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Tethered Nuclear Power for the Space Station

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ABSTRACT

A NUCLEAR SPACE power system -- the SP-100 -- is being developed for future missions where large amounts of electrical power will be required. Although it is primarily intended for unmanned spacecraft, it can be adapted to a manned space platform by tethering it above the station through an electrical transmission line which isolates the reactor far away from the inhabited platform but conveys its abundant power back to where it is needed. The transmission line, used in conjunction with an instrument rated shield, attenuates reactor radiation in the vicinity of the space station to less than one-one hundredth of the natural background which is already present. This combination of shielding and distance attenuation is less than one-tenth the mass of boom-mounted or onboard man-rated shields that are required when the reactor is mounted nearby. This paper describes how connection is made to the platform (configuration, operational requirements) and introduces a new element -- the coaxial transmission tube -- which enables efficient transmission of electrical power through long tethers in space. Design methodology for transmission tubes and tube arrays is discussed. An example conceptual design is presented that shows SP-100 at three power levels -- 100 kWe, 300 kWe, and 1000 kWe -- connected to space station via a 2 km HVDC transmission line/tether. Power system performance, mass, and radiation levels are estimated with impacts on space station architecture and operation. Specifically, a tethered nuclear power system weighing from 4-1/2 to 25 metric tons, including tether and shield, can deliver 100 to 1000 kWe continuously for 7 yr with a reactor attributable radiation flux, as measured in the immediate vicinity outside the station, of less than 3 mrem per hr. Compared with solar power sources, the tethered SP-100 offers considerable simplification to space station architecture, orientation and operations and reduces orbital drag, at equivalent power levels, by factors ranging from 2.6 to 53.

INTRODUCTION

As the space station program moves forward towards the next century its emphasis will expand beyond the present modest goal of continuous manned presence in low earth orbit for scientific research and observations, to more ambitious objectives which treat near-earth space as an environment to be exploited, rather than just a frontier to be explored. With the coming industrial experiments that are now being planned, there is a growing realization that more facility power will be required onboard than has previously been considered for space station.

The IOC (Initial Operating Capability) station of the Reference Configuration Description,(1)* shown in Fig. 1, is solar powered, in the form of large photovoltaic arrays and regenerative hydrogen-oxygen fuel cells for storage. Solar thermal power systems are also under consideration, since their collection is more efficient and thus requires less area, giving it the capability to grow to somewhat higher power levels than photovoltaics (the solar thermal power system option for the IOC station, at 80 kWe, is tabulated alongside the 75 kWe photovoltaic implementation for comparison in Table 1). They would use a heat engine (Brayton, Rankine or Stirling) combined with receiver thermal storage to allow continuous operation through the dark side of the orbit. According to the mission requirements working group (MWRG) mission model (2), onboard power demand will grow steadily from the IOC installed capability of 75 kWe to 300 kWe by the year 2000.

This transition from IOC to growth space station raises the issue of sources. For modest power levels (within 100 kWe) in low earth orbit, it is generally agreed that solar sources are the easiest to implement despite the collector area, sun tracking mechanisms and dark side energy

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*Numbers in parentheses designate references at end of paper.

storage that is required. But as facility power demand rises past this level, implementation of solar power becomes increasingly difficult. This is due mainly to the linearly increasing amounts of collector area that are required to provide higher power. Growth to 300 kWe will entail a roughly fourfold increase in power system mass and drag cross section over the IOC. Growth to a megawatt will multiply these penalties by a factor of 13.

Clearly, power demand will grow as the space station matures. It will probably grow beyond the 300 kWe currently predicted, which is based upon the MWRG analysis of currently anticipated space station missions. The mission model is considered the most reasonable estimate available but it is conservative since it only considers those missions most likely to be approved within anticipated programmatic and funding constraints, not the full set of all missions, including potential commercial opportunities, which are included in its data base. The 300 kWe estimate does not allow for unanticipated power demands, such as might occur following better-than-expected results from a materials processing experiment. Potential for growth is a fundamental part of continuous manned presence in space; therefore, a desirable attribute for space station is the flexibility to accommodate unplanned growth. When the electrical power consumptions associated with such potential industrial operations as RF induction heating container-less melt processing are considered, there is strong incentive to look at power sources that can accommodate this growth, at the multi-hundred kWe level, more readily than solar.

THE SP-100 POWER SOURCE

There is a nuclear space power system now under development that could meet all of the known (and currently projected) space station needs. This power system, known as the SP-100, is the nuclear reactor system that is being developed jointly by the DOD, NASA and the DOE for future space missions, both civil and military, where large amounts of onboard power will be required (3). Initial focus has been on the 100 kWe class space power system, but its technology is scaleable to higher power. The technology development program, which has been recently taken in under the aegis of the Strategic Defense Initiative (SDI), essentially continues work originally begun in the late 1950's, then almost abandoned after the Apollo era, to develop high performance auxiliary space power sources. The SP-100 program timetable coincides roughly with the launch and early operations of the IOC station. In its present stage of development, SP-100 is a generic class of reactor power system because there are several combinations of reactor and conversion technologies that can be used (4). The system shown in Fig. 2 is based on liquid metal cooled reactor technology and free-piston Stirling power conversion. Other SP-100 system designs include:

(1) liquid metal cooled reactor/thermoelectric direct conversion
(2) liquid metal cooled reactor/in-core thermionics
(3) liquid metal cooled reactor/Brayton turbogenerator

All of these designs are directed to meet the specifications given in Table 2. At 100 kWe delivered to the user, they will weigh less than 3000 kg and will occupy, in stowed configuration before deployment, less than one-third of the space shuttle cargo bay. Table 3 gives a representative mass breakdown, at three output power levels, of SP-100.* The 100 kWe system is a "generic" baseline design sized to meet the Table 2 requirements. The 300 kWe system is a "growth version" which would result if the baseline technology 100 kWe design was scaled to 300 kWe. The 1000 kWe system extends the scaling to megawatt size, nearly the largest complete system that can be deployed from the orbiter payload bay without resorting to on-orbit assembly.

Compared to other space power systems in this range, the unmanned nuclear system is lighter and more compact, mainly because of its internal energy source -- a fission reactor -- and because the reactor is not shielded like the terrestrial nuclear system. On earth the reactor must be totally surrounded by shielding and containment, to prevent release of fission products and life-threatening radiation to the environment. In space, however, there is essentially no environment to protect and, if the system is not manned, no human life to endanger. The radiation shield can therefore be minimal -- a barrier between the reactor and the more vulnerable components that reside with the balance of plant and nearby user payload. The shield provides a "shadow" which attenuates reactor radiation just enough to limit the accumulating physical damage to a level commensurate with reasonable confidence the equipment will survive. For an SP-100 instrument-rated shadow shield, the dose plane specification (6) measured 25 m behind the shield as shown in Fig. 3 is:

Accumulated gamma dosage: 5×10^5 rad

Fast neutrons absorbed: 10^{13} nvt

over an operational lifetime of 7 yr. This is a reduction of about five orders magnitude from the unshielded reactor radiation flux, and in human dosage is equivalent to about 15 rem per hr -- certainly a fatal dose rate, if it is allowed to accumulate over a few hours time.

For unmanned missions, this shielding practice is adequate because all hardware, including the power conversion system and radiator, is located behind the reactor and

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*Based on Stochl and Green (5) and corollary scaling relationships.

within the shadow created by the shield. The user spacecraft also lies within the shadow, behind the power system, to prevent backscatter of the out-of-shadow radiation into the shadow zone. When the user subsystems are of large dimension, such as radar antennas or low temperature radiators, the power system is translated forward further by 10 to 50 meters on an extended boom so that the diameter of the shadow cone -- which subtends a solid angle of 35° to 70° -- widens enough to mask these surfaces as well. As distance behind the shield is increased, the radiation is also further attenuated according to the well-understood inverse-square law.

Since the shadow extends only in a conical zone surrounding the spacecraft, any vehicle that uses this power system creates an exclusion zone everywhere outside the shadow, that prevents an approach by manned spacecraft once the reactor has been unlocked and gone critical. At any location near the reactor powered spacecraft, the intense radiation field produced by the unshielded, operating reactor precludes human intervention.

MANNED SPACE STATION

Historically, the reactor power systems designs meant for manned space platforms, including previous SP-100 space station integration studies (7), have focused on heavily shielded reactors located in close proximity to the station itself; from onboard "flying submarine" configurations that are fully surrounded by four-pi spherical shields (Fig. 4(a)), to boom-mounted configurations (Fig. 4(b)) that jut out from the station a few meters away so that shielding thickness facing away from the spacecraft may be reduced somewhat, saving some weight. In all these configurations the reactor is fully surrounded; the shielding thickness is that which reduces the radiation dose received by an astronaut during his tenure aboard the station to an arbitrarily determined maximum. This exposure limit, currently considered to be the largest dose that can be safely accumulated by a healthy astronaut with no permanent bone marrow damage, is currently set at 35 rem over a 90 day period (8). This is equivalent to an average dose rate of 16.2 mrem/hr.

The radiation exposure limit exerts a leveraged influence on shield mass since it is a limit on total exposure from all sources, including the natural background radiation of space (Table 4). Background radiation varies greatly with orbital position and time, and averages about 400 mrem/hr at the space station's orbit. Within the spacecraft interior this dose rate is attenuated by about two orders of magnitude. If the background dose rate seen inside the spacecraft is 4 mrem/hr, then, the present total exposure limit can allow up to 12 additional mrem/hr to be budgeted for the reactor, which exposes the astronaut to four times the background dose rate he would get if no reactor were present. If the total allowable dose were lowered for any reason, however (not an unreasonable expectation since 16 mrem/hr is over five times the equivalent rate dose allowed by civil occupational guidelines!), the incremental amount of this reduction would be taken preferentially from the reactor's radiation allowance. In this example, a 50 percent reduction of total allowable would force the reactor budget to drop by a factor of three, while a reduction of total allowable to 5 mrem/hr would force it to drop by a factor of 12. This represents a significant weight penalty for the conventional man-rated nuclear system, since the shield is already its largest component.

The onboard four-pi shield of the (7) "submarine" configuration, which must attenuate reactor radiation some ten orders of magnitude to achieve a reactor-attributed dose rate less than 5.72 mrem/hr at a distance of 3 meters from the reactor module, weighs 35 to 45 metric tons. That is more than 15 times the mass of all the other power system components combined. The boom-mounted reactor shield, which keeps the 5.72 mrem/hr dose rate within the spacecraft but allows 200 mrem/hr in any direction away from the spacecraft at 30 meters distance, weighs only 16 to 18 metric tons; this is still more than five times the weight of the other components. Nuclear systems provide power in a compact package, but the price of operating them in close proximity to man is high.

TETHERED NUCLEAR SPACE STATION

A different approach to reactor integration with manned platforms would be to treat the manned platform as a special case of the unmanned spacecraft, and use distance instead of shielding to provide the necessary attenuation. Suppose that a non-man rated nuclear power system were used, but that the payload -- space station in this case -- were put behind the power system at a very long distance inside the shadow. If the power system was 2 km away, for example, the shadow zone surrounding the station would be over 1 km wide -- plenty of room for a space station. The reactor radiation flux passing through that zone immediately outside the station would be, (Table 4) due to the combination of shielding and distance, less than 3 mrem/hr. That is less than one-one hundredth (1/100) of the average natural background radiation flux that is already present at the space station's planned orbital location. An astronaut aboard this station could therefore expect to receive a radiation dose that is essentially the same as what he would receive aboard a non-nuclear powered station.

Implementation of this approach leads to the space station concept shown in Fig. 5. The power system is connected to the space station via a tether which is also an electrical transmission line. It generates electrical power, and emits radiation and waste heat. Power goes via the transmission line to the space station where it is used. The combined spacecraft -- power system and space station elements -- or constellation, flies in a gravity gradient stabilized orbit.

All elements of the constellation are line-oriented along the local gravity gradient and held together by tension. They are distributed around the combined spacecraft center of mass. The living quarters and its associated life support systems are located at the lowest position in the string, counterbalancing the power system. Docking and zero gravity industrial facilities are located to coincide with the center of mass. Two kilometers above this grouping, at the top of the constellation, is the SP-100. Its position and trajectory are superorbital. While the station below is inhabited and the zone surrounding it a site of much activity, the power system is unmanned and the zone surrounding it is an exclusion zone.

It is possible to extend the tethered configuration to much longer lengths. This may be desired as a means for providing modest levels of artificial gravity on board the lower station modules. Figure 6 shows the levels of artificial gravity that can be attained when the lower module flies suborbital, tethered below the combined spacecraft center of mass (circular orbit).

The tether/transmission line considered here is only long enough to provide radiation attenuation, however. The orbit differential between SP-100 and the station is not sufficient to provide much artificial gravity, but it is sufficient to ensure separation between the reactor and manned platform, and stable orbital flight. The dynamics of this configuration have not been fully characterized, but are similar to the tethered satellite (11) which has been treated at some length (the reader is directed to the summary article by Bekey (12)) in the literature.

The nuclear source does not require large arrays of moving solar collectors or dark side energy storage. Orbital drag is reduced, and the EVA exclusion zones associated with solar concentrators and waste heat from thermal power systems are no longer a dominant consideration. Shuttle approach, maneuvering and docking are simplified and manned EVA, including assembly of large structures, is facilitated. The space station is allowed more freedom in its attitude and orientation since the only requirements imposed are those related to gravity gradient stablized flight.

The configuration offers advantages over conventional nuclear concepts because, while the abundant power produced by the nuclear source comes down the tether to the platform, the intense radiation and waste heat do not. The ractor is located a safe distance away from the active portion of space station where operations and experiments take place; therefore it does not interfere with these activities, nor does it impose, aside from the need to maintain a balance about the desired center of mass, architectural constraints on new construction.

The tethered nuclear concept overcomes two of the traditional drawbacks associated with space reactor power systems used for manned platforms (shielding weight, onboard radiation). It does not escape, however, the other critical issues which confront operation of space reactors in low earth orbit. These include considerations of policy, safety, environmental and radiological hazards, and concern for what happens to the reactor after it has been used. Due to these concerns there has developed, within the United States and internationally, a body of regulations which impose strict requirements on how space reactors are launched and operated.

International law, which is embodied in the United Nations "Guidelines concerning the Use of Nuclear Power Sources in Outer Space," imposes general requirements aimed at minimizing the radiological risk to the world's population from nuclear missions, and ensuring that no individual within that population, whether connected with its operation or not, is exposed beyond currently recognized safe exposure limits.

U.S. policy is more specific. Before a reactor powered space mission can be approved it must be subject to rigorous safety analysis that determines probabilities and consequences of accident and exposure events, and the potential risks to personnel, the world's population, and the environment. Every mission is considered individually, on a case by case basis. During each phase of its development the nuclear powered mission must undergo thorough reviews, by three independent government bodies. The operator must show that the nuclear system's launch and subsequent operation will present no undue risks, and that the remaining risks are justified by the benefits of the mission. Final approval authority for launch of the spacecraft rests with the President. These safety restrictions pose development obstacles not faced by other space power technologies. But they are a necessary part of reactor power system use, because of the hazards involved with nuclear materials, and the severe consequences of radiological exposure to human life. Whether it is to be used for manned or unmanned missions, every space reactor must be designed within these restrictions.

To assure safety during launch and deployment, space reactors are mechanically designed so their elements will remain locked in the subcritical position (unlike isotope sources the fission reactor does not become highly radioactive until after it has gone critical and fission products are created) even if there is an accident at the launch pad, or the launch is aborted and the reactor core gets damaged or submerged (a major consideration since water is a moderator). The reactor cannot be unlocked until it has arrived at the orbit where it will be used.

On-orbit safety is observed by keeping the power system in its inert state through deployment, and by not putting the reactor into critical configuration until it is on station, far away from any manned vehicles. For an unmanned nuclear spacecraft launched from shuttle, the reactor is not unlocked or powered up until the spacecraft has completed its transfer to final mission orbit. For the tethered SP-100, the reactor will not be unlocked until well after its installation, including construction of the tether/transmission line, has been completed. The deployment sequence, which requires further study to clarify several issues, involves assembling the transmission line from prefabricated sections previously brought on-site. These sections may be fully modularized or may require additional fabrication before they are joined. Next, the inert SP-100 power system will be taken to the site and installed. On-site system integrity checks and pre-operational tests will take place to the extent that they are required, but reactor testing at power will not occur until the crewmen have retreated to the manned zone.

Operational safety during the nuclear powered mission involves different concerns when manned missions are considered versus unmanned missions. For the unmanned system, operational safety is a concern that only extends to ensuring that the spacecraft and its equipment are sufficiently protected to carry out the mission. For the manned space station power source, however, operational safety extends much farther than the mission itself because there is human life in the vicinity of the operating reactor (even though it is located some distance away). Radiation emanating from the exposed ractor creates an exclusion zone extending several kilometers in all directions (Fig. 7) from the reactor side of the shield. EVA is not permitted inside this zone; manned vehicles must avoid it unless they are shielded. Normally all traffic remains below this area, inside the shadow zone.

For the shuttle approaching space station for orbital rendezvous, additional shielding requirements are imposed since the shuttle must confine its approch trajectory to remain entirely within the shadow zone, and the shadow must extend far enough to ensure that the approaching vehicle does not get a higher dose rate than the station. In order to maintain a uniform dose plane that extends along the space station orbital track from the docking port (the approaching spacecraft does not rise above the along-track trajectory during rendezvous), it is necessary to provide additional off-axis shield attenuation which tapers off gradually according to off-axis cone angle cosine squared. This additional "shaped shadow" edge attenuation increases shield mass by about 50 percent over the "sharp-edged cutoff" shield (70° cone angle) a penalty which is reasonable, considering the low mass of instrument rated shields.

Operational safety extends to the end of the mission, and leads to the question of how the reactor will be disposed of when it reaches the end of its useful life, or has failed. During its operation the reactor has generated an inventory of actinides and fission products, transmuted compounds which are not only highly radioactive but also chemically hazardous; much more so than the unirradiated fuel originally loaded. It is not desirable to have these materials re-introduced to earth. In time they will undergo a process of radioactive decay which eventually results in final compounds less hazardous, but this time is measured in centuries. If the spent reactor is allowed to re-enter at all, it is better to let the decay process take place in space, not earth's biosphere. To ensure that this happens, the regulations restrict operation of nuclear spacecraft to orbits of high enough altitude to be considered "nuclear safe;" that is, an orbit whose lifetime exceeds 400 yr, sufficient time for them to decay. For SP-100's ballistic coefficient this is equivalent to a circular orbit greater than 700 km altitude. The regulations permit operation at altitudes lower than this, but only under the condition that the spent reactor is re-boosted to nuclear safe orbit after its mission has been completed.

Since the space station operates at lower altitude, a tethered power system must include a means to remove and reboost its reactor to nuclear safe orbit; one that is demonstrably effective under all conditions. Whether it is disposing of a reactor that worked flawlessly throughout its life, or getting rid of one that suddenly failed, the provision for reboost must be virtually guaranteed; otherwise the tethered concept is not acceptable. Operating a reactor in low earth orbit carries a significant operational concern since, as events have shown, automatic re-boost methods do not always work.

For the tethered SP-100, end-of-life disposal will probably entail removing the entire power system and replacing it with a new unit. Part or all of the transmission line may be affected. Considering the high degree of integration for this power system, and the damage it will have accumulated over its lifetime from radiation, meteoroids, and material degradation, this appears to be the most expedient approach. Outage will be minimized by maintaining one or more non-nuclear backup power systems for (non-industrial) essential loads, and keeping a spare system (new, unused, inert reactor) with a stockpile of tether sections on-orbit.

Disposal under normal conditions may be accomplished by remote teleoperators and built-in mechanisms that sever the tether connection. The teleoperator ensures that the discarded unit is attached to an orbital transfer vehicle (OTV) and that reboost is properly initiated. The OTV may be nothing more than a battery of electric thrusters, attached to the power system and energized by its residual capacity, that will propel it in an outwardly winding spiral path over several months, to safe orbit. Once the radioactive unit has been removed from the site, its replacement can be installed by manned EVA.

Under emergency conditions reactor disposal can be accomplished by one of several possible means. The tethered SP-100 allows considerable latitude in response to unanticipated events because, unlike a robot spacecraft, the payload is a manned utility platform. Countermeasures can be improvised as necessary when automatic systems fail and normal disposal means cannot be used. Consider a worst case, for example, an event where the system fails at full power, damaging or destroying itself to the extent where no signal or response to commands occur, and where radiation prevents close enough approach to assess the damage. This event is an emergency because primary power is lost. But it is not a life-threatening situation. The accident site is remote and immediate reaction to it is not necessary. If all other methods fail, the damaged reactor can be disposed of by manned EVA, without hazard, from the immediate vicinity of the station. This is done by attaching an OTV to the tether directly above where it connects to the platform, then cutting the power system free SP-100, tether, attached OTV and all. It will drift upwards seeking a new apogee, an additional 12 km in this case, while the station drifts downwards by a lesser amount. When the two bodies are sufficiently separated, the OTV can be fired, towing the discarded power plant away.

SPACE TRANSMISSION LINE

Implementation of the tethered SP-100 nuclear powered space station concept requires development of the tether/transmission line. While structural requirements for this tether, based on the forces required to hold the 3000 kg power system in its superorbital position 2 km above the constellation center of mass, might be met by a common household extension cord (a restraining tension of only 22 nt (5 lb) is necessary in the absence of perturbations), electrical power transmission requirements dictate a more complex structure. For efficient transmission with low mass, the line must be high voltage. It must operate in the plasma environment of near earth space and, at lower orbital inclinations, will sweep out high values of geomagnetic flux. The environment renders conventional high voltage practice unworkable, since the space plasma, which varies in density with altitude (Fig. 8) essentially limits the voltages used on exposed conductor surfaces to 100 to 200 V in low earth orbit (14). Conventional spacecraft electrical design practice avoids the plasma breakdown phenomenon by resorting to lower voltages, and allowing some corona loss to the plasma. For a 2 km transmission line, however, this would lead to excessive conductor cross section. The transmission line must not only be a high voltage line, but it must be electrically isolated from the plasma over its length.

Due to the uncertain behavior of the spacecraft plasma interactions over the transmission line's length and potential drop, conventionally shielded cables or paired wires with layered insulation will probably not be adequate. Insulation materials degrade quickly in the active ion and thermal environment; pinholes, breaks or other openings may, depending on the electric field seen locally by the plasma, give rise to focused leakage currents several times the thermally predicted density, leading to further ionization and breakdown (15). Arcing will permanently damage a conventional cable. If its electrical insulation must cope not only with the stresses of power transmission, which are known, but also the spacecraft plasma interactions, which are to some extent still unknown, the material requirements for this insulation may pose unacceptable development risk for the tether/transmission line.

That risk can be avoided, however, if the transmission line high voltage insulation can be divorced from spacecraft plasma interactions. This is the approach taken here. The electrical cross section of the terrestrial transmission line's wires is re-configured, into a pair of solid wall concentric tubes (Fig. 9). Then, the power circuit is arranged so that the inside tube is used to carry high voltage from the source to the load, while the outside tube provides the return path. Figure 10 illustrates how the source-to-user connection is made for the tethered SP-100. The outside tube becomes an extension of the spacecraft hull, and is ground for source and loads. Power system voltage gradients do not come into contact with the space plasma, but are confined to the annular region between the tubes. The transmission line is insulated by maintaining a vacuum in this region or, alternatively, by filling it with pressurized gas.

This conductor geometry, the coaxial tube, comprises the basic element of the space power transmission line. It consists of two concentric tubes, or a solid rod inside a tube, held in place by open frame shielded spacers, and isolated from each other by an annular gap.

Vacuum is the preferred choice of insulation for the gap because it is essentially weightless (other than the equipment required to maintain it) and it is the most rugged form of insulation. A properly prepared vacuum gap of modest dimension (3 mm to 3 cm) will hold off sinusoidally alternating voltages up to 50 peak kV/cm separation; it can also withstand, when properly conditioned, up to 80 kV/cm dc (16). What is necessary for vacuum insulation is to maintain a pressure low enough that the mean free path inside the annulus exceeds the gap distance by an order of magnitude or better -- the Paschen limit. For centimeter gaps, a pressure less than 10^{-5} is required. That is a pressure higher than the naturally occurring space vacuum at 500 km altitude, which suggests that vacuum insulation for this line might be achieved by simply exposing the unassembled tube sections to space and baking them out prior to assembly.

Pressurized gas could also be used as an insulating medium for the gap. At 1 ATM, both Freon 12 ($CCL_{12}F_2$) and sulfur hexafloride (SF_6) have dielectric breakdown strengths of approximately 75 kV/cm, about two and one-half times the value for dry air. This is close enough to the breakdown gradient for vacuum that, from an electrical insulation standpoint, gas could be considered interchangeable with vacuum even though the physical mechanisms leading to breakdown are different. Resorting to pressurized gas would add the complication of reservoirs, pumping and pressure monitoring systems to the transmission line; on the other hand, it would allow higher line currents due to improved heat transfer. Gap geometry and dimensions would not be affected.

Regardless of the insulating media chosen, however, the coaxial tube's annular gap provides electrical isolation for the transmission line that has several practical advantages. Its breakdown behavior is that of a spark gap; that is, standoff capacity does not degrade with use. Unlike dielectric insulators, the gap in a properly designed system can tolerate repeated overvoltage and arcing with no loss of standoff capacity. That is because the arc, due to the plasma locally formed, is a relatively low resistance path compared to the conductor material leading to and from it. When an arc is struck, its energy will dissipate over a much larger bulk volume than the surface point it touches. Experiments involving repeated discharges in vacuum over 200 kV and 40 kA peak (17) have shown that only minute quantities of electrode surface are vaporized compared to the bulk energy which is dissipated. Once the arc is allowed to extinguish itself and the localized ion cloud to dissipate, the system returns to its former state unchanged. The flashover behavior of the annular gap is repeatable, and can be controlled by design.

The primary consideration is to ensure that arcing, when it does occur, will take place across a void and not along any surface bridging the two conductors (For example, dielectric standoffs). The coaxial tube seperators (Fig. 11) which support the core inside the jacket tube employ a standoff design that was demonstrated for terrestrial high voltage vacuum transmission (18). The standoffs (glass beads) are attached to both sides of an intermediate cylinder (which is electrically floating) which masks them from the walls and forms a positively located equipotential surface. The arcs are forced to cross the gap at the edge of this shield; keeping them outside the shielded region and preventing them from tracking along the bead surface.

DESIGN METHODOLOGY

The space transmission line assembly consists of a regularly spaced array of several tubes, grouped in parallel, and enclosed by a cylindrical meteoroid bumper (Fig. 12). This configuration is the result of an iterative design process, which takes into account the following requirements according to the rationale presented below:

POWER TRANSMISSION - The line is designed to convey the specified power over the required distance, at a fixed percentage of loss, with minimum mass. Methodology is equivalent to terrestrial practice in that the allowed power loss leads to selection of a working voltage and electrical cross section. Equal areas are assigned to the forward and return paths (core and jacket). Although their diameter ratio (core OD to jacket ID) is fixed by minimum E field considerations, the overall tube diameters result directly from selection of working voltage since they are sized to an E field limit (typically 30 kV/cm). The electrical cross sections obtained can, depending on other requirements, be configured into a single tube or an array of several parallel thinwall tubes. Aluminum is the conductor material chosen since it has the highest specific strength for its conductivity.

METEOROID HAZARD - Based on the more pessimistic estimates of plasma interaction with spacecraft structures over potentials of several kilovolts, it is assumed that a single meteoroid puncture could disable a tube. Therefore the tube must be so heavily armored as to prevent its being punctured by the largest meteoroid it may encounter, or it must be paralleled with other tubes. Generally, an array of redundant tubes is used since redundant elements usually give a lower overall system mass and provide a known margin of reserve capacity. The methodology used is similar to the meteoroid survival approach developed for heat pipe radiators (19, 20), where probability that a given number will survive out of an original population of identical elements is a binomial distribution function of the number of elements and the survival probability of a single individual tube.

The transmission tube must be designed to resist puncture by all meteoroids no larger than a certain size. This size, which is an upper limit on what the transmission line can be expected to encounter during its life, is estimated by the meteoroid flux distribution model (21):

$$\log N_t = -14.37 - 1.213 \log M$$

where N_t is number of particles of mass M or greater (M is between 1 μg and 1 g) per square meter per second.

The model is used to predict probability that a meteorite no larger than mass M will strike exposed area A (n times or less) during mission time T:

$$P\ (\text{Fewer than n strikes}) = \exp\ (-N_t AT) \sum_{r=0}^{r=n} \frac{N_t AT}{r!}$$

Since larger areas and longer missions imply that larger meteorites will be encountered, there is an incentive for reducing transmission tube size.

The penetration resistance of an individual tube depends on its wall thickness. For the range of meteoroid velocities encountered, impact energies are dissipated by hydrodynamic shock rather than by fracture, so that the meteoroid effectively vaporizes on contact, along with material in the impact zone. Because of high velocities, wall thickness required to prevent penetration can be minimized by separating it into two components; the relatively thick main wall, and a thin barrier of sacrificial material placed in front of the main wall by a buffer space of several meteoroid diameters or more. The thin wall, referred to as a bumper, serves to break up and disperse the incoming meteorite into a cloud of molten droplets and smaller fragments which then impact the main wall over a wide area instead of a single point. Penetration resistance can thus be increased not only by added mass in the form of more material thickness, but also by added space, in the form of wider bumper gaps.

Figure 13 shows the minimum mass combinations of bumper to main wall thickness ratio, bumper gap versus meteoroid diameter D experimentally determined (22) for aluminum projectiles fired into aluminum targets at impact velocity $V/C = 6$ (C in this case is the speed of sound in the solid metal). Assuming equivalent meteoroid mass, this relation can be used to estimate the wall thickness, bumper spacing and thickness required to prevent tube puncture.

Application of meteoroid survival criteria results in the array of parallel tubes shown in Fig. 12. The individual tubes are all enclosed by a common bumper that is spaced at least a minimum distance away from the outer wall of each tube. The array will be arranged in a symmetric pattern, made compact so that a cylindrical bumper of minimum circumference will enclose it with adequate spacing, but spread out enough to lower the probability that a single hit will damage more than one tube. When individual transmission tubes are considered, typically more wall thickness is required for meteoroid protection than is necessary for the power transmission requirements. This has negative impact on array mass, but beneficial impact on other aspects, since thicker tube walls have more cross section and will allow lower voltages to be used.

STRUCTURAL REQUIREMENTS - The tether/transmission line is the element which holds the constellation together against the gravity gradient of low earth orbit and forces of orbital flight, perturbations due to anomalies, disturbances caused by station operations such as mass transfer, docking and so on. While detailed analysis of tethered space station dynamics including propulsion system interactions has not been made, some useful insight can be gained by considering the simple case (23) of a uniformly stressed tether in orbit connecting a superorbital object of mass M to the constellation center of mass. If R is the superorbital radius traversed by mass M and Rcm is the circular orbit radius of the entire constellation, the tether material cross section required at Rcm to hold M in position is given by the expression:

$$A \approx Ao \exp\left(\frac{rho}{sig}\, GeRe\left(\frac{Re}{R} + \frac{1}{2}\,\frac{ReR^2}{Rcm^3} - \frac{3}{2}\,\frac{Re}{Rcm}\right)\right)$$

where rho is the material density and sig the tensile stress; Ge is the gravitational force at radius Re (zero altitude), and the initial cross section Ao, at superorbital position R, is related to M by:

$$A = \frac{MGe}{sig}\;\frac{Re^2}{R^2} - \frac{R\;Re^2}{Rcm^3}$$

At short tether distances the cross-sectional area and its variation are small. The 2 km SP-100 transmission line, for example, has more than enough cross section anyway, due to the meteoroid survival requirement. Over long tethers, however, the exponent term for cross section grows rapidly and, for materials of normal specific strength (such as aluminum) the tether must be tapered to a cross section far in excess of that required for electrical transmission. If a 250 km tether were used to separate SP-100 from space station, for example, its cross section at the station (assuming 10 ksi maximum stress) would be more than 250 times its cross section at SP-100, just to support the larger gravity gradient and additional (compounded) tether mass.

For tethers of moderate length (2 to 20 km), the design process does not need to consider the structural requirements separately, because the material cross section required to satisfy electrical and meteoroid survival criteria is more than adequate to hold the power system against the centripetal forces of its superorbital position (the 2 km tether experiences less than 25 psi stress). For these cases the design process can be abbreviated to the procedure outlined in Fig. 14 (opposite page), where tensile loading is not considered.

EXAMPLE SPACE STATION TRANSMISSION LINES

The iterative design process (Fig. 14) was used to generate tether/transmission line designs for the nuclear powered space station. Three cases, corresponding to the reactor power sources tabulated previously, were considered:

1. 100 kWe transmission line, connecting the "generic" SP-100 to space station
2. 300 kWe transmission line for growth SP-100
3. 1000 kWe transmission line that accommodates a megawatt class SP-100 powering the growth space station

In all three cases, the transmission line requirements were:

(1) Two kilometer separation

(2) Transmission loss, with all tubes operating, less than two percent

(3) 10 yr reliability (survival probability) of 0.99 or greater

When this design process was followed, the transmission line geometry and dimensions shown in Figs. 15(a) to (c) resulted. Depending upon power level, working voltages range from 4.5 to 7.9 kV. All tubes were sized to a gradient of 20 kV/cm. The mass estimate for complete transmission line assemblies was based on three coaxial tubes and a bumper with additional percentage assessments, based on material cross section, for the tube and bumper supports, and an additional fractional weight, based on annular void volume of each tube, for standoff insulators and vacuum equipment. Depending on the power level, transmission line assembly masses ranged from 422 to 1195 kg/km. The complete set of transmission line characteristics, including design operating conditions, are summarized in Table 5.

EXAMPLE SPACE STATION POWER SOURCES

With the transmission lines characterized, it is possible to estimate the overall sizes, weights and drag cross sections of tethered reactor power sources. The tethered SP-100 systems, shown in Table 6, are adapted from Table 3 by adding the tether/transmission line and its high voltage power processing at back end, and substituting the heavier "shaped shadow" edge attenuation (which maintains uniform dose plane along space station orbital track) shield for the original conical shield. A comparison with the solar sources of Table 1 illustrates how compact man rated nuclear power sources can be made through tethering.

Taking the generic SP-100 system weights and frontal area and combining them with the values tabulated for the 100 kWe transmission line, we obtain a power source that is about half the weight of either solar system, and less than half the drag area this includes the broadside cross section of the 2 km tether. If we combine the 300 kWe growth SP-100 with the 300 kWe transmission line, the result is a power source slightly heavier than the IOC solar system but four times the capacity. Its drag cross section, including tether, is still significantly less (266 versus 531) than the lowest drag (thermal) solar power source. When drag cross section is used as the basis for comparison, only the megawatt class SP-100 and 1000 kWe tether are equivalent to the 80 kWe solar thermal system. This source is three times as heavy as the solar system; but it delivers 12.5 times as much power.

All of these sources weigh considerably less than the shielding which would be required if the reactor were mounted near the station. Yet astronaut radiation seen onboard the station has been reduced to essentially the same level as for non-nuclear sources.

CONCLUSIONS

Tethering, as we have shown in the foregoing discussion, appears to be an effective way to integrate the SP-100 nuclear system with manned space platforms. The advantages over previous reactor power system integration methods include

(1) reduced shield mass and reduced system mass

(2) greatly reduced astronaut radiation exposure

(3) reduced operational hazard

Tethering is made possible by the coaxial transmission tube array, a new element which provides an efficient means of electrical power transmission in space with reasonable size and weight. The tethered nuclear power sources have significant mass and performance advantages over other power sources. Therefore the SP-100 nuclear space power system should also, when combined with the tether/transmission line described here, merit further study as a candidate prime power source for the manned space station.

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TABLE 1. - IOC SPACE STATION SOLAR POWER SOURCES

[JSC 1998, "Space Station Reference Configuration Description."]

Installed power (continuously available)	Photovoltaic 75 kWe		Thermal 80 kWe
Mass			
collectors	4459 kg	2-modules (Includes concentrators, thermal receivers and storage, power conversion and radiators)	8400 kg
energy storage	2289 kg		
radiators and heat exchangers	489 kg		
PMAD	899 kg		899 kg
Total	8136 kg		9300 kg
Orbital drag cross section	1784 m^2		531 m^2
No. exclusion zones in EVA area	none		2

TABLE 2. - SP-100 DESIGN REQUIREMENTS

Power output:	(remaining at end of life)	100 kWe baseline 300 kWe growth 1000 kWe megawatt class
Lifetime:	at full power power level unspecified	7 yrs 10 yrs
Radiation:	(measured inside shadow, total integrated dose deposited in silicon, dose plane located 25 m behind shield)	fast neutrons 10^{13} nvt gammas 5×10^5 rad
Safety:	meets OSNP-1, "Nuclear Safety Criteria and Specifications for Space Nuclear Reactors," DOE meets NHB1700.7A, "Safety Policy and Requirements for Payloads Using the Space Transportation System," NASA meets JSC 13830, "Implementation Procedures for 515 Payloads System Safety Requirements," NASA JSC meets JPL 601-4 rev A, "JPL Flight Projects Safety Guidelines and Requirements," NASA JPL	
Reliability:	95 percent probability of success (no failures); no single point failures	
Environment:	any sun-relative orientation at 1 AU; any location within Van Allen belt	
Size and weight (to bussbar, 100 kWe system):	3000 kg, and less than 1/3 shuttle cargo bay	

TABLE 3. - MASS SUMMARY FOR REPRESENTATIVE SP-100 SPACE REACTOR POWER SOURCES

Mass, kg	100 kWe	300 kWe	1000 kWe
Reactor (1100 °K)	400	510	685
Shield (Instrument rated, conical shadow)	350	565	950
Power conversion system and heat transport (Stirling engine, 1.9 temperature ratio)	1010	2460	6950
Radiator (500 °K main and auxilary)	730	2190	7300
Power processing (to 400 VDC)	200	460	1125
Structure	270	620	1700
Total	2960	6805	18710 kg
Based on Stoehl and Green (5) and corollary scaling relationships.			

TABLE 4. - RADIOLOGICAL EXPOSURE FROM SP-100 (100 kWe) at 300-400 km ORBIT

Natural background[a] at orbit inclination:	Typical space walk		Within Space Station	
	MEV/cm^2/da	REM/hr	MEV/cm^2/da	REM/hr
0°	10^8	0.002	10^4	2×10^{-7}
30°	2×10^{10}	.4	2×10^8	0.004
60°	$\sim10^{11}$	2	$\sim10^9$	.02
90°	$\sim10^{11}$	1	$\sim10^9$	.02

Reactor operating gammas	Out-of-shield cone REM/hr	In shield shadow REM/hr
100 m from reactor	11	0.51
316	1	.051
1000	0.1	.0051
2000	.025	.00125
3160	.010	.00051
10000	.001	.00005

Reactor operating fast neutrons	Out-of-shield cone REM/hr	In shield shadow REM/hr
100 m from reactor	1441	0.42
316	144	.04
1000	14	.004
2000	3.5	.001
3160	1.4	.0004
10000	0.14	.00004

[a] Reference 9 "Space and Planetary Environment Criteria Guidelines for use in Space Vehicle Development," NASA TM-82501 and (10) "Models for the Trapped radiation Environment" NASA SP3024.

TABLE 5. - SP-100 - 2 km TETHER/TRANSMISSION LINE SPECIFICATIONS

	100 kWe	300 kWe	1000 kWe
Electrical			
voltage, kV	4.5	5.6	7.8
current each leg, A	7.4	17.9	42.7
resistance (ohm/km)	1.804	1.154	0.589
(round trip ohms)	7.216	4.616	2.356
capacitance picofarad/km	556	556	556
inductance henry/km	10^{-12}	10^{-12}	10^{-12}
Thermal (250 °K background)			
surface temperature, °K	253	259	273
core temperature, °K	270	304	353
Mechanical			
Mass, 3 tubes with bumper	660	1050	1841
mounting rings and spacers	85	140	240
vacuum equipment	100	160	308
Total mass of assembly	845 kg	1350 kg	2389 kg
Stress, (nominal, 500 km circular orbit)	24.7 psi	37 psi	53 psi
Meteoroid Hazard			
Survival Probability (10 yr mission)			
individual tube	.810	.827	.833
3 out of 3 surviving	.531	.566	.572
2 out of 3 surviving	.904	.921	.923
1 out of 3 surviving	.992	.995	.995

TABLE 6. - TETHERED SP-100 REACTOR POWER SOURCES

	100 kWe	300 kWe	1000 kWe
Mass, kg			
reactor	400	510	685
shield (instrument rated, shaped shadow, uniform dose plane)	525	848	1425
PCS and heat transport	1010	2460	6950
radiator	730	2190	7300
power processing (includes HV dc/dc and inverters)	800	1800	4500
structure	270	620	1700
tether/transmission line assembly	845	1350	2389
Total	4580	9780	24950
Drag cross section, m^2			
SP-100	22	66	218
tether	180	200	220
Total	202	266	438

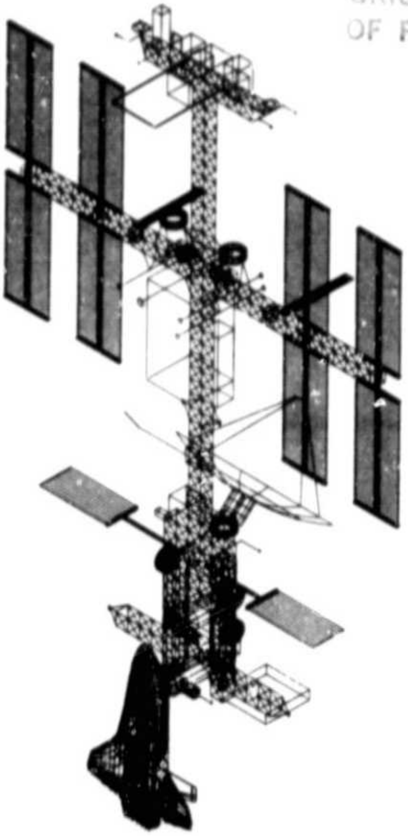


Figure 1. - Space station reference configuration IOC.

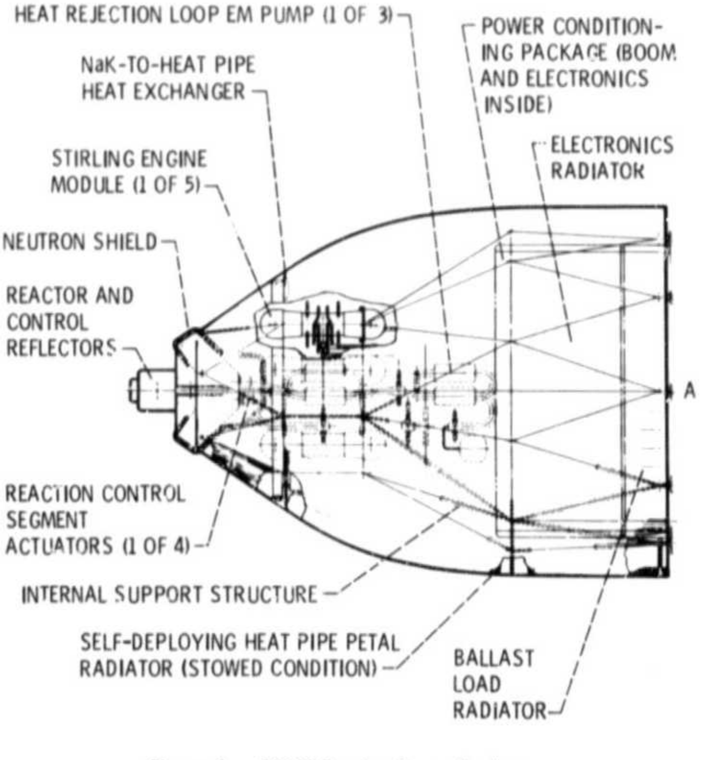


Figure 2. - SP100 Reactor Power System.

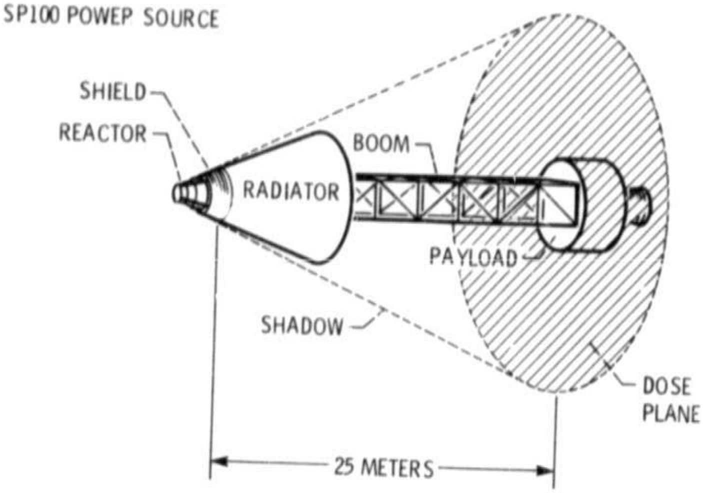
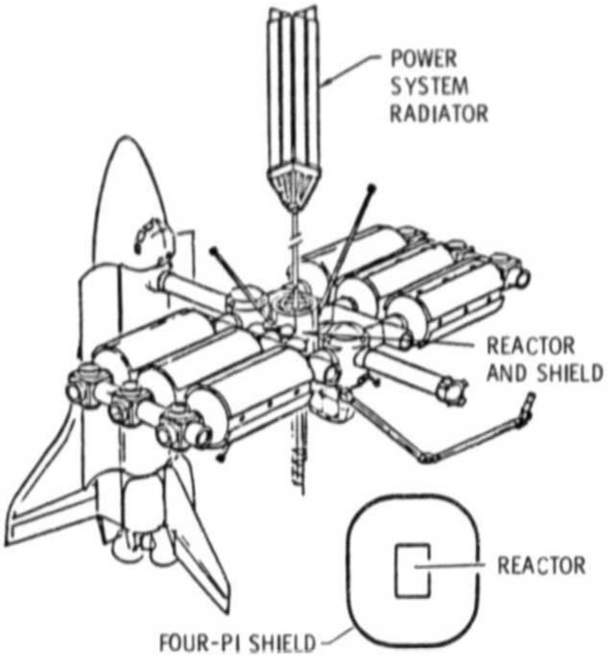
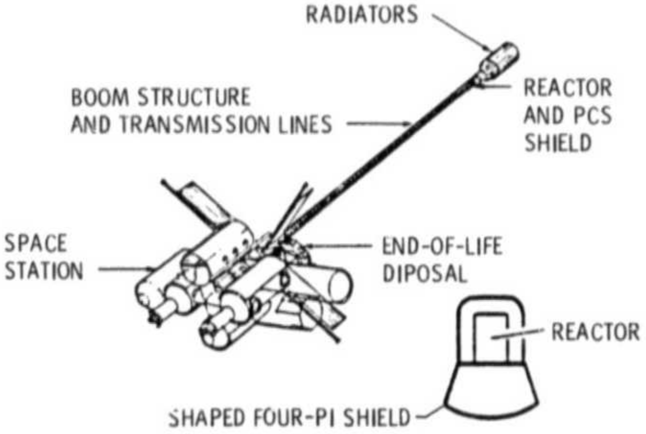


Figure 3. - Unmanned spacecraft.



(a) Reactor Near Space Station CG ('Submarine' Concept).



(b) Boom-Mounted Reactor System.

Figure 4.

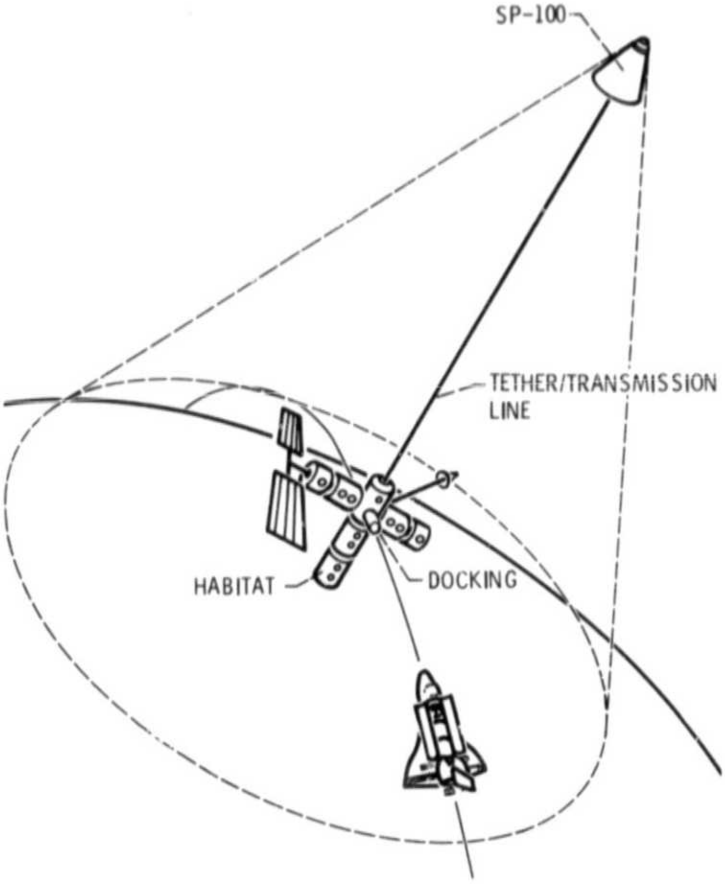


Figure 5. - Space station, powered by tethered SP-100.

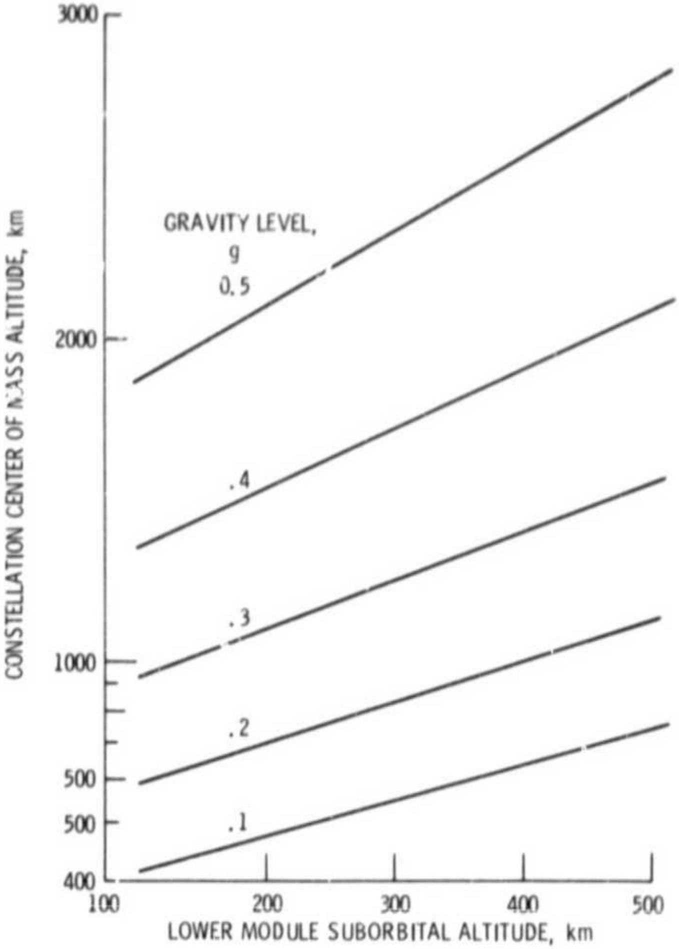


Figure 6. - Gravity level at lower module for different altitudes (circular orbit).

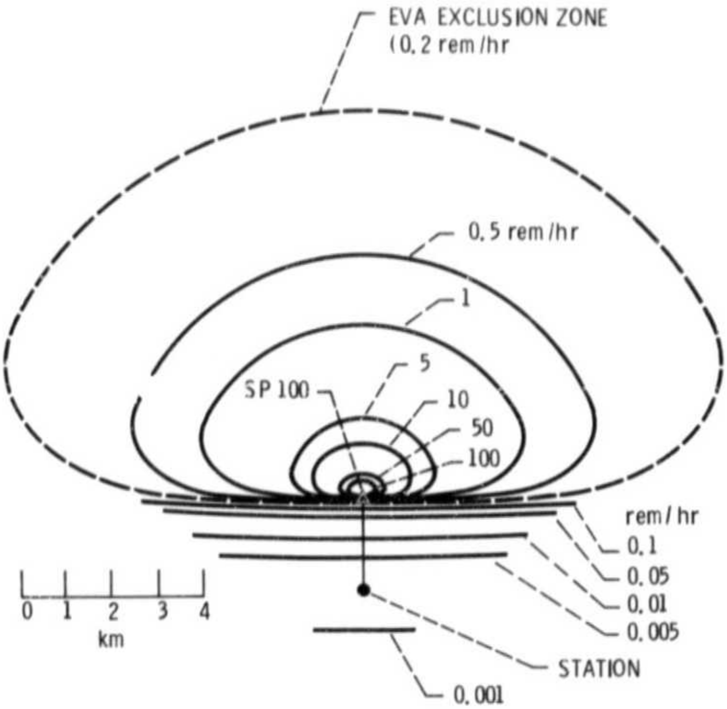


Figure 7. - Reactor attributed dose contours for tethered nuclear space station.

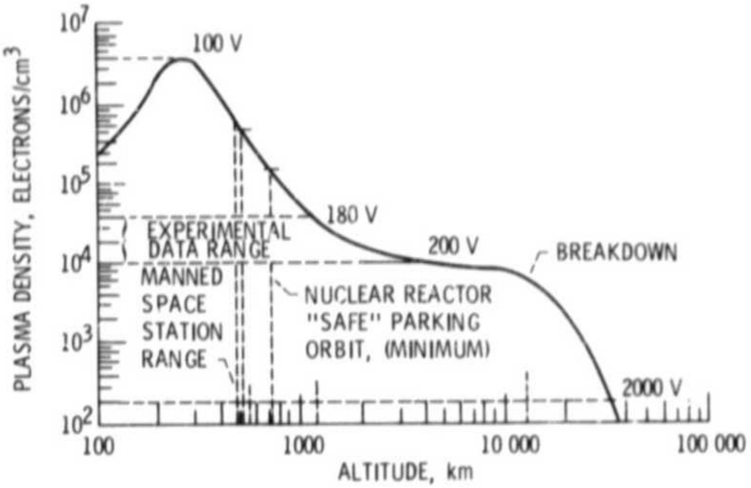
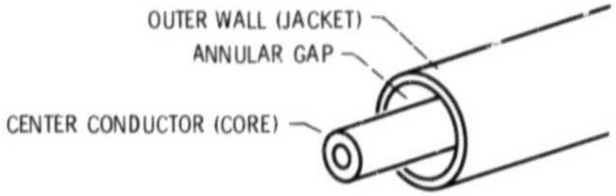


Figure 8. - Plasma density and breakdown voltage vs. altitude. From Kennerud (ref. 13) "High Voltage Solar Array Experiments" NASA CR 121280 (Boeing).



OUTER WALL IS SPACECRAFT, POWER SYSTEM ELECTRICAL GROUND
CORE IS SEVERAL (TO TENS OF) kV POSITIVE
GAP IS INSULATED BY VACUUM ($\leq 10^{-5}$, PASCHEN LIMIT) OR BY PRESSURIZED GAS
CORE AND JACKET HAVE SAME CROSS SECTIONAL AREA
TUBES ARE ALUMINUM -- LOW MASS, HIGH CONDUCTIVITY

Figure 9. - Coaxial transmission tube.

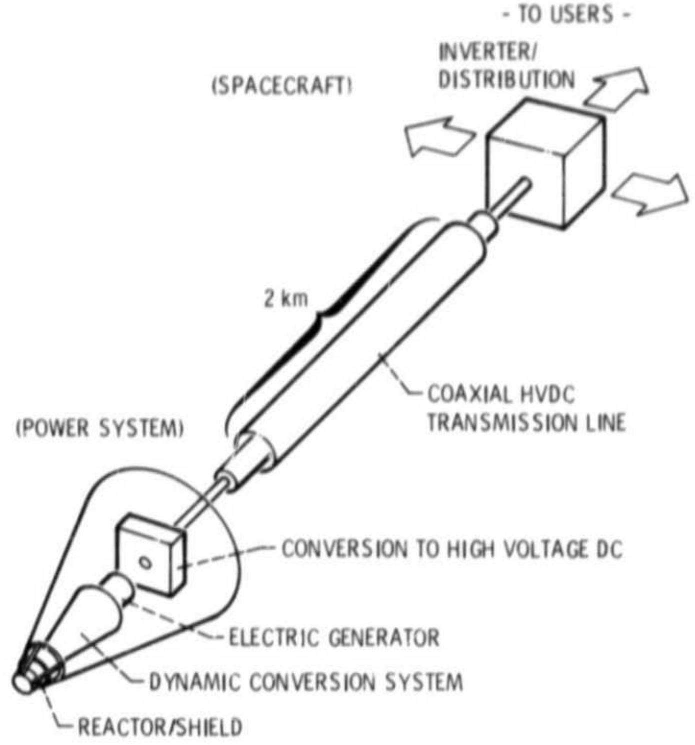
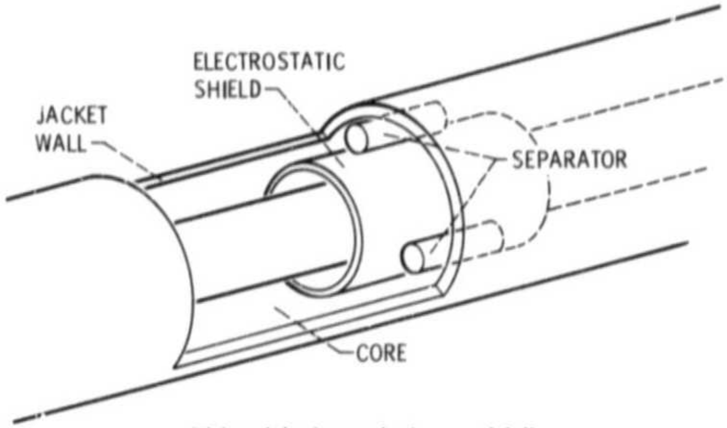
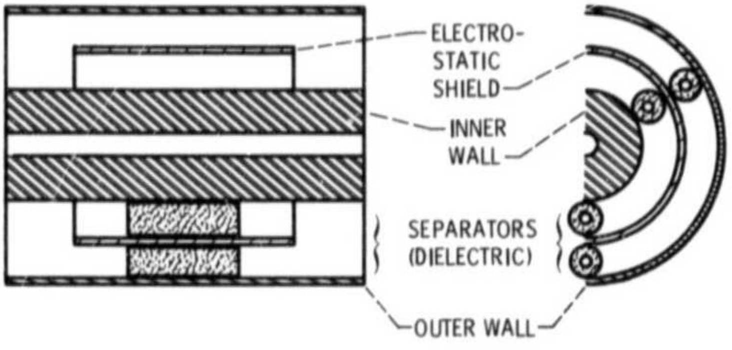


Figure 10. - Manned space station connection to nuclear power system.



(a) Insulator/separator/spacer detail.



(b) Electrostatic shield provides flashover protection.

Figure 11. - Cutaway view of transmission tube and separators.

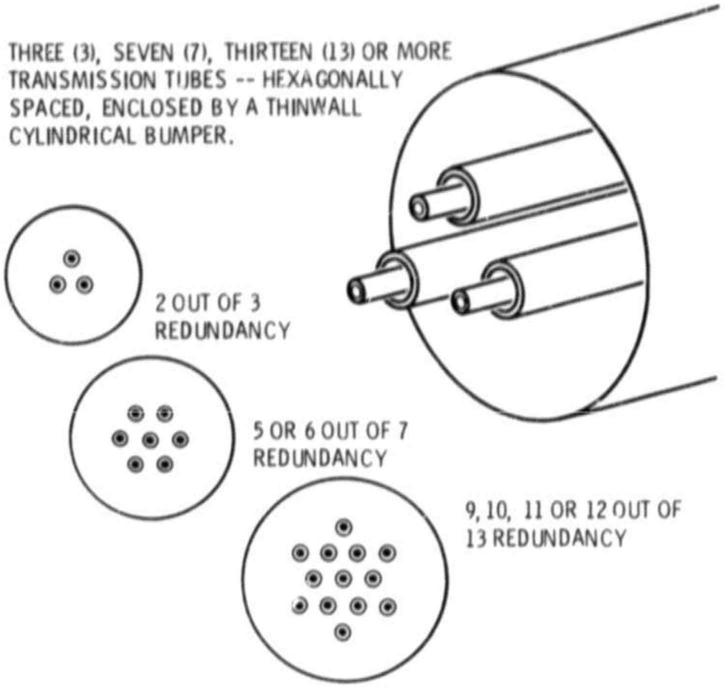


Figure 12. - Parallel redundancy for reliability.

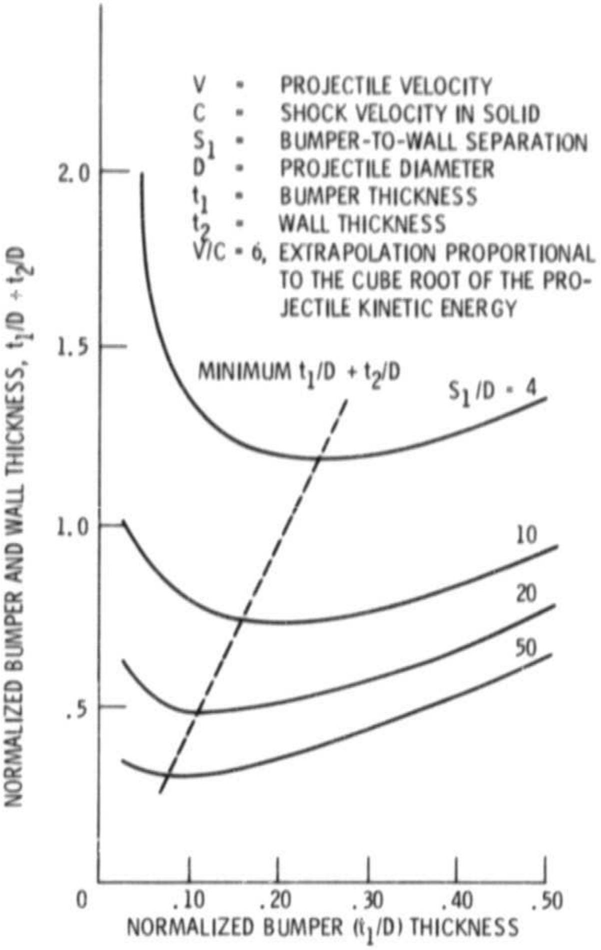


Figure 13. - Minimum weight two-sheet aluminum barrier to prevent penetration (from ref. 22).

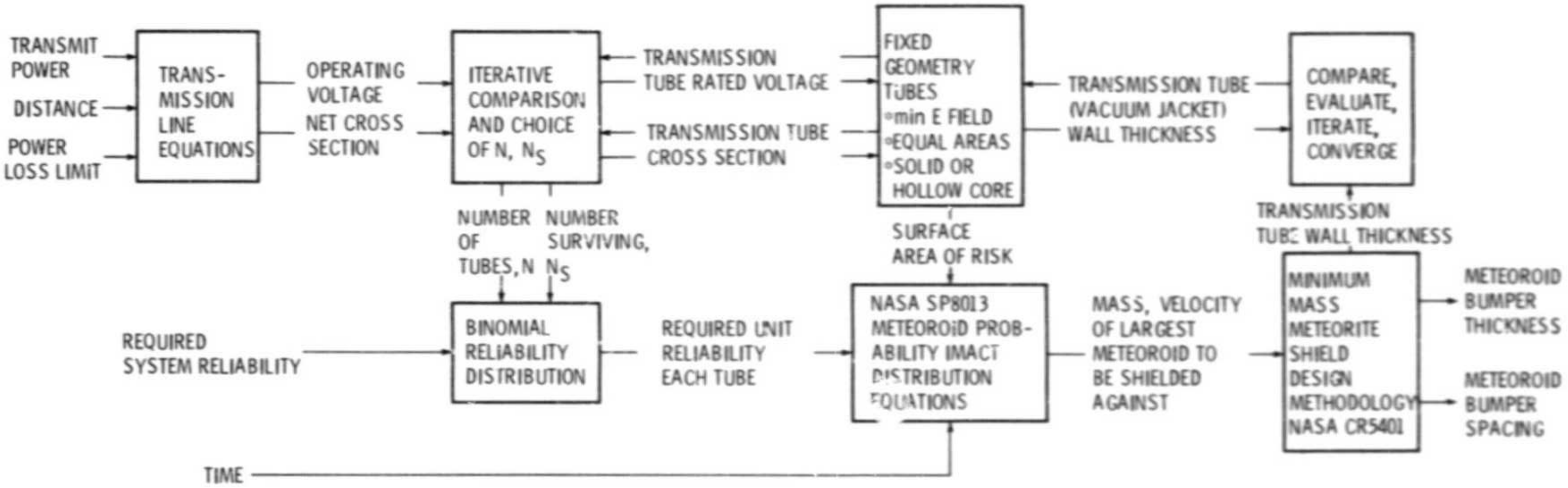
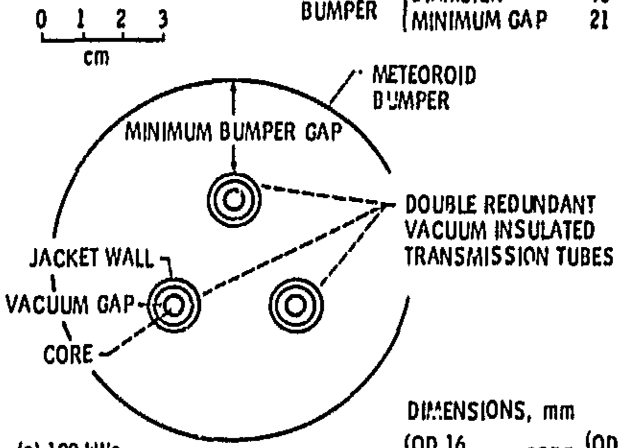


Figure 14. - Abbreviated Design Procedure.

DIMENSIONS, mm

TUBE {OD 13, ID 12.2} CORE {OD 4.5, ID (SOLID)}

BUMPER	THICKNESS	0.1
	DIAMETER	90
	MINIMUM GAP	21

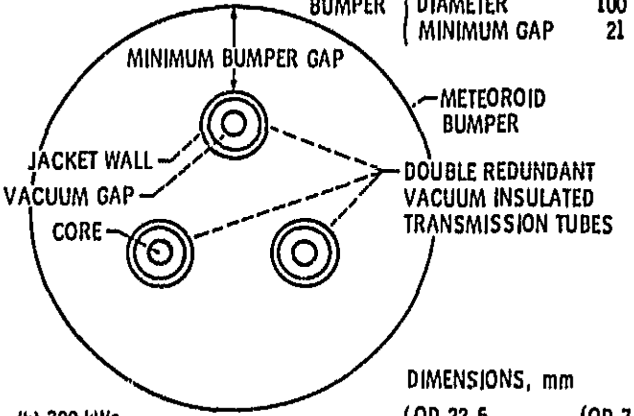


(a) 100 kWe.

DIMENSIONS, mm

TUBE {OD 16, ID 15} CORE {OD 5.5, ID (SOLID)}

BUMPER	THICKNESS	0.15
	DIAMETER	100
	MINIMUM GAP	21

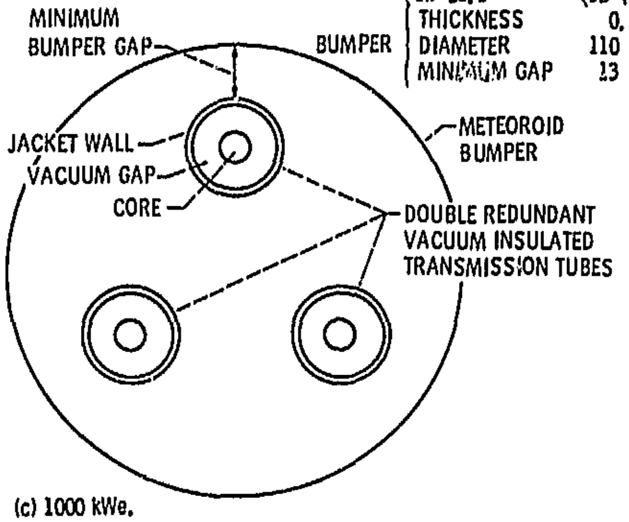


(b) 300 kWe.

DIMENSIONS, mm

TUBE {OD 22.5, ID 21.1} CORE {OD 7.8, ID (SOLID)}

BUMPER	THICKNESS	0.15
	DIAMETER	110
	MINIMUM GAP	13



(c) 1000 kWe.

Figure 15. - Space transmission line.

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15. Supplementary Notes

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16. Abstract

A nuclear space power system the SP-100 is being developed for future missions where large amounts of electrical power will be required. Although it is primarily intended for unmanned spacecraft, it can be adapted to a manned space platform by tethering it above the station through an electrical transmission line which isolates the reactor far away from the inhabited platform and conveys its power back to where it is needed. The transmission line, used in conjunction with an instrument rated shield, attenuates reactor radiation in the vicinity of the space station to less than one-one hundredth of the natural background which is already there. This combination of shielding and distance attenuation is less than one-tenth the mass of boom-mounted or onboard man-rated shields that are required when the reactor is mounted nearby. This paper describes how connection is made to the platform (configuration, operational requirements) and introduces a new element the coaxial transmission tube which enables efficient transmission of electrical power through long tethers in space. Design methodology for transmission tubes and tube arrays is discussed. An example conceptual design is presented that shows SP-100 at three power levels 100 kWe, 300 kWe, and 1000 kWe connected to space station via a 2 km HVDC transmission line/tether. Power system performance, mass, and radiation hazard are estimated with impacts on space station architecture and operation. Specifically, a tethered nuclear power system weighing from 4-1/2 to 25 metric tons, including tether and shield, can deliver 100 to 1000 kWe continuously for 7 yr with a reactor attributable radiation flux, as measured in the immediate vicinity outside the station, of less than 3 mrem per hr.

17. Key Words (Suggested by Author(s)) Space nuclear power Space Station Space tethers Space power transmission	18. Distribution Statement Unclassified - unlimited STAR Category 20

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