steep for shorter trip times. Thus, beyond a point, it becomes very unprofitable to further reduce trip time at the expense of IMLEO and power level. All-Up missions of shorter duration will then require reduced specific mass resulting from either reduced system lifetime and/or more advanced NEP system technologies.

Figure 4 graphically displays, for a fixed set of system technology assumptions, the mission penalty which would derive from going from single to multi-reactor power systems. At 15 MWe, a single reactor NEP system based on Growth SP-100, potassium Rankine, and ion propulsion technologies, would perform the reference piloted Mars mission in 577 days for 484 metric tons (MT) IMLEO. Dividing the power system into three modular 5 MWe units in a 3+0 configuration would result in a mission penalty of 16 days and 47 MT. A highly redundant 15 MWe 2+1 configuration of three 7.5 MWe modules operating in parallel at 67 percent power would require an additional 20 days and 127 MT over the 3+0 system, or 36 days and 174 MT over the single reactor.

Looking at 10 MWe NEP systems, a single reactor 1+0 configuration would require 618 days and 373 MT IMLEO. The 3+0 would require 640 days and 421 MT, and the 2+1 would require 647 days and 515 MT. Thus, the 3+0 represents a mission penalty of 22 days and 48 MT over the single, and the 2+1 an additional 7 days and 94 MT over the 3+0.

An interesting alternative approach would be to look at the mission potential of a common modular system design, say 5 MWe, when combined in various multi-reactor configurations. A single 5 MWe module (1+0) would require a rather long 694 days of piloted trip time, but would require only 265 MT IMLEO. Combining three of these modules together with no module redundancy, forming a 15 MWe 3+0 system, would allow a decreased trip time of 593 days at 531 MT. Taking an essentially similar system, but down-rating it to a highly redundant 10 MWe 2+1 configuration of three 5 MWe modules operating at 67 percent, would result in a longer, yet presumably more reliable mission of 647 days and 515 MT.

It should be noted that these results present relative single versus multi-reactor performance for one particular All-Up mission during the 2016 opportunity. Other opportunities for this same mission will typically require marginally increased trip times and IMLEO. A "Split" piloted mission with Earth flyby return would allow trip times some 200 days faster, at the expense of an additional, dedicated cargo vehicle. Relative specific masses between the single and multi-reactor NEP systems, and therefore associated mission performance, should remain similar, however.

CONCLUSIONS

A number of potential benefits have been identified for adopting a modular, multi-reactor NEP power system configuration for piloted Mars application. Crew safety is enhanced through the potential for greater reliability, and the reduction of single point failure modes. Modularity of the power system results in smaller and lighter launch packages, reduced on-orbit construction requirements, and could allow vehicle and power level to be customized to suit a range of payloads and missions. The range of lunar cargo, Mars cargo, and piloted Mars missions could then be performed with a single, standardized power module design. Commonality of standardized power modules across applications would allow programmatic reductions in development and production costs, and more importantly, would leverage flight experience from early unmanned missions to provide well characterized and validated systems for later manned use.

These advantages were found to come at the expense of a heavier power system and marginally degraded mission performance for a piloted Mars mission. Piloted trip times for a 2016 opposition All Up Mars mission were found to be increased by only a few percent for the two cases examined. Initial mass requirements in LEO were more heavily impacted, ranging from 10 percent for the case with no module redundancy, to 40 percent for the case with a redundant module.

The various advantages afforded by the multi-reactor system would seem to far outweigh the mission impact in increased time and mass for the 3+0 vehicle without module redundancy. A more redundant 2+1 or 3+1 vehicle might alternatively be desirable for early missions where reliability was uncertain, but at the expense of a large penalty in initial mass. From a programmatic and architectural standpoint, early development of standardized 5 MWe power modules in an evolving lunar and Mars infrastructure would allow 5 MWe lunar and Mars cargo missions, and 10 to 20 MWe piloted Mars missions to be performed with the same power system design. More importantly, crew safety will benefit through enhanced system and mission reliability, and early flight system validation.

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REFERENCES

[1] K. J. Hack, J. A. George, and L. A. Dudzinski, "Nuclear Electric Propulsion Mission Performance for Fast Piloted Mars Missions," AIAA 91-3488, Conference on Advanced SEI Technologies, September 1991.

[2] J. A. George, "Multi-Reactor Configurations for Multi-Megawatt Spacecraft Power Supplies," AIAA 90-2111, 26th Joint Propulsion Conference, July, 1990.

[3] General Electric, "SP-100 Reactor Scalability Study," Contract No. DE-AC03-895F17787, July, 1989.

[4] J. A. George, "Multimegawatt Nuclear Power Systems for Nuclear Electric Propulsion," AIAA 91-3607, Conference on Advanced SEI Technologies, Sept. 1991.

[5] J. H. Gilland, R. M. Myers, and M. J. Patterson, "Multimegawatt Electric Propulsion System Design Cosiderations," AIAA 90-2552, 21st International Electric Propulsion Conference, July, 1990.

[6] J. C. Moyers and J. P. Nichols, "ALKASYS, A Computer Program for Studies of Rankine-Cycle Space Nuclear Power Systems," ORNL/TM-10427, Sept., 1987.

[7] A. Friedlander and J. McAdams, "NEP Performance for 2016 Mars Opposition-Class Missions," SAIC Task Order No.7, NAS3-25809 to NASA LeRC, July, 1990.

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