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A Feasibility Assessment of Installation, Operation, and Disposal Options for Nuclear Reactor Power System Concepts for a NASA Growth Space Station

Harvey S. Bloomfield and Jack A. Heller
Lewis Research Center
Cleveland, Ohio

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A FEASIBILITY ASSESSMENT OF INSTALLATION, OPERATION, AND DISPOSAL OPTIONS FOR NUCLEAR REACTOR POWER SYSTEM CONCEPTS FOR A NASA GROWTH SPACE STATION

Harvey S. Bloomfield and Jack A. Heller
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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SUMMARY

This report presents the results of a preliminary feasibility assessment of installation, operation, and end-of-life disposal options for three nuclear reactor power system concepts applied to a 300-kW growth version of the NASA space station. The assessment was focused primarily on the ramifications of nuclear safety and radiation constraints on space station operations. We also discussed the pros and cons of the three installation concepts and evaluated the merits of existing and near-term chemical propulsion system concepts for the reactor end-of-life disposal to a wide range of ultimate destinations. The three concepts investigated were based on existing SP-100 program technology and used tether, single-boom, and dual-boom attachment to a projected dual-keel space station. A total radiation exposure dose of 20 rem was established for an astronaut's assumed 3-month occupation of the station. This dose consisted of approximately 75 percent natural background radiation and 25 percent reactor-attributed radiation. Human-rated shielding configurations were generated for each concept to provide radiation protection for a projected set of normal operating activities and locations including on-station activity (habitat and laboratory modules), normal and emergency extravehicular activity (EVA), and shuttle orbiter approach, docking, and departure. Allowable EVA time for end-of-life separation of a shutdown reactor power system was also considered.

Impulsive (chemical) energy requirements and propulsion vehicle system and propellant characteristics were identified for six potential final disposal destinations, ranging from a long-life, 1000-km Earth orbit to a solar system escape trajectory. A variety of existing and near-term expendable chemical upper-stage vehicles, both cryogenic and storable, were studied to identify their operational payload and Delta-V capabilities. Also, a matrix of one-of-a-kind propulsion system components and reactor power system payload combinations was evaluated to identify potential attachment, integration, separation, and radiation safety issues as a function of time of attachment, (i.e., before reactor startup and after reactor shutdown).

The results of this assessment have generally confirmed the feasibility of installation, operation, and end-of-life disposal for the three concepts investigated. A number of open issues, however, remain with regard to definition of space station experiment requirements and the effect of reactor power system location.

All three attachment concepts were found to be compatible with boost to 1000-km Earth orbit at the end of life with any of the existing chemical propulsion, shuttle-compatible upper stages. For this disposal destination we

recommend the payload-assist-module (PAM) upper stage be attached to and integrated with the nuclear power system after reactor shutdown. Should higher energy non-Earth orbit disposal destinations be required, Earth-escape elliptical solar orbit is the preferred mode. Although the propulsive energy requirement is more than an order of magnitude greater than that for a 1000-km Earth orbit, it can be achieved by the lightweight tether mount concept with any shuttle-compatible upper stage vehicle placed in low Earth orbit with a single launch. The heavier single and dual-boom concepts can also be boosted to Earth escape but will require one-of-a-kind propulsion systems that are assembled in space following separate launches of the liquid propellant and the upper-stage hardware after reactor shutdown.

From the critical viewpoint of minimizing launch mass for installation and disposal the tethered reactor power system concept is clearly superior. This concept is a novel space application of terrestrial electric utility gas-filled transmission cable technology currently under study at NASA Lewis. The tether concept achieves its low mass by trading shield mass for reactor-to-space-station separation distance. Also, the 2-km tether length minimizes radiation exposures for shuttle approach and departure.

We recommend that the electrolysis of water to produce gaseous oxygen and hydrogen propellant be investigated to assess potential launch mass savings. This propellant is attractive for boost to all reactor disposal locations, and the synergistic operational benefits associated with the use of water on the space station and volume-constrained shuttle launches may be significant.

INTRODUCTION

A preliminary feasibility assessment of the integration of reactor power system concepts with a projected growth space station architecture was conducted to address a variety of potential installation, operational, disposition, and safety issues.

A previous NASA Lewis sponsored study (ref. 1) evaluated a variety of nuclear power concepts for space station requirements in the multi-hundred kilowatt range and concluded that free-flyer platform reactor power systems were less attractive then space station-attached concepts using structural boom and tether mounts.

The present study goals were, therefore, to identify and characterize attractive space station-attached reactor power system concepts and assess their installation and disposition feasibility. The scope of the study was limited to normal installation and disposition operations at the beginning and end of mission, respectively, and did not consider abort or severe malfunction scenarios. Installation concepts were defined to include the location and methods of attachment and detachment of the reactor power system from the space station. Disposition concepts were defined to include both the final disposal destination and the propulsion method used.

The study methodology shown in figure 1 was selected to provide a logical approach for assessing the feasibility of each installation concept with respect to a matrix of disposal locations and propulsion methods. The approach used to select installation concepts was based on defining a set of criteria for a projected nuclear powered growth space station to screen candidate concepts. Selected concepts were then characterized from a configuration and operational viewpoint, with disposal mass as a key parameter. Disposal destinations that met current aerospace nuclear safety criteria were identified and characterized in terms of operational and energy requirements with Delta-V energy requirements as a key parameter. Propulsion methods that met a current and near-term time frame criterion were identified and characterized from a payload mass and Delta-V energy capability viewpoint. These propulsion capabilities were then matched against installation concept disposal mass and disposal destination Delta-V energy requirement to assess the feasibility of each combination.

The study matrix shown in table I consisted of three installation concepts, six disposal destinations, each with one or more trajectory options, and two chemical propulsion methods.

Identification of reactor power system installation locations on the space station was based on a projection of architectural growth options for an additional 300 kWe nuclear power level requirement above an existing 100 to 300 kWe solar powered station. This included consideration of reactor power system location impact on projected in-place solar power systems, payloads, and occupied station modules, and impact on station and Shuttle operations. A projected "Dual Keel" space station configuration assumed to exist prior to reactor power system installation, is shown in figure 2. The locations of in-place solar power systems, payloads, crew and laboratory modules, etc. are indicated. Reactor power system location impact on additional space station elements, such as free-flyers and coorbiting platforms, was assumed to be minimal because of the relatively large separation distances involved.

Three attractive installation concepts were identified for further characterization. They are:

(1) A single 300 kWe reactor power system using instrument-rated shadow shielding, mounted on a 2 km long tether attached to the station upper payload boom.

(2) A single 300 kWe reactor power system using shaped 4 π man-rated shielding, mounted on a 60-m boom extension below the station lower payload boom.

(3) A dual balanced 150 kWe reactor power system each using shaped 4 π man-rated shielding, mounted on 100-m boom extensions of the station crossbeam.

The reactor power systems proposed were based on the SP-100 Program Thermoelectric baseline (SiGe-GaP) conversion concept with modifications in power level and shielding and boom configuration as required for the different installation locations. The two SP-100 reactor power system configurations assumed for this study are shown in deployed form in figure 3.

Identification of disposal destinations was generally based on the application of the aerospace nuclear safety philosophy of "delay and decay." This philosophy provides for sufficient isolation time such that radioactivity levels are reduced to meet radiation safety standards before exposure to the population. This can be accomplished by placing a shutdown reactor power system in a long-life orbit. Alternatively, the reactor power system can be disposed to solar or lunar destinations that can provide a zero or near-zero probability of Earth reencounter, and therefore provide infinite isolation time by precluding exposure to the Earth's populace. In addition, all destinations except solar impact and solar system escape allow for future reactor retrieval, if desired.

Six disposal destinations were identified for further characterization. They include four non-Earth encounter destinations, one long-life orbit (1000 km) destination, and one Earth return destination. Although the Earth return destination does not meet the delay and decay safety philosophy, it was included for purposes of comparison.

A variety of trajectory options have been characterized for all non-Earth encounter destinations and a controlled reentry and shuttle recovery option have been characterized for the Earth return destination.

Identification of propulsion methods was based on consideration of current and near-term state-of-the-art technologies. Two generic high thrust chemical propulsion concepts were characterized to cover a wide range of payload mass and potential destination capabilities. The propulsion concepts included high performance cryogenic propellants and both liquid and solid storable propellants for a range of integrated and nonintegrated system options. Solar and nuclear powered electric propulsion vehicle concepts were not included in this study because of their relatively immature vehicle system technology at this time. However, their significant increase in payload capability to high Delta-V disposal destinations plus their potential for near-term technology availability warrants further evaluation in future reactor power system disposal studies. Of particular interest are feasibility studies of disposal scenarios that use the space station reactor power system to provide electricity for an integrated on-board electric propulsion vehicle. This concept has the potential for simple low cost disposal, but further study of systems integration issues is required.

INSTALLATION CONCEPTS

A common set of ground rules was initially applied to all installation concepts to provide a consistent basis for comparison. These included the following:

(1) All concept configurations must maintain the existing space station center of gravity location while minimizing impact on station payloads and/or operations.

(2) A uniform and consistent exposure dose rationale, to be used for all installation locations, shall be arbitrarily based on a maximum total biological radiation exposure dose of approximately 20 rem/quarter year for all normal space station activities.

(3) Boom mount installation concepts shall use man-rated shaped shield configurations employing a shadow cone to shield space station activity locations and a spherical geometry for all other activity locations.

(4) Boom-mounted installation concepts shall use space station 5 m square booms with a lineal mass of 17 kg/m, and the tether concept shall use a 0.1 m diameter, 2 km long tether with a mass of 1400 kg.

(5) Single 300 kWe reactor power systems will be based on an 8 MWt reactor power level with reactor dimensions of 88 cm long by 69 cm diameter.

(6) Dual 150 kWe reactor power systems will be based on a 4 MWt reactor power level with reactor dimensions of 74 cm long by 55 cm diameter for each system.

As the study progressed it became clear that further definition was required for the first two ground rules. The first ground rule, requiring preservation of the original space station center of gravity, will significantly affect the overall configuration of both the single power system tether mount and the single power system boom mount installation concepts; the dual boom concept is inherently balanced. They will both require large ballast moments to offset their unbalanced power system locations and masses. The approach taken herein was to provide a nonoperating space reactor power system as ballast mass. Thus, a replacement reactor power system would already be on-board the space station, and replacement time would not be subject to shuttle launch schedules. No attempt was made to evaluate the potential reliability benefits of this approach.

In the case of the tether mount concept, space station center of gravity location is preserved by mounting a space deployed nonoperating tether and reactor power system directly opposite, and in-line with, the operating system. For the boom mount single reactor power system concept it was not possible to provide an opposed, in-line, equal mass system because of potential interference with upper boom payload functions. Therefore a longer moment arm, lower mass approach had to be used in combination with a spare undeployed reactor power system location on the space station. Additional details of ballast mass and location are provided in the appropriate installation concept sections of this report.

The second ground rule, meeting a 20 rem/quarter biological exposure dose for all normal space station activities, had a number of issues that needed further resolution. First, a definition of normal activities was required. For each activity it was then necessary to determine location, time spent at location, existing in-place shielding, and finally, the natural background biological dose rate, including attenuation by existing shielding. Existing shielding includes attenuation by space station and shuttle skin (wall) thickness for on-station and in-shuttle locations, and astronaut space suit visor thickness for EVA operations. The results of these definitions and estimates are summarized in table II. Realistic locations and reasonable exposure times for each activity were selected and defined in sufficient detail to provide conservative dose estimates.

For example, operations in space station were assumed to account for over 98 percent of each astronaut's time. This includes all activities within the confines of space station modules with local shielding of 2.4 g/cm^2 to reduce natural radiation levels to 7.1 mrem/hr.

EVA operations were subdivided into two distinct types occurring at different locations for the boom mounted installation concepts. Of the 34.2 total

EVA hours allocated, 32.2 hr were assumed to occur within the confines of the man-rated shadow shield provided for each boom mounted installation concept. A discussion of the boom mount shield configurations used in this study is presented at the end of this section. These are referred to as routine EVA operations from a radiation dose standpoint since reactor-attributed dose rates are less than natural background levels. For the tether mount installation concept, all EVA operations are in a low dose rate environment and are therefore considered routine.

Emergency EVA operations were defined to take place in the relatively high dose rate regions outside the shadow shield cone angle of the boom mounted installation concepts. A 2 hr exposure duration time was assigned to this activity which was assumed to occur in the highest dose rate region 300 m from the space station center of gravity. Natural background radiation dose rates for all EVA operations were attenuated to 9.0 mrem/hr by the assumed 0.9 g/cm^2 shielding thickness of the astronaut space suit visor.

Shuttle orbital operations including approach, docking, separation, and departure, also required further definition for dose calculations. A two part scenario for approach and docking was based on calculational data supplied by NASA/JSC.[1] The first part consists of a single shuttle maneuver that begins about 15 km downrange from the space station and ends with a momentary stop 300 m uprange from the space station on the orbital track. The second part consists of a multiple burn and coast flight profile from the 300 m point to final attachment at the docking port. From a radiation dose standpoint the time duration allotted for the initial maneuver to 300 m is negligible; the major dose contribution occurs over the last 300 m until the shuttle enters the low dose rate region inside the shadow shield cone. Shuttle flight profiles over the final 300 m were purposely assumed to traverse the highest dose rate regions for each boom mount installation concept. These profiles differed from those provided by NASA/JSC, but were adopted to provide conservatism in exposure dose. For the tether concept all final flight paths are equivalent from a radiation dose standpoint since natural background radiation is the major dose contributor.

A 0.68 hr total approach and docking time from 300 m, as calculated by NASA/JSC was used for all flight profiles. A 20 percent contingency was added to yield an 0.82 hr duration for approach/dock/departure. The 3.3 hr duration shown in table II represents two shuttle approach/dock/departure operations assumed to occur every 90 days.

The shuttle fly-by activity was defined to represent, for example, a "wave-off" from an attempted rendezvous. A total time of 0.4 hr was assigned to this activity which is assumed to occur at the momentary shuttle stop location of 300 m from the space station. For purposes of dose rate calculations a circular fly-by maneuver at a 300 m radius around the space station was assumed equivalent to a stationary hold at 300 m.

Also shown in table II are the natural background biological dose rates for all activities. These dose rates are based on a combination of recent shuttle flight 51J (October 3, 1985) measurements inside crew quarters, and

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[1] Personal communication from C. Anderson, NASA Lyndon B. Johnson Space Center, Houston, Texas, October 15, 1985.

calculations performed at NASA Johnson Space Center[1] for a 500 km orbit at 28.5° inclination. Previous assumptions used for natural background radiation in reference 1 apparently overestimated EVA dose rates by a factor of about 50, while underestimating in-shuttle and in-station dose rates by a factor of 2.

The activity/location time durations and natural background dose rates shown in table II were combined with selected reactor shield configurations to provide a total exposure dose of 20 rem/quarter for each installation concept. The shielding configuration selected for the tether mount concept was based on a modification of the current SP-100 instrument-rated design and will be described in the 300 kWe tether mount installation section. Shielding configurations for boom mount reactor power system concepts were generated by a man-rated conical/spherical shaped geometry computer program developed at NASA Lewis. This program utilizes layered neutron and gamma ray shields to minimize secondary gamma ray dose rates. Reactor source input is limited to spherical geometry so that equivalent volume spheres were substituted for actual cylindrical reactor geometries.

Variable geometry subroutines allow combinations of spherical and conical sections to meet varying dose rate requirements at different locations to provide minimum mass shaped shield geometries. For the boom mount installation concepts a conical shadow shield geometry was used to provide low dose rates within the confines of the space station and a spherical shield geometry was used for emergency EVA and shuttle operations. The dose rates specified for each activity location were determined by an iteration procedure to arrive at a total integrated dose of 20 rem for all normal activities for each installation concept. The layered shield thickness values calculated by the code are based on an algorithm generated from a few-group Monte Carlo calculation and are conservative. The resulting shield mass, however, is not expected to be overly conservative since the calculation does not account for realistic mass additions that would be imposed by an engineered shield design.

Finally, it should be noted that at the time of this writing a recommended astronaut dose limit was under review by NASA and other radiation safety groups. The arbitrary selection of 20 rem/quarter for this study was not meant to prejudge the dose recommended by this review. In addition, the high shield attenuation factors used cause the natural space background radiation to be the dominant source of exposure with reactor-attributable dose accounting for only one-fourth of the total. Therefore, any recommended changes in exposure level will not significantly affect the shield mass results of this study.

The next three sections of this study present the configuration and operational characteristics of each selected installation concept. A summary section is included to provide an overall comparison of concept characteristics.

300 kWe TETHER MOUNT INSTALLATION

Although this installation concept relies on a relatively new method of power transmission in space, a recent tether conceptual design and application study (ref. 2) established the feasibility basis for its consideration in this

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[1] Personal communication from A. Hardy, NASA Lyndon B. Johnson Space Center, Houston, Texas, October 15, 1985.

study. The tether mount concept has the potential to provide both the lowest launch mass and the lowest disposal mass of all the installation concepts identified. This significant advantage is achieved by trading reactor power system shield mass for separation distance via a long tether.

The concept selected for further characterization was based on a single 300 kWe reactor power system attached to space station by a two kilometer long by 0.1-m diameter tether which is also an electrical transmission line. The two kilometer separation distance selected allows the existing SP-100 instrument-rated shield design to serve as a man-rated configuration for all locations near the space station. However, two installation issues were identified that required additional definition; shielding requirements for shuttle approach and departure maneuvers, and potential interference of the reactor power system with payloads located on the station upper boom.

The shield configuration issue arises from the fact that the existing SP-100 instrument-rated shadow shield design is based on a narrow 17° shadow cone half angle. The resultant shadow cone, at a 2-km separation distance, provides a reactor-attributable dose rate of 2.3 mrem/hr over a 1.17 km^2 area with a diameter of 1.2 km at the space station orbit plane. Although this low dose rate covers sufficient area for all in-station and EVA activities, the shield geometry does not provide a large enough shadow for either shuttle approach or some possible fly-by maneuvers. Therefore, the SP-100 shield geometry was modified to include a tapered side shield, or wing. The wing provides a uniform 2.3 mrem/hr dose rate along the space station orbital plane out to 300 m, which is sufficient to limit all shuttle operation doses to negligible levels. A total modified shield mass of 2300 kg was estimated of which 800 kg is due to the additional wing. The shield configuration used for the tether mount installation is shown in figure 4 and the resulting radiation exposure levels are shown in table III. Total integrated dose for all normal activities is estimated at 20.37 rem.

The issue of potential power system interference with payloads on the upper boom is due to their functional requirements. The proposed payloads consist of experimental observatories which may require an unobstructed view of deep space, and the presence of an operating reactor power system within their field of view may be unacceptable especially from an infrared radiation aspect. However, consideration of both tether detachment and shuttle approach/departure flight paths have led to a preliminary selection of upper boom attachment for the operating reactor power system.

The final configuration selected for the 300 kWe tether mount concept is shown to scale in figure 5, and the corresponding mass statement is given in table IV. The final configuration includes the required ballast in the form of an equal and opposite deployed spare (nonoperating) reactor system located at the end of a two kilometer tether below the space station. This ballast configuration was selected over other potential ballast locations within the confines of the space station framework from a simple mass penalty rationale. Locating the required ballast moment arm of 21 by 10^6 kg-m at the furthest point below the station's center of gravity on the lower payload boom, would have required an unacceptable ballast mass of about $4x10^5$ kg. The selected ballast location should not pose any major interference penalties for communication payloads located on the lower boom.

Two options appear feasible for detachment prior to final disposition. In the first, the tether would be detached from the shutdown reactor power system at the power system end and it would remain attached to the space station. Detachment must be accomplished by remote teleoperators or built-in separation devices because high dose rates preclude manned EVA operations for this option. Since this option leaves the tether attached to the space station for reuse with the replacement reactor power system, a potential mass savings of 1400 kg for both disposition and subsequent launches would result. However, if the tether is damaged by radiation or meteoroids it can be detached at the space station end and disposed of with the power system. This option was selected even though it has a 1400 kg disposal mass penalty. The benefit of tether detachment at the space station end is the elimination of all radiation dose issues associated with detachment operations. For example, total dose rates at the space station immediately after reactor shutdown are at background levels of 9.0 mrem/hr. This low dose rate permits over 100 hr of manned EVA operations per additional rem exposure for detachment operations.

300 kWe BOOM MOUNT INSTALLATION

This concept was identified for consideration because it preserves the space station's vertical gravity gradient with a single 300 kWe reactor power system attached to a conventional boom. The power system is located on a 60-m boom extending downward from the Station's lower payload boom and is line oriented along the local gravity gradient. This location is sufficiently removed from upper boom payloads so that interference should be minimal.

The shielding configuration for this concept is based on the man-rated conical/spherical shaped shield design described previously. The shield configuration selected for this installation concept provides a reactor-attributable dose rate of 1.5 mrem/hr at 115 m inside the shield shadow at the habitat location and a dose rate of 200 mrem/hr at 160 m everywhere outside the shield shadow. The reactor power system - space station geometry relationship is shown to scale in figure 6, and the resulting reactor-attributable dose rates are shown in figure 7. The shield geometry consisted of a combined 30° half-angle cone shadow shield and a 330° spherical shield. Shield geometry and dimensions are shown in figure 8. The resulting radiation exposure levels for all activity locations are shown in table V. It is important to note the relatively high reactor-attributable dose rates estimated for activity locations outside the shield shadow cone; EVA, shuttle approach/dock/departure and shuttle fly-by. These high dose rates are of some concern even though total integrated dose meets the 20 rem/quarter ground rule.

The 166 mrem/hr dose rate for emergency EVA occurring outside the shadow cone was conservatively based on a location 185 m from the reactor power system and in the highest dose rate region 300 m directly below the space station center of gravity.

The 366 mrem/hr average dose rate for shuttle approach/dock/departure results in an integrated 555 mrem exposure dose to shuttle crew during each 0.82 hr approach and departure operation when a man-rated shield specification of 200 mrem/hr at 160 m is used. Shuttle approach/departure flight paths within 300 m were assumed to be along the space station orbital track outside the shadow shield. This trajectory takes the shuttle through the highest dose rate regions and thus provides conservatism in integrated dose results. The total dose of 1.11 rem is based on two approach/departure operations per quarter. The shuttle fly-by activity was estimated to add an exposure dose of only 0.03 rem while circling the space station or remaining stationary at a distance of 300 m on the orbital track. The total integrated dose for the single 300 kWe boom mount concept was 20.06 rem, within 2 percent of the 300 kWe tether mount dose.

Two installation issues have been identified for this concept. The first is the location of ballast mass required to maintain the existing space station center of gravity location, and the second is potential reactor power system interference with lower boom payloads. The first issue required further definition because the use of an equal and opposite spare reactor power system attached to the upper payload boom will probably cause unacceptable visual interference with payload functions. The proposed solution uses two ballast locations.

A spare undeployed reactor power system is located under the upper payload boom within the space station framework, and a second smaller ballast mass is located above the station at the end of a long tether. A 1-km tether length was selected for the additional ballast location. The proposed use of multiple thin monofilament line tethers and the low volume (about 2.5 m^3 for water) of the additional ballast should not interfere with upper boom payload functions. The second issue, that of interference with lower boom payload functions, cannot be resolved until these functions are defined further. However, it is estimated that lower boom payload observation and viewing requirements will not be as stringent as those for upper boom payloads.

The final configuration for the 300 kWe boom mount concept is shown to scale in figure 9, and the corresponding mass statement is given in table VI.

The proposed detachment scenario for this installation concept was based on leaving the 60-m boom attached to the space station and detaching the shutdown reactor power system by either manned EVA, remote teleoperator or built-in separation devices. In order to evaluate potential radiation issues associated with manned EVA the radiation dose rates and allowable EVA times as a function of separation distance for two arbitrary shutdown times were calculated and are shown in table VII. The resulting allowable time estimates for manned EVA are presented in terms of hours allowed per each additional rem of exposure dose. Detachment of the reactor power system could be accomplished at any point on the structural boom location within the confines of the shadow shield at a separation distance of up to 60 m. At a 10 m separation distance natural background radiation is the major dose contributor and about 100 hr of EVA operations per rem would be allowed after a reactor shutdown time of 1 month. This result is equivalent to that obtained for the tether mount concept immediately after reactor shutdown.

DUAL 150 kWe BALANCED BOOM MOUNT INSTALLATION

This installation concept differs from the previous 300 kWe single reactor concepts by employing two operating 150 kWe power systems thereby providing an added measure of operating reliability. Location of each reactor power system on a 100-m extension of the space station crossbeam preserves the station's center of gravity without the use of a nonoperating power system as ballast.

This location is sufficiently removed from all space station payloads so that interference with payload functions is minimal.

The total reactor-to-habitat separation distance of 165 m required a 20° shield cone half-angle to shadow the entire space station. The installation geometry and dimensions used for this concept are shown in figure 10. Dose rates inside the shadow shields of both reactor power systems were specified to provide a total reactor-attributable dose rate of 1.5 mrem/hr at the intersection of the space station crossbeam and vertical centerline; the same specification used for the single 300 kWe boom mount concept. A dose rate of 115 mrem/hr at 160 m was selected outside the shadow shield of each reactor power system to limit total integrated dose to 20 rem per quarter. Shield geometry and dimensions generated by the NASA Lewis manned shield code are shown in figure 11.

Figure 12 presents a dose rate contour plot for the dual boom installation concept. This plot shows reactor attributable dose rates within each shadow shield cone, outside each shadow cone, and dose rates in the shared region outside both shadow cones. The resulting radiation exposure levels for all activity locations are shown in table VIII. As in the case of the single 300 kWe boom mount concept, relatively high dose rates were estimated for all activities outside the shadow shield cones. The 178 mrem/hr dose rate for emergency EVA operations was conservatively based on a location 135 m from either reactor power system and in the highest dose rate region 300 m from the space station center of gravity along the orbital track. The 371 mrem/hr dose rate for shuttle approach/dock/departure was conservatively based on a shuttle flight path along the orbital track just outside the shadow shield of either reactor power system. This trajectory yields an average dose rate more than double that obtained with a trajectory along the station's vertical center line. Shuttle approach and departure times of 0.82 hr each were used to calculate the total dose of 1.22 rem, assuming two approach/departures per quarter. Shuttle fly-by at 300 m from the space station contributed only 0.09 rem for this 0.4 hr duration activity. The total integrated dose for the dual 150 kWe boom mount concept was 20.24 rem which is within one percent of both the single 300 kWe boom and tether mount doses.

No significant installation issues have been identified for this concept. Of some concern, however, is the two-axis rotational capability of the space station crossbeam. This capability is required for solar power system pointing, and could limit the moment arm capability for high mass reactor power systems on long boom extensions of the crossbeam. Also, the possibility of existing rotating solar power systems operating in parallel with reactor power systems may require the reactor power system to rotate also. This does not appear to present any major operational problems and may actually be beneficial from a radiation heat rejection standpoint.

The final configuration selected for the 150 kWe dual boom concept requires no additional ballast mass and was shown to scale in figure 10. The corresponding mass statement is given in table IX. A significant feature of this concept is the capability of splitting both launch and disposition mass into two separate packages, each consisting of a complete 150 kWe reactor power system.

The proposed detachment scenario is similar to that described for the single 300 kWe boom mount installation. The 100 m boom extensions would remain attached to the space station and the shutdown reactor power systems would be detached. As shown previously on table VII, manned EVA is feasible for the detachment operation at a nominal 10 m separation distance.

SUMMARY OF INSTALLATION CONCEPTS

Three installation concepts that were designed to meet a uniform set of integrated criteria for a projected 300 kWe nuclear growth space station have been identified and characterized. Each concept has been configured to exhibit the following requirements:

(1) Minimal interference with space station operations and payloads.

(2) Maximum total radiation exposure dose of 20 rem/quarter year to space station crew for a uniform set of normal activities.

(3) Preservation of the space station center of gravity location.

A mass summary for the three selected installation concepts, including an estimate of number of shuttle launches required, is shown in table X. Since all launch masses exceed the projected shuttle capability of 18 000 kg each concept was broken down into multiple launch packages. It was assumed that each shield could be split into two sections, one of which is highly integrated with, and attached to, the reactor. The two shield sections are further assumed to be designed for on-orbit attachment and assembly. These assumptions provided the minimum number of shuttle launches indicated.

Launch masses do not include any allowance for on-board integrated propulsion system hardware. Although this mass may be relatively small, the trade-off between integrated versus nonintegrated propulsion systems is an important one. This subject will be treated in detail later in this study.

DISPOSAL DESTINATIONS

The disposal destinations described herein have been selected to provide characterization of a representative group of potential locations for shutdown reactor power systems; they do not represent the results of a selection process to identify preferred locations. Also, although abort or malfunction scenarios were beyond the scope of this study they could pose substantial safety and recovery issues. With the exception of the Earth return cases, all destinations studied will provide shutdown reactor decay times greater than 300 years. Some destinations also exhibit highly elliptical orbits with almost zero probability of intersection with the Earth's orbit.

The six destinations identified in table I, were characterized from an energy (Delta-V) and operational requirements viewpoint. The advantages and disadvantages of each destination are described and a summary comparison is provided. The operational characterization of each destination included the following: number of burns, time interval between burns, specific launch time and guidance requirements, and retrieval availability. The last item, retrieval availability, or potential for reactor power system recovery, may be of interest from a post-operation evaluation aspect. All other items are of interest from a propulsion system operational reliability aspect.

Long Life Earth Orbit

An Earth orbit altitude of 1000 km has been selected to conservatively satisfy the reentry safety requirement of long orbital lifetime. This orbit will provide at least a 300 year decay time for ballistic coefficients of typical SP-100 class reactor power systems.

To achieve an increase in circular orbital altitude from 500 to 1000 km, two propulsion maneuvers are required. After the reactor power system payload has been detached from the space station the propulsion system imparts a Delta-V of 130 m/sec to the payload, placing it in an elliptical transfer orbit. After about a 1 hr coast time up to the 1000 km altitude, a second burn is initiated with a Delta-V of 130 m/sec to circularize the orbit. In the event of a second burn propulsion failure, the resulting elliptical orbit would have an orbital decay life time exceeding 3 years, which should be sufficient to permit corrective action.

The advantages of employing the high Earth parking orbit are:

(1) A very low Delta-V requirement of 260 m/sec.

(2) Insertion can be initiated at any calendar time.

(3) A wide variety of propulsive methods can be used.

(4) A simple, on-board event timer constitutes all of the guidance and control required.

(5) The reactor is available for future retrieval, if desired.

The only disadvantage identified for this destination is the requirement for two propulsion burns to insert and circularize the orbit.

Solar Orbits

Solar orbits identified for characterization are: (1) elliptical Earth escape, (2) circular heliocentric orbits at greater and lesser than 1.0 Astronomical Units[1] (AU), and (3) planetary swing-bys. These orbits retain the disposed payload in the Solar System for potential future retrieval while providing essentially infinite delay and decay time.

Earth escape. - This highly elliptical orbit about the Sun can be accomplished by a single burn that provides a Delta-V of about 3200 m/sec. The advantages of this solar orbit approach are:

(1) a moderate Delta-V requirement of 3200 m/sec,
(2) insertion can be initiated at any calendar time,
(3) single burn propulsion,
(4) no spacecraft guidance required, and
(5) reactor available for future retrieval, if desired.

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[1] AU-mean distance of Earth from the Sun, about 1.5×10^8 km.

Circular heliocentric orbits. - To provide a clear, positive separation from the Earth's orbit about the Sun the reactor power system could be placed in essentially circular orbits of greater and lesser than 1.0 AU[1]. For this study the 1.10 and 0.90 AU orbits were selected to provide examples of the representative Delta-V's required for circular orbits that do not cross the Earth's actual elliptical heliocentric orbit. For each orbit, two burns are required for a total Delta-V of about 4500 m/sec with a coast period of about 16 months between burns. The advantages of this solar orbit approach include: (1) initiation at any time, (2) power system available for future retrieval if desired, and (3) simple on-board event timer required for guidance.

Disadvantages include the requirement for two propulsive burns and a moderately high Delta-V of 4500 m/sec.

Planetary swing-bys. - Destinations in highly elliptical orbits that do not intersect Earth's orbit were also investigated. These consist of orbits achieved by using the gravitational attraction of planets such as Mars and Venus. The total Delta-V required for each case, however, is about the same as that required for the circular heliocentric orbits, 4500 m/sec. A single initial burn is required, a second burn is eliminated by the use of the respective planetary gravitational attraction to complete the maneuver. In addition, the swing-by cases will require up to a 2 year time interval between optimal initiation of reactor disposal operations to take advantage of the relative location of the Earth with respect to these planets to minimize trip time. The advantages of this solar orbit approach are the same as those for circular heliocentric orbits plus inclusion of only a single burn requirement. Disadvantages include the same moderately high Delta-V requirement of 4500 m/sec and up to a 2 year interval between separation and launch.

Solar System Escape

Several solar system escape scenarios were examined; direct and Jupiter swing-by. This destination also provides a permanent, nonretrievable disposal location.

Direct. - The direct solar system escape can be achieved with only a single propulsive burn. The reactor power system payload is placed in a hyperbolic trajectory in the plane of the ecliptic, and can be launched at any calendar time with minimal guidance required. The major disadvantage of this permanent disposal scenario is that it requires a large Delta-V of about 8760 m/sec which severely limits the choice of a propulsion scheme.

Jupiter swing-by. - A lower energy variation of the direct escape destination can be employed by guiding the package into a trajectory approaching, and then swinging by, Jupiter. This reduces the total required Delta-V to 7600 m/sec, but requires a mid-course correction burn maneuver to achieve the desired close proximity behind Jupiter. Precise launch times to Jupiter are also required and are limited to one specific time per year because of the relative positions of Earth and Jupiter.

Solar impact. - An additional permanent, nonretrievable destination is the Sun, itself. Two variations of solar impact were investigated; direct and Jupiter swing-by.

Direct. - To achieve direct solar impact a single burn Delta-V equal and opposite to that of the Earth's mean orbital velocity of 29 800 m/sec is required. This extremely high energy requirement causes this solar impact variation to be a nonviable option.

Jupiter swing-by. - With the added complexity of additional spacecraft guidance and mid-course correction solar impact can be achieved with a greatly reduced Delta-V of 7600 m/sec. In this concept the propulsion vehicle is guided to pass near the "front" of Jupiter. Thus, Jupiter's orbital velocity nearly cancels that of the vehicle resulting in a near zero velocity with respect to the Sun, and subsequently the payload impacts the Sun. This method, however, is limited to about a once-a-year launch opportunity when the Earth and Jupiter are in optimum positions relative to one another.

Lunar Landing

A potentially useful destination for the reactor power system would be a remote location on the Moon. In this approach the payload would be soft landed at the desired site. A Delta-V of 4000 m/sec would be required to acquire a lunar orbit and then a second Delta-V of about 1800 m/sec would be required for a precision soft landing on the Moon. An on-board event timer would provide sufficient guidance accuracy to place the reactor power system within the desired area.

One potential advantage of this destination is the possibility of reusing portions of the intact reactor power system for future lunar missions. At the present time there does not appear to be any policy prohibiting the controlled deposition of nuclear (fissile) material on the moon; however, an examination of potential accident modes and consequences is needed to assess this option.

Earth Return

In the event that it becomes necessary to return the reactor power system to Earth for scientific, economic, or political reasons, several return concepts were examined. These concepts do not maintain the generally accepted aerospace nuclear safety philosophy of delay and decay, however, they have been evaluated for reasons of completeness and study comparison. Two cases were considered: (1) intact controlled reentry of the reactor power system landing at a preselected remote landing area, and (2) return of the (stowed configuration) reactor power system in the shuttle.

Controlled reentry. - This Earth destination option requires reentry with a single burn expendable propulsion system which includes an on-board event timer guidance mechanism. With the very low Delta-V requirement of about 150 m/sec the package is easily returned to Earth. The preselected impact area could be over deep ocean or a remote free-world land location where final reentry could be accomplished with parachutes. The transit time to fully deorbit is not critical, and the fuel requirements of the propulsion vehicle are minimal. However, a detailed examination of potential accident modes and their consequences from both a nuclear safety and safeguards aspect is required to assess this option.

Shuttle return. - A second method of achieving a controlled Earth return destination is with the use of the shuttle. In this method, the shutdown reactor power system must be disassembled and reconfigured to the launch configuration for stowage in the shuttle payload bay. This appears to be a major technical issue requiring consideration of at least the following:

(1) disassembly of reactor power system to meet shuttle mass limits

(2) refolding or removal of radiator sections

(3) location of reactor and shield to provide shuttle crew radiation protection

(4) location of reactor power system and possible additional ballast to meet shuttle center-of-gravity requirements

(5) removal of reactor decay heat in shuttle bay

Overriding these major technical issues is the question of shuttle crew safety. For example, even assuming a safe landing, a failure of the decay heat removal system or a hard landing impact could result in release of liquid metal into the shuttle bay. Based on these concerns, and the consideration of possible accident scenarios the shuttle return option does not appear to be either viable or desirable.

SUMMARY OF DISPOSAL DESTINATIONS

The results of the characterization of all of the disposal destinations and are shown in table XI which summarizes the energy requirements and operational characteristics of each destination. In terms of energy requirements alone, both the long life orbit and Earth return destinations are clearly superior. However, if the operational advantages of a single burn or maneuver are of interest, the Earth escape solar orbit destination is attractive. It combines moderate energy requirements with a single burn capability, and no requirement for launch time or guidance. Another criterion of potential interest is retrieval availability at some future time. All destinations except solar impact and solar system escape have this capability. Critical safety issues associated with failure to achieve a desired disposal destination need to be assessed in future studies.

CHEMICAL PROPULSION CAPABILITY AND INTEGRATION CONCEPTS

The assessment of chemical propulsion capability includes consideration of calculational methodology and integration concepts and a summary of results. The methodology section describes the analytical basis for evaluation of propulsion capability and provides a generalized quantitative assessment of propellant mass requirements as a function of payload mass and disposal destination. These results were then applied to the complete matrix of propulsion systems and payload integration scenarios to assess potential feasibility issues. The summary section provides recommendations of attractive integration concepts for high energy disposal destinations from an operational viewpoint. Also, as discussed in the Disposal Destinations section, assessment of issues associated with disposal vehicle failure or malfunction was considered to be beyond the scope of this study and needs to be evaluated in future studies.

Methodology

The method used to characterize chemical propulsion methods was based on the application of the classic two-body problem equation to compare disposal destination required velocity increment with payload capability. The use of this approach limits application of the results to high thrust propulsion vehicles where changes in velocity are impulsive, or instantaneous. In addition, this generic approach is independent of the type of chemical propellant used. Figure 13 presents selected solutions of the following expression for characteristic velocity increment. i.e., the velocity imparted to a body as the burning time approaches zero, as a function of payload mass fraction:

$$\text{Delta-V} = -9.815 I_{sp} \ell n \left[1 + MF \left(\frac{W_L}{W_T} - 1 \right) \right]$$

where

Delta-V = velocity increment, m/sec

I_{sp} = specific impulse, sec

MF = propellant mass fraction

W_L = reactor power system disposal (payload) mass, kg

W_T = total initial vehicle mass, kg

and

$W_T = W_L + W_P + W_H$

MF = $W_P/(W_P + W_H)$, assumed to be 0.85

where

W_P = propellant mass, kg

W_H = vehicle hardware or burnout mass, kg

Specific impulse values of 450, 350, and 300 sec were selected to respectively represent: a projected high performance cryogenic propellant, a projected high performance storable propellant, and a state-of-the-art performance storable propellant. Also shown on figure 12 are the Delta-V energy requirements for specific destinations ranging from circular 1000 km Earth orbit to solar system escape or solar impact. These results indicate the relative ease of achieving a 1000 km Earth orbit destination with high payload mass fraction propulsion vehicles; higher energy destinations will require vehicle concepts with payload mass fractions below 0.3. The high payload mass fraction vehicles are well represented by shuttle-compatible propulsion vehicle systems as shown in table XII which lists the propulsion characteristics and capabilities for some expendable cryogenic and storable propellant vehicles. Payload mass fractions at maximum propellant capacity are also shown for each of the three reactor power system disposal masses.

The results shown in figure 13 and table XII provide the basis for the conclusion that any shuttle-compatible upper stage vehicle can thrust any of the reactor power system disposal payloads into a 1000 km Earth orbit with an orbital decay time exceeding 300 years. However, should higher energy destinations be required, additional propellant capacity is needed. Therefore, an evaluation of one-of-a-kind expendable propulsion vehicles using high performance storable and cryogenic propellants was conducted up to a maximum propellant capacity sized to meet a solar system escape destination. The results for a constant propellant mass fraction of 0.85 are shown in figure 14 for storable propellant vehicles with specific impulse of 350 sec, and in figure 15 for cryogenic propellant vehicles with specific impulse of 450 sec. Both figures show propellant mass requirements for disposal payload masses up to 50 000 kg as a function of destination Delta-V with the disposal payload masses for each installation concept identified. The propellant mass requirements for the 1000 km Earth orbit destination range from 500 to 3000 kg, again indicating the relative ease in achieving this destination. For the Earth escape elliptical solar orbit destination, propellant mass requirements range from 14 000 kg to about 88 000 kg. Table XIII shows the propellant mass launch requirements for this destination for each installation concept in terms of number of shuttle launches needed. These results show that a single shuttle launch requirement limits this destination to the tether concept; both boom mount concepts require two or more shuttle launches.

PROPULSION INTEGRATION

The results presented have provided a quantitative assessment of propellant mass requirements as a function of payload mass and destination Delta-V. However, there are a number of propulsion integration issues that will strongly affect the overall assessment of chemical propulsion capability.

An investigation of these issues was conducted by examining potential propulsion system and payload integration scenarios as a function of time of integration. Based on the assumption that the reactor power system is installed on space station prior to launch of any propulsion components or systems, three levels of propulsion integration were found to characterize all possibilities. These are defined as full, partial, and nonintegrated concepts to represent the level of propulsion system/payload integration level prior to reactor startup. Table 14 outlines the integration characteristics of each concept in terms of the integration time and location of the disposal package elements; propellant, upper stage vehicle, and reactor power system payload. The integration issues identified for each concept are characterized in table 15, and a description of the concept operational scenarios is given below.

The scenario for the fully-integrated concept is based on a single shuttle launch of an integrated propulsion system (propellant plus upper stage) which is then attached to the reactor power system prior to reactor startup. This concept requires no orbital assembly of propulsion components, and both propellant/upper stage and propulsion system/payload integration is conducted without any reactor radiation dose rate constraints. However, the multi-year time duration between propulsion system/payload attachment and disposal launch requires the use of a long shelf life storage propellant.

The scenario for the partially-integrated concept is based on in-space integration of all upper stage hardware to the reactor power system prior to reactor startup with propellant integrated after reactor shutdown. Two options are potentially feasible for propellant integration. In the first, loaded propellant tanks would be attached to the upper stage structure; in the second option the upper stage would include empty propellant tanks which would be loaded by pumped propellant transfer. In either case, propellant integration operations will be constrained by the restrictions imposed by the shutdown reactor dose rate environment, however, either storable or cryogenic propellant may be used.

The four options shown for the nonintegrated concept are all based on final payload and propulsion system integration after reactor shutdown, the options differ only in the time of integration of propellant and upper stage. In options A and B, propellant and upper stage are integrated before reactor startup and are therefore limited to storable propellants and low energy destinations. Options C and D are characterized by propellant and upper stage integration after reactor shutdown and can therefore use cryogenic or storable propellants. This difference gives option C the capability of Earth escape destination for the 300 kWe thether mount concept payload when used in combination with cryogenic propellant.

SUMMARY OF CHEMICAL PROPULSION CAPABILITY AND INTEGRATION

The assessment of chemical propulsion capability is conveniently summarized in terms of requirements and recommendations for each disposal destination.

For the low energy 1000 km Earth orbit destination, the use of a shuttle-compatible upper stage, such as the solid rocket motor Payload Assist Module (PAM) series, is recommended. Two methods of propulsion system/payload integration are equally feasible. The fully-integrated concept provides a single shuttle launch of the integrated propellant/upper stage to low Earth orbit where it is attached in a single operation to the reactor power system payload in a radiation-free environment prior to reactor startup. The major integration issue identified for the concept is the unknown effect of long-term exposure of the propellant and the upper stage to the operating reactor radiation and the space environment. An alternative method of propulsion system/payload integration is option C of the nonintegrated concept. This option also provides a single shuttle launch of the integrated propellant/upper stage to low Earth orbit where it is integrated with the reactor power system payload after shutdown. This eliminates the long-term exposure issue of the fully-integrated method but requires propulsion system/payload integration in the radiation environment of the shutdown reactor. This requirement is not considered to be a major feasibility issue for EVA radiation exposure as shown previously.

For higher energy destinations chemical propulsion capability is limited only by the number of shuttle launches required to place the propulsion system into low Earth orbit. From a cost aspect, the combination of thether mount installation and Earth escape destination is clearly the most attractive since the propulsion system can be placed in low Earth orbit with a single launch of a shuttle-compatible upper stage vehicle (nonintegrated concept option C). However, all installation concepts payloads can reach Earth escape destination with the partially-integrated and nonintegrated option D concepts. Comparison of issues for these concepts, as shown in table 15 reveals that both concepts require one integration operation in the shutdown reactor radiation environment and a total of two in-space integration operations. The characteristic that distinguishes the concepts from each other is the difference in the type of propulsion components to be integrated in the shutdown radiation environment. The partially-integrated concept requires only propellant integration, while the nonintegrated concept requires integration of both the propellant and the upper stage. From a component mass aspect both are approximately equivalent since propellant is about 85 percent of the total propulsion vehicle mass. However, from the operationally more important aspect of component volume, the nonintegrated concept is less attractive because it includes the additional volume of the upper stage. In addition, we have previously defined a propellant integration option for the partially-integrated concept that was based on propellant transfer by pumping into empty propellant tanks that have already been integrated with the upper stage and payload prior to reactor startup. This option is particularly attractive from an operational standpoint since the integration requires only the attachment of fluid couplings. Further, from a structural standpoint, it is advisable to hard mount the propulsion system and payload inside the framework of the space station five meter square boom. This could easily be accomplished before reactor startup when the payload, upper stage and empty propellant tanks are integrated. It is therefore concluded that the partially-integrated concept, using pumpable liquid propellant, is the most attractive scenario for high energy destinations.

The liquid propellant to be used can be either storable or cryogenic. The only criterion for selection examined in this study was that of propellant mass. As shown in table 13, the higher specific impulse of cryogenic propellant yields a significant mass savings of about 35 percent for Earth escape destination. However, other selection criteria may be equally important. For example, the potential liquid propellants include cryogenic hydrogen/oxygen, storable bipropellant NTO/MMH (nitrogen tetroxide/monomethylhydrazine), storable monopropellant hydrazine (N2H4) and storable water electrolyzed to gaseous hydrogen/oxygen. The proposed use of water in space station operations may have particular significance in propellant selection. The state-of-the-art of high specific impulse (370 sec) water electrolysis propulsion is proven in low thrust rocket engines, and electrolysis for space and terrestrial life support applications is well developed. In addition, the nontoxicity and high density properties of water make it an excellent candidate for mass make-up on any volume-limited shuttle payloads required for space station operations. Therefore, the issue of propellant selection for high energy destinations should remain unresolved until further definition of water availability and synergism with space station operations is established.

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2. Bents, D.J.: Tethered Nuclear Power for the Space Station. Energy for the Twenty First Century (20th IECEC), Vol. 1, SAE, 1985, pp. 1.210-1.227. (NASA TM-87023).

TABLE I. - STUDY MATRIX

Installation concepts	Disposal destinations	Chemical propulsion methods
Single 300 kWe tether mount Single 300 kWe boom mount Dual 150 kWe balanced boom mount	Long life orbit - 1000 km Solor orbit - Earth escape - circular heliocentric - planetary swing-by Solar system escape - hyperbolic trajectory - Jupiter swing-by Solar impact - direct - Jupiter swing-by Lunar impact Earth return - controlled reentry - shuttle recovery	Cryogenic propellant Storable propellant

TABLE II. - DEFINITION OF SPACE STATION ACTIVITIES

Activity description	Activity location	Time spent at activity/location		Shielding provided (to eyes) at activity location (aluminum equivalent)		Natural background biological dose rate	
		Percent	Hours per 90 day period	Inches	g/cm^2	$\frac{\text{mrem}}{\text{day}}$	$\frac{\text{mrem}}{\text{hour}}$
Operations in space station	Habitat, lab, logistics module	98.24	2122.1	0.35	2.4	170	7.1
Routine EVA operations	Within shadow shield cone	1.49	32.2	0.13	0.9	215	9.0
Emergency EVA operations[a]	Outside shadow shield cone[a]	0.1	2.0				
Shuttle approach/ departure[b]	From 300 m to docking port	0.15	3.3	0.51	3.5	143	6.0
Shuttle fly-by[c]	300 m from station outside shadow shield cone	0.02	0.4	0.51	3.5	143	6.0
	Total	100	2160				

[a] For boom mount installations only. All operations for tether mount installation are inside shadow.

[b] Two docking operations assumed per quarter.

[c] Stationary or circular maneuver.

TABLE III. - RADIATION EXPOSURE LEVELS - 300 kWe TETHER MOUNT CONCEPT

Activity and location	Dose rate (mrem/hr)			Integrated dose (rem)		
	Background	Reactor	Total	Background	Reactor	Total
Operations inside space station	7.1	2.3	9.4	15.07	4.88	19.95
Operations outside space station (EVA)	9.0	2.3	11.3	0.31	0.08	0.39
Shuttle approach/ dock/departure	6.0	2.3	8.3	0.02	0.01	0.03
Shuttle fly-by	6.0	3.2	9.2	0	0	0
Total				15.4	4.97	20.37

TABLE IV. - MASS STATEMENT - 300 kWe TETHER CONCEPT

Item	Mass, kg
300 kWe reactor power system without shield	6 800
Modified shadow shield	2 300
2-km tether	1 400
Total disposition mass	10 500
Ballast	
Spare reactor power system	9 100
Attached tether	1 400
Attachment and ballast subtotal	10 500
Total launch mass	21 000

TABLE V. - RADIATION EXPOSURE LEVELS - 300 kWe BOOM MOUNT CONCEPT

Activity and location	Dose rate (mrem/hr)			Integrated dose (rem)		
	Background	Reactor	Total	Background	Reactor	Total
Operations inside space station	7.1	1.5	8.6	15.07	3.18	18.25
Operations outside space station (EVA)						
Inside shadow	9.0	1.5	10.5	0.29	0.05	0.34
Outside shadow	9.0	157	166	0.02	0.31	0.33
Shuttle approach/ dock/departure	6.0	[a]330	336	0.02	1.09	1.11
Shuttle fly-by	6.0	57	63	0	0.03	0.03
Total				15.4	4.66	20.06

[a] Time and trajectory average dose rate inside shuttle during approach or departure.

TABLE VI. - MASS STATEMENT - 300 kWe BOOM MOUNT CONCEPT

Item	Mass, kg
300 kWe reactor power system without shield	6 800
Shaped shield	25 500
Total disposition mass	32 300
Attachment boom	1 020
Ballast	
Spare reactor power system ballast	32 300
Attachment boom	1 020
Additional mass at 1 km	2 490
Attachment and ballast subtotal	36 830
Total launch mass	69 130

TABLE VII. - RADIATION EXPOSURE DOSE RATES AND ALLOWABLE TIMES FOR EVA DETACHMENT OF 300 kWe REACTOR POWER SYSTEM

Reactor shutdown time[a]	Total dose rate[b] (mrem/hr) at separation distance, m			Allowable time (hours) for an additional 1 rem exposure at separation distance, m		
	3	10	60	3	10	60
1 month	21.8	10.2	9.0	45.9	98.0	111.1
1 year	13.0	9.4	9.0	76.9	106.3	111.1

[a] Infinite reactor operation time assumed before shutdown.

[b] Includes background dose rate of 9 mrem/hr.

TABLE VIII. - RADIATION EXPOSURE LEVELS - DUAL 150 kWe BOOM MOUNT CONCEPT

Activity and location	Dose rate (mrem/hr)			Integrated dose (rem)		
	Background	Reactor	Total	Background	Reactor	Total
Operations inside space station	7.1	1.5	8.6	15.07	3.18	18.25
Operations outside space station (EVA)						
Inside shadow	9.0	1.5	10.5	0.29	0.05	0.34
Outside shadow	9.0	169	178	0.02	0.34	0.36
Shuttle approach/ dock/departure	6.0	[a]365	371	0.02	1.20	1.22
Shuttle fly-by	6.0	162	168	0	0.07	0.07
Total				15.40	4.84	20.24

[a] Time and trajectory average dose rate inside shuttle during approach or departure.

TABLE IX. - MASS STATEMENT - DUAL 150 kWe BOOM MOUNT CONCEPT

Item	Mass, kg
Two 150 kWe reactor power systems without shield	8 000
Two shaped shield	33 900
Total disposition mass[a]	41 900
Two attachment boom	3 400
Ballast	0
Attachment subtotal	3 400
Total launch mass[b]	45 300

[a] May be disposed of in two separate packages of 20 950 kg each.

[b] May be launched in two separate packages of 22 650 kg each.

TABLE X. - MASS SUMMARY FOR INSTALLATION CONCEPTS

Installation concept	Launch mass, kg	Minimum number of shuttle launches	Disposal mass, kg
300 kWe tether mount	21 000	2	10 500
300 kWe single boom mount	69 130	4	32 300
Dual 150 kWe boom mount		3	
Individual	22 650		20 950
Total	45 300		41 900

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TABLE XI. - SUMMARY COMPARISON OF DISPOSAL DESTINATIONS

Destination	Number of burns or manuevers required	Propulsion system ΔV requirements, m/sec			Time interval between burns, hours	Launch time requirements	Requirement for guidance	Retrieval Availability
		First burn	Second burn	Total				
Long life Earth orbit - 1000 km	2	130	130	260	1	None	On-board event timer	Yes
Solar orbits								
- Earth escape	1	3 200	----	3 200	-------	None	None	Yes
- Circular heliocentric	2	TBD	TBD	4 500	11 500	None	On-board event timer	Yes
- Planetary swing-by	1	4 500	----	4 500	-------	Once every 2 years for alignment	On-board event timer	Yes
Solar system escape								
- Direct	1	8 760	----	8 760	-------	None	None	No
- Jupiter swing-by	1	7 600	----	7 600	-------	Once every year for alignment	On-board event timer	No
Solar impact								
- Direct	1	29 800	----	29 800	-------	None	None	No
- Jupiter swing-by	1	7 600	----	7 600	-------	Once every year for alignment	None	No
Lunar landing	2	4 000	1800	5 800	Several	None	On-board event timer	Yes
Earth return								
- Controlled reentry	1	150	----	150	None	None	On-board event timer	Yes
- Shuttle return	-	------	----	------	-------	None	-----------	Yes

TABLE XII. - CHARACTERISTICS OF EXPENDABLE SHUTTLE-COMPATIBLE UPPER STAGE PROPULSION SYSTEMS AND PAYLOADS

Propulsion system					Installation concept disposal mass fraction, W_L/W_T		
Upper stage	Propellant						
Type	Type	I_{sp}, sec	Maximum capacity, Wp, kg	Mass fraction, MF	300 kWe tether, W_L 10 500 kg	Single 150 kWe boom mount, W_L 20 950 kg	Single 300 kWe boom mount, W_L 32 200 kg
Centaur G-prime	Cryogenic	444	21 000	0.86	0.30	0.46	0.57
Centaur G	Cryogenic	444	13 200	.80	.39	.56	.66
Delta transfer stage	Storable liquid	318	21 000	.86	.30	.46	.57
Inertial upper stage	Storable solid	300	12 500	.85	.42	.59	.69
Transfer orbit stage	Storable solid	292	9 800	.90	.49	.66	.75
Payload assist modules							
PAM-A	Storable solid	274	3 500	.90	.73	.84	.89
PAM-D	Storable solid	285	2 000	.91	.83	.90	.94
PAM-DII	Storable solid	281	3 200	.89	.74	.85	.90

TABLE XIII. - PROPELLANT LAUNCH REQUIREMENTS FOR DISPOSAL TO EARTH ESCAPE - ELLIPTICAL SOLAR ORBIT DESTINATION

Installation concept	Number of shuttle launches required to bring propellant to 500 km low Earth orbit[a]	
	I_{sp} = 450 sec	I_{sp} = 350 sec
300 kWe tether	0.8	1.2
300 kWe boom	2.4	3.7
Dual 150 kWe boom	3.0	4.9

[a] 18 000 kg shuttle capability basis.

TABLE XIV. - CHARACTERIZATION OF INTEGRATION CONCEPTS

Concept integration level before reactor startup		Propulsion/payload elements integrated at time and location			
		Before reactor startup		After reactor shutdown	
		On Earth	In space	On Earth	In space
Full integration		Propellant and upper stage	Payload	None	None
Partial integration		None	Upper stage and payload	None	Propellant and payload
Not integrated	A	Propellant and upper stage	None	None	Payload
	B	None	Propellant and upper stage	None	Payload
	C	None	None	Propellant and upper stage	Payload
	D	None	None	None	Propellant upper stage and payload

TABLE XV. - INTEGRATION CONCEPT ISSUES

Concept integration level		Propellant requirements	Payload/propulsion elements				Capability for high energy destinations
			Integrated in reactor shutdown radiation environment	Integrated in space	Exposed to long-term reactor radiation	Exposed to long-term space environment	
Full integration		Storable only	None	Propellant and upper stage to payload	Propellant and upper stage	Propellant and upper stage	No
Partial integration		Storable or Cyrogenic	Propellant to upper stage and payload	(1) Upper stage to payload (2) Propellant to upper stage and payload	Upper stage	Upper stage	Yes
Not integrated	A	Storable only	Propellant and upper stage to payload	Propellant and upper stage to payload	None	Propellant and upper stage	No
	B	Storable only	Propellant and upper stage to payload	(1) Propellant to upper stage (2) Propellant and upper stage to payload	None	Propellant and upper stage	No
	C	Storable or Cryogenic	Propellant and upper stage to payload	Propellant and upper stage to payload	None	None	Yes-for tether concept only
	D	Storable or Cryogenic	Propellant and upper stage to payload	(1) Propellant to upper stage (2) Propellant and upper stage to payload	None	None	Yes

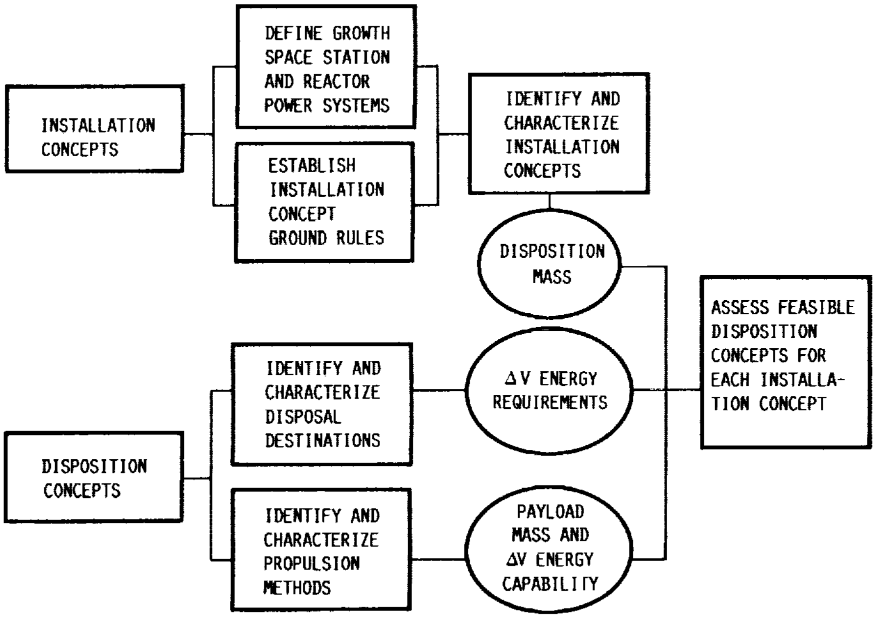

FIGURE 1. - STUDY METHODOLOGY.

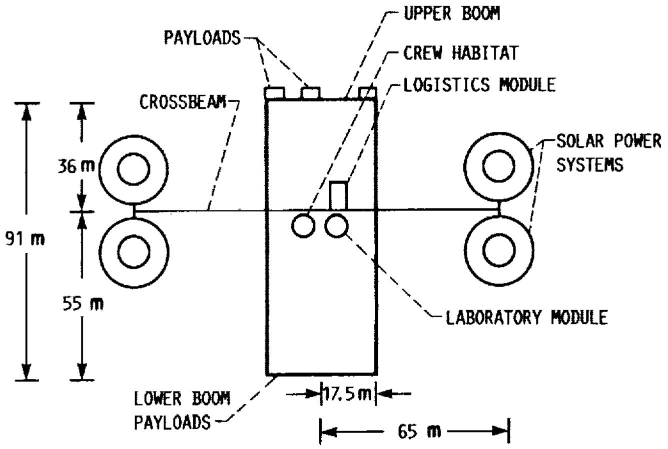

FIGURE 2. - PROJECTED DUAL KEEL SPACE STATION CONFIGURATION.

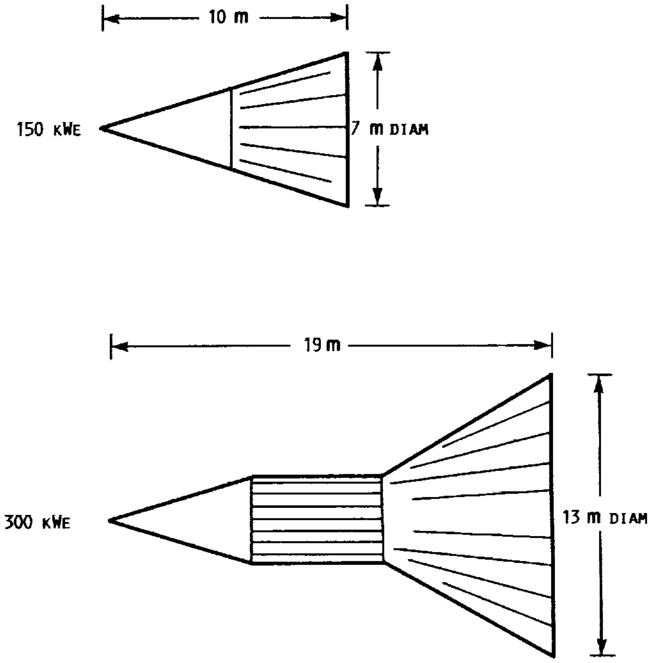

FIGURE 3. - NUCLEAR REACTOR POWER SYSTEM ENVELOPES.

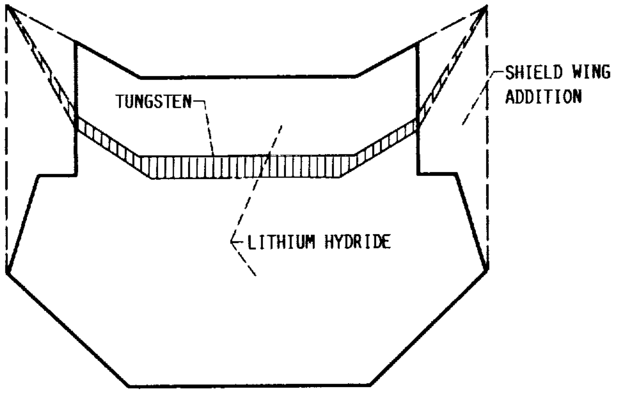

FIGURE 4. - 300 kWe TETHER MOUNT SHIELD CONFIGURATION.

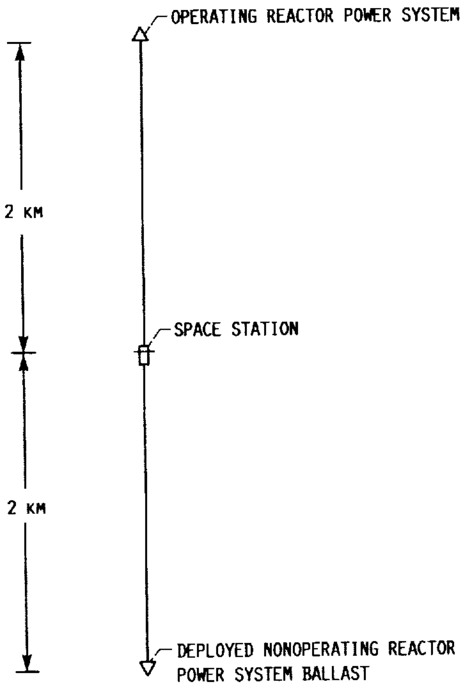

FIGURE 5. - 300 kWe TETHER MOUNT CONFIGURATION.

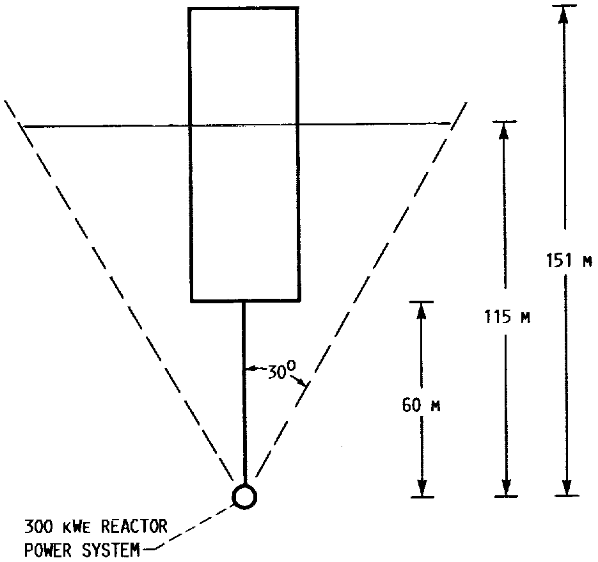

FIGURE 6. - REACTOR POWER SYSTEM - SPACE STATION GEOMETRY, 300 kWe BOOM MOUNT INSTALLATION.

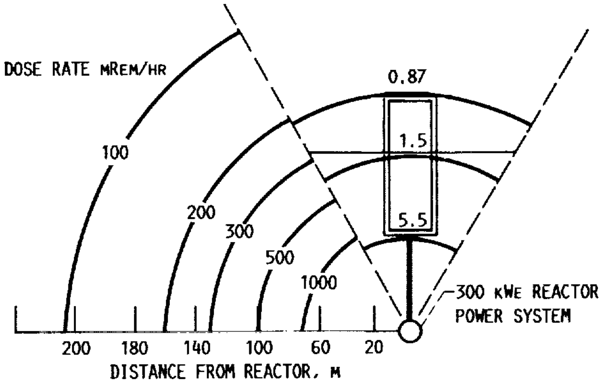

FIGURE 7. - 300 kWe BOOM MOUNT REACTOR ATTRIBUTABLE DOSE RATES.

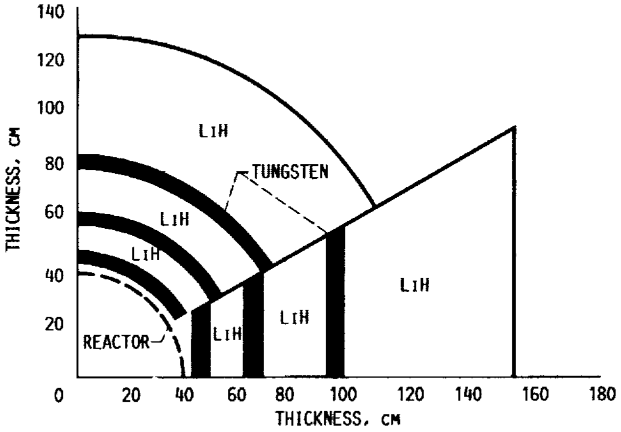

FIGURE 8. - 300 kWe BOOM MOUNT SHIELD GEOMETRY.

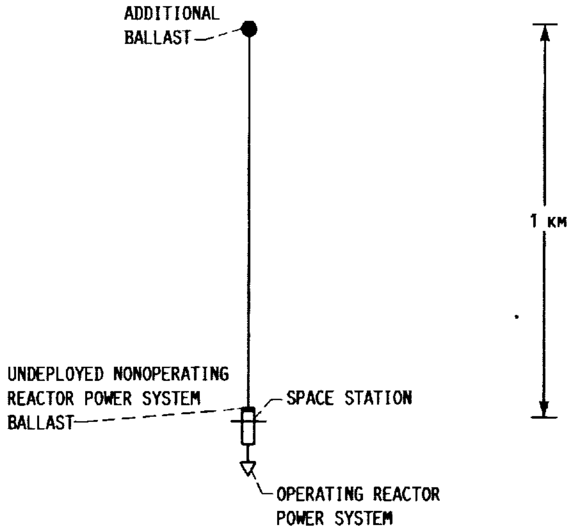

FIGURE 9. - 300 kWe BOOM MOUNT CONFIGURATION.

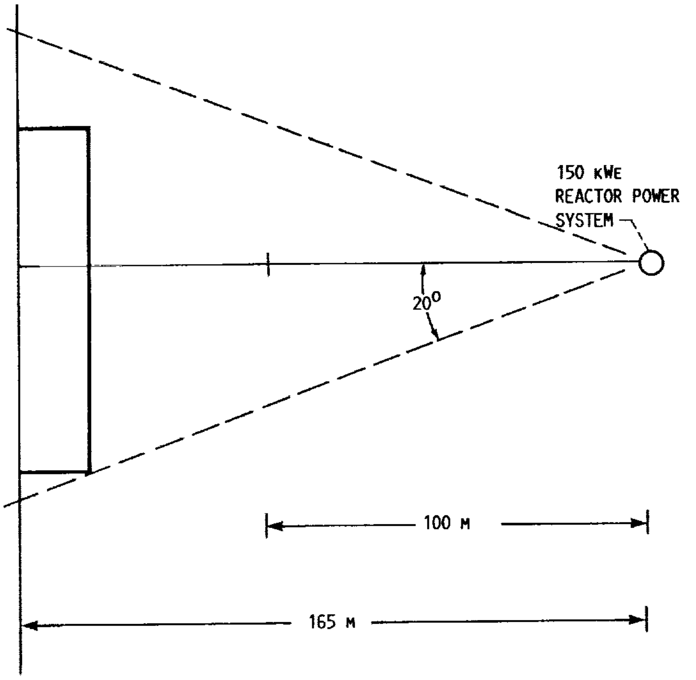

FIGURE 10. - REACTOR POWER SYSTEM-SPACE STATION GEOMETRY, DUAL 150 kWe BOOM MOUNT INSTALLATION.

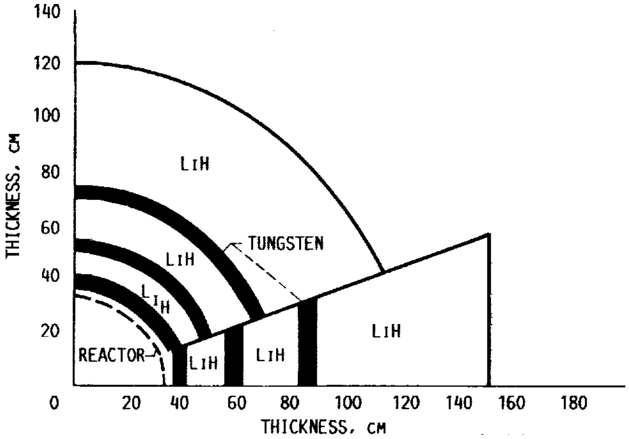

FIGURE 11. - DUAL 150 kWe BOOM MOUNT SHIELD GEOMETRY.

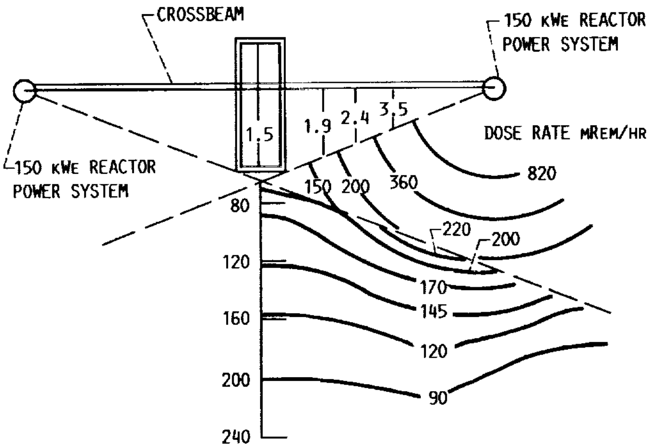

FIGURE 12. - DUAL 150 kWe BOOM MOUNT REACTOR ATTRIBUTABLE DOSE RATES.

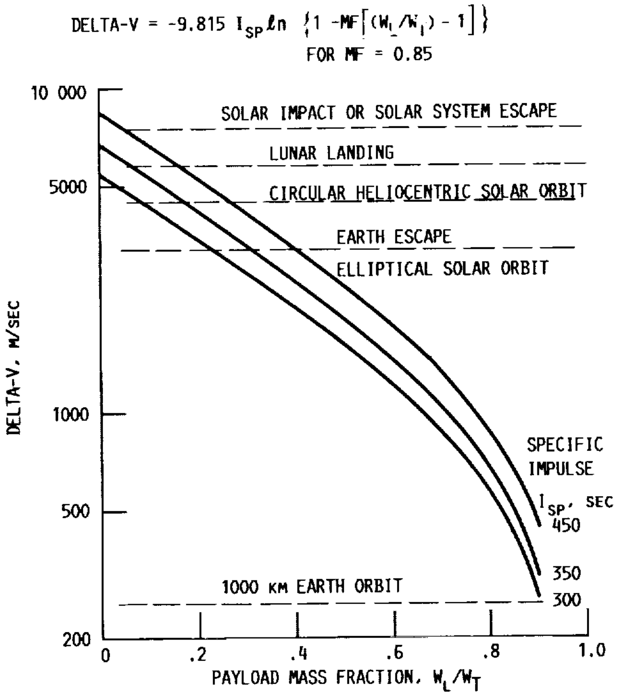

FIGURE 13. - CHEMICAL PROPULSION CAPABILITY.

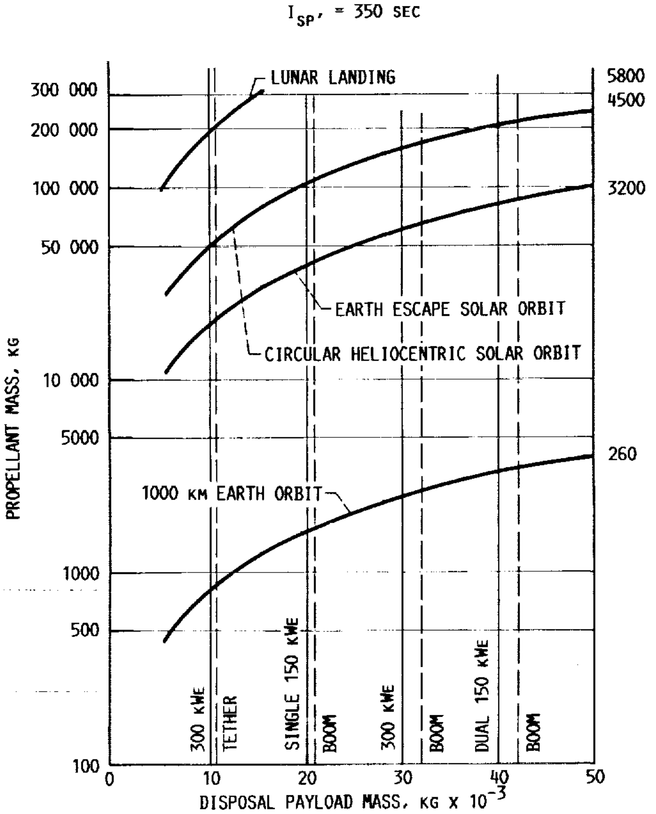

FIGURE 14. - CHEMICAL PROPULSION CAPABILITY, STORABLE PROPELLANT.

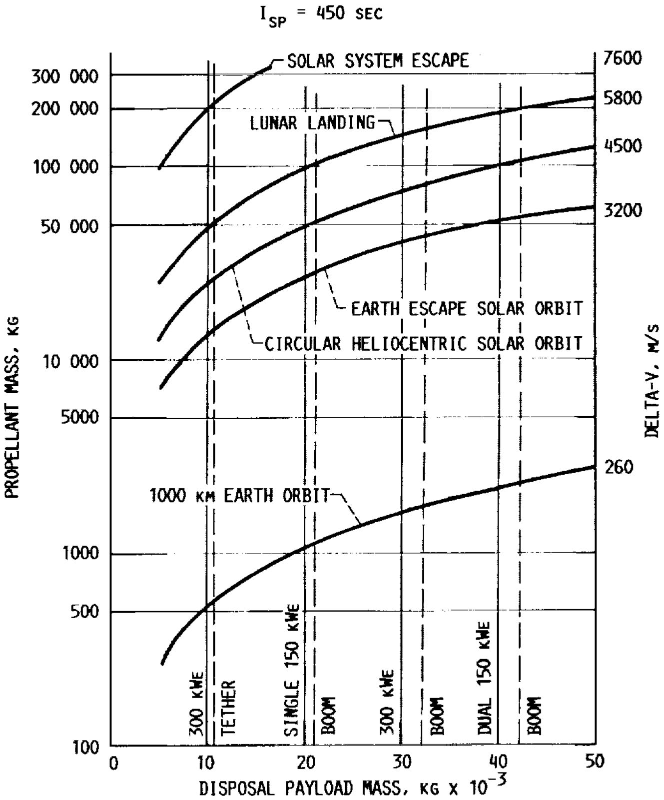

FIGURE 15. - CHEMICAL PROPULSION CAPABILITY, CRYOGENIC PROPELLANT.

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15. Supplementary Notes

16. Abstract

This report presents the results of a preliminary feasibility assessment of installation, operation, and end-of-life disposal options for three nuclear reactor power system concepts applied to a 300-kW growth version of the NASA space station. The assessment was focused primarily on the ramifications of nuclear safety and radiation constraints on space station operations. We also discussed the pros and cons of the three installation concepts and evaluated the merits of existing and near-term chemical propulsion system concepts for the reactor end-of-life disposal to a wide range of ultimate destinations. The three concepts investigated were based on existing SP-100 program technology and used tether, single-boom, and dual-boom attachment to a projected dual-keel space station. A total radiation exposure dose of 20 rem was established for an astronaut's assumed 3-month occupation of the station. This dose consisted of approximately 75 percent natural background radiation and 25 percent reactor-attributed radiation. Human-rated shielding configurations were generated for each concept to provide radiation protection for a projected set of normal operating activities and locations including on-station activity (habitat and laboratory modules), normal and emergency extra-vehicular activity (EVA), and shuttle orbiter approach, docking, and departure. Allowable EVA time for end-of-life separation of a shutdown reactor power system was also considered. Impulsive (chemical) energy requirements and propulsion vehicle system and propellant characteristics were identified for six potential final disposal destinations, ranging from a long-life, 1000-km Earth orbit to a solar system escape trajectory. A variety of existing and near-term expendable chemical upper-stage vehicles, both cryogenic and storable, were studied to identify their operational payload and Delta-V capabilities. Also, a matrix of one-of-a-kind propulsion system components and reactor power system payload combinations was evaluated to identify potential attachment, integration, separation, and radiation safety issues as a function of time of attachment, (i.e., before reactor startup and after reactor shutdown). The results of this assessment have generally confirmed the feasibility of installation, operation, and end-of-life disposal for the three concepts investigated.

17. Key Words (Suggested by Author(s))

Nuclear reactor space power
Growth space station
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