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TITLE

SPACE REACTORS - WHAT IS A KILOGRAM?

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ABSTRACT

The use of nuclear electric propulsion can triple the payloads to GEO for a single Shuttle launch. Life orbits of 300 years can be used to allow most of the fission and activation products to decay before a reactor reenters the biosphere. Enough radioactive materials remain with very long lifetimes to make it desirable to design the reactor to disperse upon reentry and little additional risk to the biosphere is introduced by initiating NEP operations from 300 km.

SUMMARY

Technology options should be measured against a full range of requirements.

Mass and specific mass are often used as initial screening parameters to differentiate between various possible power options. Based on a single Shuttle per satellite, the power plant size for advanced solar arrays with energy storage devices is projected to be 160 kWe for low Earth orbit compared to 20 kWe for geosynchronous orbit; for nuclear reactor power systems the comparison is many megawatts versus 100 kWe (Shuttle packaging limitations have been neglected in all cases).

A significant criterion for the selection of a power system for high Earth orbits, such as geosynchronous, could be the orbit transfer system associated with the power source. Electrical propulsion orbit transfer vehicles transfer larger payloads to geosynchronous orbit than chemical rockets, but transit time is measured in months instead of hours. Several hundred kilowatts-electric, a level obtainable with nuclear power plants, reduces the transit times to 3-4 months.

Radiation levels for multimegawatt thermal nuclear reactor designs for 300-y orbit lifetimes are examined. The amount of residual longlife radioactive products seems sufficient to require dispersal on atmospheric reentry.

Restrictions on initial orbits for nuclear orbital transfer vehicles can reduce the final payload by 40-50%. Radiation levels are a function of the operating time. For a possible abort situation prior to achieving a 300-y orbit lifetime, factoring in operating times, the need for restrictions is questionable. This is especially true if one uses electric propulsion with a specific impulse of 1000 s and power levels of 300 kWe.

Shielding to protect personnel must be provided for nuclear reactors in space stations. The shield mass can range from a few thousand kilograms for a reactor on long tethers or free flyers to 50,000 kilograms for a centrally located reactor. Several approaches are feasible within Shuttle constraints.

MASS AND SPECIFIC MASS

Mass is the common parameter used to compare power systems for use in space (Fig. 1). The kilogram unit of mass is defined to be a cylinder of platinum-iridium alloy, which is preserved in a vault at Sevres, France, by the International Bureau of Weights and Measures.(1) The mass comparison implies an assumption that a given launch vehicle is used to deliver a spacecraft to a desired orbit and thus, a kilogram of one power source has the same value as a kilogram of another power source. Volume bay limitations of the launch vehicle, the Shuttle, are neglected in this assumption.

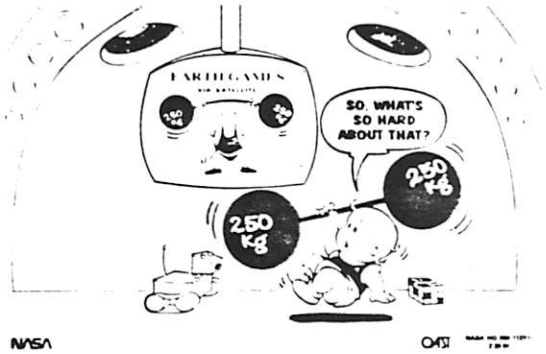


Fig. 1. What is a Kilogram?

Fig. 2 provides first-order comparisons of the mass of solar photovoltaics with energy storage (current and improved), solar dynamics, and nuclear power (including an electronics protection shield) as a function of power level. Solar systems tend to be proportional with power level because as power level changes, the quantity of solar panels or concentrators change as well as the storage elements. There is some nonproportionality in structures and in the solar dynamic systems in the conversion equipment, but these tend to be secondary effects. The mass of nuclear systems, on the other hand, is not proportional to power produced because a certain size reactor is needed to form a critical configuration but small incremental changes result in large power increases (increasing reactor mass 40% will double power output), shielding is an exponential function of thickness (doubling reactor power leads to about a 33% increase in mass), and thermoelectric conversion tends to be linear with power but dynamic electric converters are not. One should not use a mass comparison at one point to draw conclusions at other power levels. The comparison shows that nuclear is significantly less massive as power levels increase.

Since the Shuttle is projected to be the principal U.S. launch vehicle through this century, we will use it in our analysis of transport to low Earth orbit (LEO). Allowing 15% for packaging in the Shuttle bay, the initial spacecraft mass available is 25,000 kg. Based on using 100% of the Shuttle capacity for transfering a power source to a 300-km orbit and disregarding packaging limitations, we could transport a 90-kWe solar photovoltaic system with improved technology, a 360-kWe solar dynamic system and a multimegawatts nuclear system.

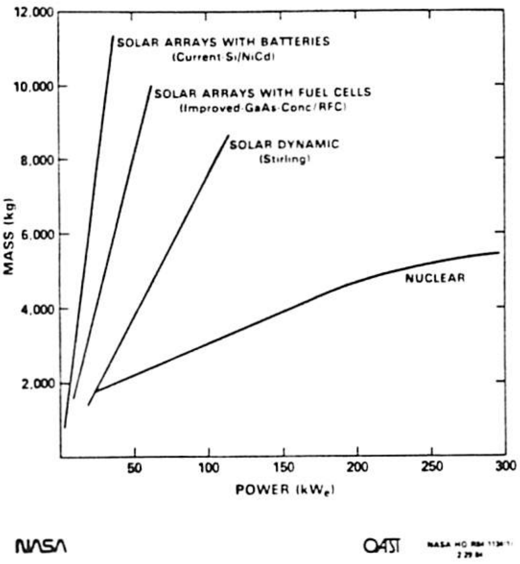


Fig. 2. Comparison Of Power Plant Mass As A Function Of Power Level.

Comparisons at geosynchronous Earth orbit (GEO) are very interesting. Using as a reference the Shuttle /Centaur transportation system, if half the spacecraft is power supply, then the power supply can have a mass of 3000 kg (see Fig. 3). Within the 3000-kg constraint, power levels in GEO will be about 10 kWe for current solar photovoltaic systems; 20 for improved solar photovoltaic systems; 40 for solar dynamic systems and 100 for nuclear systems. Table I compares these values with those for LEO. Notice the significant reduction in total power, as much as a factor of 9 difference. We will continue our comparisons in the section for nuclear electric propulsion (NEP) orbit transfer.

TABLE I

COMPARISON OF PEAK POWER AS A FUNCTION OF TECHNOLOGY

(NEGLECTING PACKAGING CONSTRAINTS) - KILOWATTS-ELECTRICAL

	LEO	GEO
Solar Photovoltaics (Current)	90	10
Solar Photovoltaics (Improved)	155	20
Solar Dynamic	360	40
Nuclear	Many MW	100

Another way to evaluate power systems is to use specific mass. The specific mass (kg/kWe) is the ratio of the mass (kg) to power (kWe). Representative values are shown in Fig. 4. The nuclear values change significantly with power level decreasing from around 70 kg/kWe for 25 kWe to 20 kg/kWe for 300 kWe. Selecting any single value as representative for nuclear power systems would be misleading.

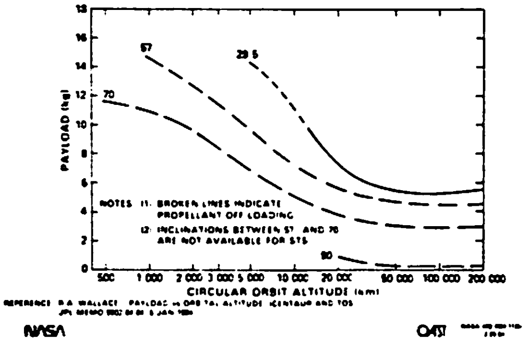


Fig. 3. Centaur G Performance Payload Vs Altitude Circular Orbit.

ORBIT TRANSFER FROM LEO TO GEO

Future orbit transfer missions can be performed by a variety of stages. Because of the maturity and known capabilities of the Centaur, this will be used as a representative chemical stage. Typical electric propulsion devices are given in Table II. Using nuclear power for the energy source, performance curves for nuclear electric propulsion (NEP) are plotted see Fig. 5. The power plant can be considered as part of the NEP stage if it is only for orbit transfer, part of the payload if it requires the power to be there anyway, or both if the payload needs a lesser amount of power. Approximately 19,000-kg payload can be delivered to GEO in a 120 day transit time.

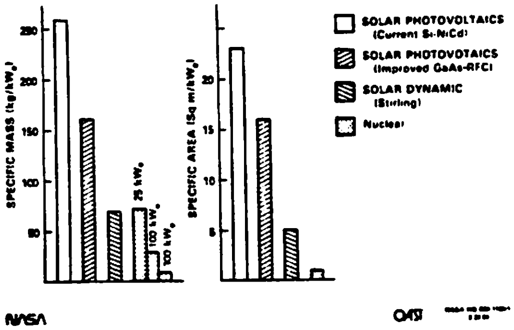


Fig. 4. Specific Mass And Areas Of Several Power Systems.

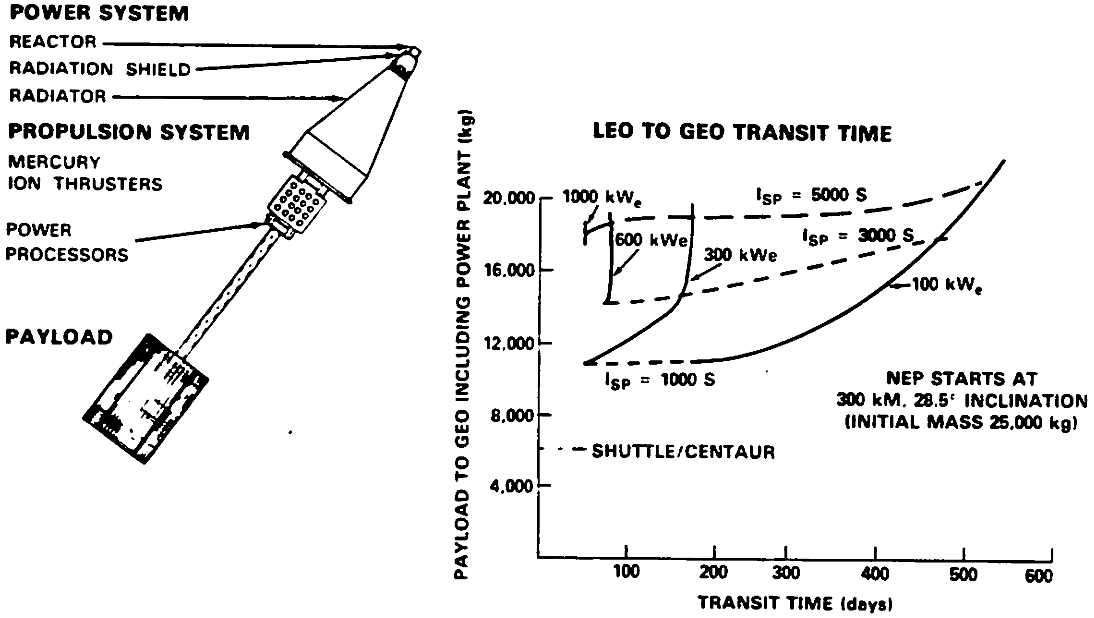
TABLE II

DATA FOR ELECTRIC PROPULSION VEHICLES*

Device	Specific Impulse	Total System Efficiency	Tankage Fraction	Thruster Size	System Power	Propulsion System Mass
NH_3 arcjet	1000 sec	60%	15%	30 kWe	100 kWe	500 kg
				30	300	1500
				30	600	3000
				30	1000	5000
Hg ion thruster	3000	68%	5	30 cm	100 cm	1360
				30	300	3960
				50	600	3640
				50	1000	5670
Hg ion thruster	5000	78%	5	30 cm	100	940
				30	300	2670
				50	600	2860
				50	1000	4500

*Source: Ross M. Jones, Jet Propulsion Laboratory, Letter 312/84.3-2426, dated 6 March 1984.

Now, one has an interesting bookkeeping problem. If the Shuttle/Centaur is used as our reference configuration, we can construct a chart like Table III. For Shuttle/Centaur, the maximum spacecraft mass is about 6,000 kg to GEO. Assuming half the spacecraft mass is assigned to the power system and that a solar dynamic system is used to represent future solar power technology, one could deploy a 40-kWe power system. This



SOURCE ROSS J JONES, JET PROPULSION LABORATORY,
LETTER 312/84 3-2426, MARCH 6, 1984

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Fig. 5. Shuttle/Nuclear Electric Propulsion To GEO

leaves a balance-of-payload of 3000 kg. Using a 300-kWe power system for NEP in order to reduce transit times from LEO to GEO to 120 days and assuming the power source will be used by and charged to the payload, the payload is 19,000 kg. If, however, the payload does not need that much power, we may substract off this mass giving us a balance-of-payload of 13,000 kg. Finally, if the spacecraft needs 40 kWe for the payload (the amount a solar dynamic system was computed to be able to deliver), we can charge the equivalent nuclear power plant mass to the spacecraft and the balance to the propulsion system. The payload balance is 15,000 kg. The latter payload is 5 times the payload in a spacecraft containing a solar dynamic power system delivered by a Shuttle/Centaur transportation vehicle. Using the Shuttle/Centaur as a reference and the power plant and NEP as changes from that reference, our power plant bookkeeping has negative mass values -16,000, -10,000, -12,000 kg, depending on the case assumed.

RADIATION LEVELS AFTER 300 YEAR ORBIT LIFETIMES

Safety concerns are a major factor in design and operation of reactors for space power. To protect the Earth's population against undue risk, radiation levels at the time of a nuclear reactor reentering the Earth's atmosphere should be low. Most fission products decay away, if the operating lifetime of a satellite in orbit is sufficiently long. A long-lived, high orbit is defined in the reactor safety specification (2) as an orbit at an altitude of 300 or more years. We will examine the radiation levels at the end of a 300-y orbit.

Fig. 6 plots the radioactivity for a 2-MWt reactor as a function of operating times; Fig. 7 plots the orbital lifetimes as a function of altitude. A cylindrical reactor reentering the atmosphere would fall near the upper curves; a space station would fall near the lower curves.

TABLE III

ACCOUNTING FOR NUCLEAR POWER PLANT

Power supply (kWe)	40	(1)	300	300	300
Balance-of-payload (kg)	3000		19,000	13,000	15,000
Transit time (days)	1/4		120	120	120
Comparison of payloads using Shuttle/Centaur as reference (kg)			-16,000	-10,000	-12,000

*PP = power plant
(1) Solar-dynamics
(2) Assumes spacecraft long-term power need in 40 kWe and nuclear powerplant mass is 2000 kg

(3) 300 kWe mass used = 6000 kg.

Absorption of fission products by the human body is characterized by their interactions. There are "bone-seekers" (Sr, Y, Zr, Nb, Ba, La, Pr, Nd, Pm), "thyroid-seekers" (I), "kidney-seekers" (Ru), and those preferentially absorbed in muscle tissues (Cs, Ba). Each isotope has a different probable body residence time (biological half-life) and different pathways in the biosphere that can lead to human ingestion or inhalation. The amount of damage done to tissues and cells depends on such factors as the residence time and the type and energy of ionizing radiation emitted.

Inventories of the various classes of fission products at the point of shutdown, 10 years later, and after 300 years have been calculated (See Table IV for a summary) using the Origen code. The results are based on a reactor power level of 2000 kWt and a 7-y operation time. The calculations show that if the reactor reenters the biosphere after 300 years in orbit (this corresponds to around a 750-kilometer initial orbit), the fission product activity has been reduced from approximately 10^7 Ci to under 100 Ci. At that time the biological radioactive elements that might be absorbed by the human body have decayed to low levels consisting mainly of 30 Ci of muscleseekers (^{137}Cs, half-life 30 y and its daughter ^{137m}Ba, halflife 2.6 m) and 21 Ci of bone-seekers (^{90}Sr, half-life 27.7 y and its daughter, ^{90}Yr, half-life 64 h). Thyroid and kidney-seekers are negligible 300 y after reactor shutdown.

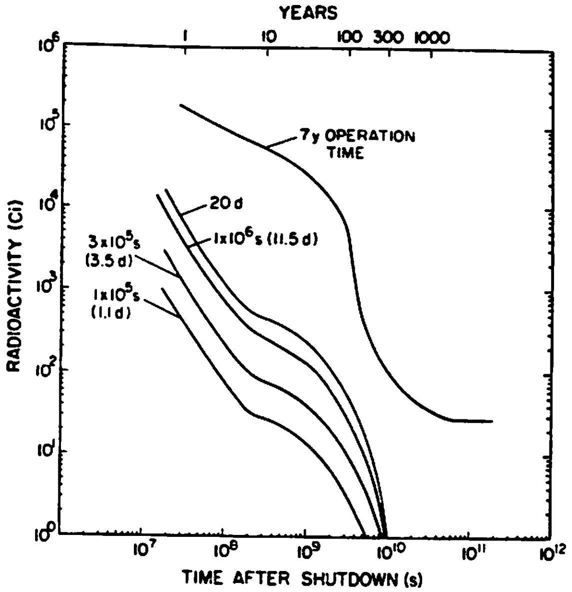

Fig. 6. Two Megawatt Thermal Radioactivity Decay.

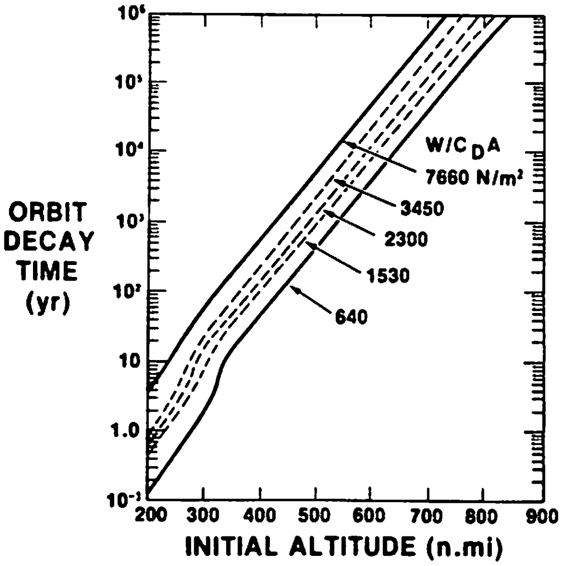

Fig. 7. Orbit Decay Time

Actinides are another source of radiation. Their quantity is proportional to the operating time, fuel enrichment and reactor spectrum. The dominant actinide is ^{239}Pu, which has a half-life of 24,390 y. At low thermal power and operating times the actinide levels are very small; but at two megawatt-thermal power operating for seven years, they represent a four Curie radiation source.

Certain designs may use materials that are activated while in the reactor, such as Nb-1Zr-0.1C fuel cladding. Their presence can result in the generation of additional long-lived radioactive isotopes. For the reactor in reference 3, activation of the fuel cladding results in an increase of 22 Ci at the end of 300 y because ^{94}Nb is generated (halflife of 2 x 10^4 y).

TABLE IV

RADIOLOGICAL ACTIVITY LEVELS FOR 2-MWt

7 - YEAR OPERATION FAST REACTOR (CURIES)

Fission Products (^{90}Sr, ^{90}Y, ^{137}Cs, ^{137m}Ba, ^{151}Sm	9.9 x 10^6	5.1 x 10^4	92	4
Structure (^{94}Nb)	22	22	22	20
Actinides (^{239}Pu)	5.9	5.7	4	4
TOTAL	9.9 x 10^6	5.1 x 10^4	118	28

The total dose level after 300 y is 118 Ci. It is derived mainly from long-lived isotopes. If the orbit time is increased to 600 y, the dose level decreases to 34 Ci and 2000 y to 28 Ci.

Safety standards are given in terms of roentgen equivalent man (rem). An approximate relationship between decay rate, represented by a radioactive source of 3.7 x 10^{10} disintegrations per second, a curie, and dose rate, is provided by the following equation: (4)

Dose rate in roentgen r at distance R cm from curie from curie source =

$$5.2\text{x}10^6\ CE/R^2 \text{ mr/hr} \qquad (1)$$

where the energy E is in Mev.

The assumptions in the above equation are (1) the radiation consists of gamma rays; (2) there is an average photon energy level: (3) there is a point source; and (4) there is negligible attenuation of radiation by the air.

If absorbing material exists between the source and the region where the radiation dose rate is being calculated, equation (1) becomes:

Dose rate roentgen r at distance R cm from C curie source with x cm absorber

$$= 5.2\text{x}10^6\ CEe^{-\mu x}/R^2 \qquad (2)$$

where μ is the attenuation coeficient of cm^{-1} places between the source and point at which the dose rate is being calculated.

A typical value for E for a fast reactor is 0.65 Mev. Radiation dose levels are usually specified 10 m from the source. (5) Using equation (1) and neglecting any reflector attenuation, a 118-Ci source is approximately equal to 400 mr/hr. Further assumptions are necessary to convert this dose rate to roentgen equivalent man. Assuming a quality factor of 1, a person at 10-m distance from the reactor would receive his maximum allowable yearly dose in less than a day. A number of estimates are included in this calculation; however, it does indicate that design and/or operational features needs to be included in space reactor power systems to avoid potentially high exposure rates to the population. Fragmenting the reactor into large pieces or dispersal into small particles are desirable design solutions. The mechanisms should be passive, utilizing atmospheric reentry forces.

ORBIT TRANSIT INITIATION BELOW 300-YEAR ORBIT

To avoid payload penalities with the Shuttle, one would prefer an initial operational orbit at about 300 km. An orbit of 300 y (about 750 km) can be reached by adding 2 Orbital Maneuvering Systems (OMS) (Fig. 8). However, this results in a 50% payload reduction. Safety questions associated with starting at 300-km altitude relate to: (1) The quantity of additional fission products present at reentry if an abort occurs prior to reaching a 300-y orbit; (2) the biological hazards of those fission products; and (3) whether the spacecraft can be powered into the atmosphere. The last condition can be avoided by independent and redundant controls and communications to the thrusters and power supply to insure NEP cut off if the spacecraft direction is wrong. The first two questions will be addressed.

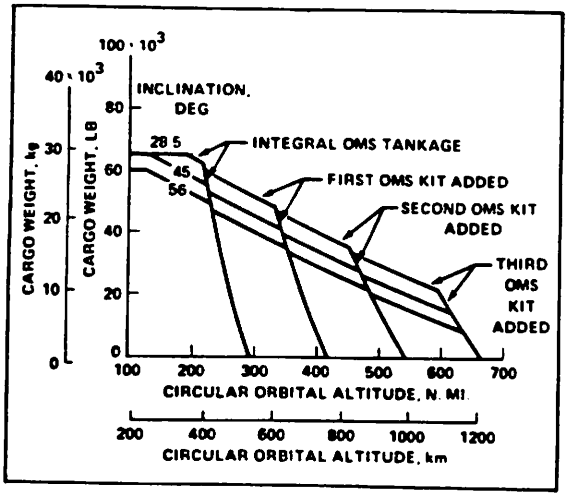

Fig. 8.a. Maximum cargo weights at various circular orbital altitudes for flights with delivery only launched from KSC.

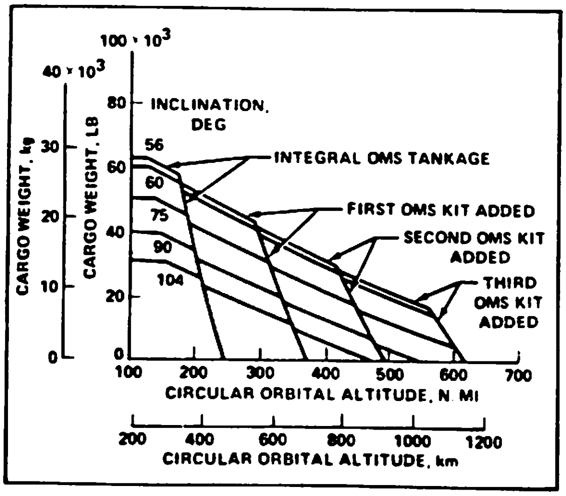

Fig. 8.b. Weight limits on delivery and rendezvous flights launched into circular orbit from VAFB.

Starting with the equation for electric propulsion efficiency:

$$\epsilon = gTisp/2P \qquad (3)$$

where ϵ = total system efficiency; g = 9.8 m/s^2; T = thrust (N); I_{sp} = specific impluse (s); and p = total system power (We).

Rearranging (3):

$$T/P = 2\epsilon/gIsp \qquad (4)$$

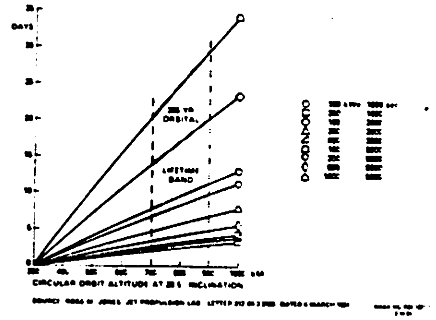

Fig. 9. Transit Time From 300-1000 kM On Trips to GEO.

For fixed power levels, lower values of I_{sp} results in higher thrust levels. The higher the thrust levels, the shorter the transit time and time below a 300-y orbit. Studies of 1000, 3000, and 5000 s specific impluses behavior confirm this (Fig. 9). Aborts were assumed at various times during orbit transfer and the radiation levels compared with a 300-y orbit (Table V). It was concluded that for a short duration of time the fission products could be greater than those produced by long-term operation in a 300-y orbit. For 100 kW_e, this is several weeks for I_{sp} = 5000 s specific impluse and it is about 1 day for an I_{sp} = 1000 s. The peak level for 1000 s is about 800 Ci.

TABLE V

REENTRY RADIATION LEVELS FOR ABORTED NEP MISSIONS STARTING FROM 300 km ORBIT
(2-MW$_t$ Reactor)

100 kWe NEP

Boost Time		Orbit Decay Time (y)			Radiation Levels at Reentry (Ci)		
Sec	Days	Isp = 1000 s	3000 s	5000 s	Isp = 1000 s	3000 s	5000 s
1 x 10^5	1.1	0.7	0.6	0.6	800	1.6 x 10^3	1.0 x 10^3
3 x 10^5	3.5	3	1	0.6	255	120	3.0 x 10^3
1 x 10^6	11.5	3000	40	7	0.06	115	376

300 kWe NEP

Boost Time		Orbit Decay Time (y)			Radiation Levels at Reentry (Ci)		
Sec	Days	Isp = 1000 s	3000 s	5000 s	Isp = 1000 s	3000 s	5000 s
1 x 10^5	1.1	0.3	0.8	0.7	86	580	800
3 x 10^5	3.5	700	40	6	0.5	35	110
1 x 10^6	11.5			3000			6.06

Radioactivity dose levels below those for 300 year orbit following seven-year operation at reentry

If a more efficient electical conversion subsystem is used with the 2-MW$_t$ heat source, 300-kWe output power can be achieved. Higher power reduces the time where radiation levels at reentry are above the 300-y orbit levels following an abort. For 300 kWe, this is less than 1 day for an I_{sp} = 1000 s and 3.5 days for I_{sp} = 5000 s. The radiation levels are such as to conclude that reactors designed to disperse on reentry could be started on a NEP transfer from below the 300-y orbit with little additional safety risk or damage to the biosphere. The distribution of radioactive elements at several points in Table V were reviewed. The results shown in Table VI indicate some build up in boneseekers above the 7-y reference but does not change our conclusions.

MANNED SPACE STATION SHIELDING

Shielding is important for nuclear power plants, especially when they are used in manned systems. Benefits of nuclear power in a growth space station include: (1) elimination of the large solar array structures, especially as power levels increase; (2) elimination of lifelimiting storage devices; (3) simplified operations at the station; and (4) greater tolerance to contamination from station effluents and vehicle thruster exhaust. The radiological protection of the crew is necessary because (Fig. 10) the dose levels will be extremely high unless the reactor is separated by a large distance. The distance to reduce gamma radiation levels to 2 mrem /hr is about 17 km. Shorter distances are feasible if the reactor is enclosed in a shield. The reactor may be shielded in the direction of the space station only (a shadow shield), by preferential shielding that encloses all sides of the reactor but is thicker facing the station (a 4π shield) or by an equally effective shield in all directions (See Fig. 11). The reactor can be placed in the center of the station, offset on a boom, tethered to the station, or on a freeflyer that is separate from the station (Fig. 12). Characteristics of various configurations are summarized in Table VII. Fig. 13 gives representative shield masses as a function of separation distance (6). A reactor located on a 30-m extension boom outside the space station will be considered here. This is a good possible location for a power plant including the shield since both can fit within a single Shuttle, reasonable constraints are imposed on space station operations, and maintenance and disposal are relatively straightforeward.

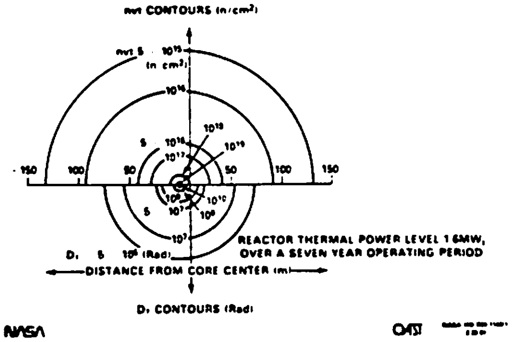

Fig. 10. Radiation Levels Around An Unshielded Reactor.

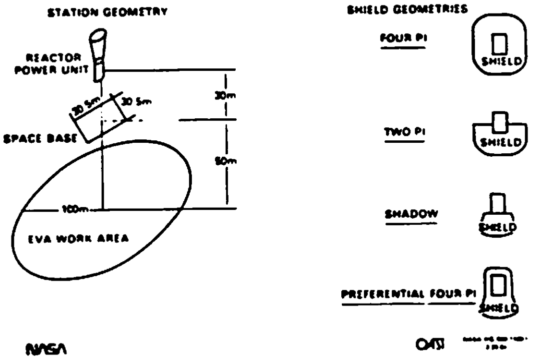

Fig. 11. Shield Concepts

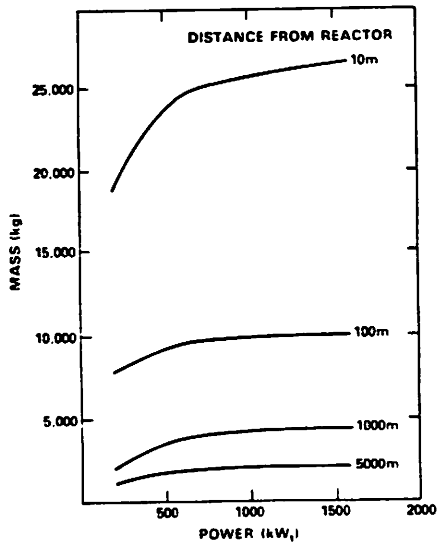

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Fig. 13. Manned Shield Mass

TABLE VI

FISSION RADIOACTIVE ELEMENTS ABSORBED BY HUMAN BODY (Ci)

	7 y operation 300 y orbit	1.1 d operation 3 y orbit	3.5 d operation 3 y orbit
Bone-seekers (Sr, Y, Zr, Nb, Ba, La, Pr, Nd, Pm)	40	46	138
Throid-Seekers (I)	---	--	---
Kidney-Seekers (Ru)	---	--	---
Muscle Tissues (Cs, Ba)	30	14	41
TOTAL ALL RADIOACTIVITY	118	86	225

The crew must be protected against radiological hazards. Since space station members will be working outside the station housing, exclusion zones or limitations to their freedom to work must be minimized. As seen in Fig. 14, the volume of space planned for manned operations is very large - large enough to build a 100-m antenna or structure. A 4π shield minimizes the limitations imposed. Such a shield would have a mass of approximately 15000 kg.

TABLE VII

Features of Reactor Location on Space Stations

Near Center of Gravity Configuration (CG)

- Best Attitude Flexibility
- Allows Full EVA Operation
- Minimum Power Transmission Line Distances
- Heaviest Shield (40-50 Tonnes With 3-M Exclusion Distance)
- Separates Radiator From Reactor

Boom Configuration

- Limited Exclusion Area
- Shield 10-20 Tonnes Depending On Reactor Size And Boom Length
- Attitude Limitations But Highly Stable Gravity Gradient Mode
- Power Transmission Lines Longer Than CG
- Radiator Near Heat Source

Features of Reactor Location on Space Stations (Continued)

Tethered Configuration

- Less Exclusion Area And Reduced Traffic Constraints
- Lower Shield Mass
- Separates Heat Rejection Radiator From Space Station
- Introduces Gravitational Forces

Free-Flyer Reactor Configuration

- Reactor In Nuclear Safe Orbit
- Lightest Shield
- Requires Power Transmission Or Tugs For Final Transport
- Uses Independent Spacecraft Systems

Will the power plant and shield fit into the Shuttle bay? The diameter of the reactor and 4π shield is approximately 3 m and that of the Shuttle bay is 4.5 m. The combination will fit. The mass for a 300 kWe is compatible with the Shuttle bay. Higher power levels require more efficient converters, such as a Stirling cycle; these may be accommodated without exceeding Shuttle constraints.

An alternative approach to the addition of mass that is used exclusively for shielding is to fill compartments with materials that double as shielding. Water is an excellent neutron shield, easily packaged to fill Shuttle trips. One might consider locating water storage tanks for manufacturing processes, facilities uses, etc., between the reactor and spacecraft and around the reactor to make dual use of materials. Other materials such as segments of gamma shields can be transported in sections and assembled in space--this is a very high density material, that does not occupy much volume. Proper planning could result in a shield that could be approached in a working environment within 3 m; this would have a 40,000-50,000 kilogram mass. A single Shuttle could be used to initially insert the power system in orbit with the added material supplied from a stockpile brought up over time or materials for dual purposes. The radiological safety of a normally operating reactor producing hundreds of kilowatts (with potential growth into multimegawatt production) is a very manageable problem.

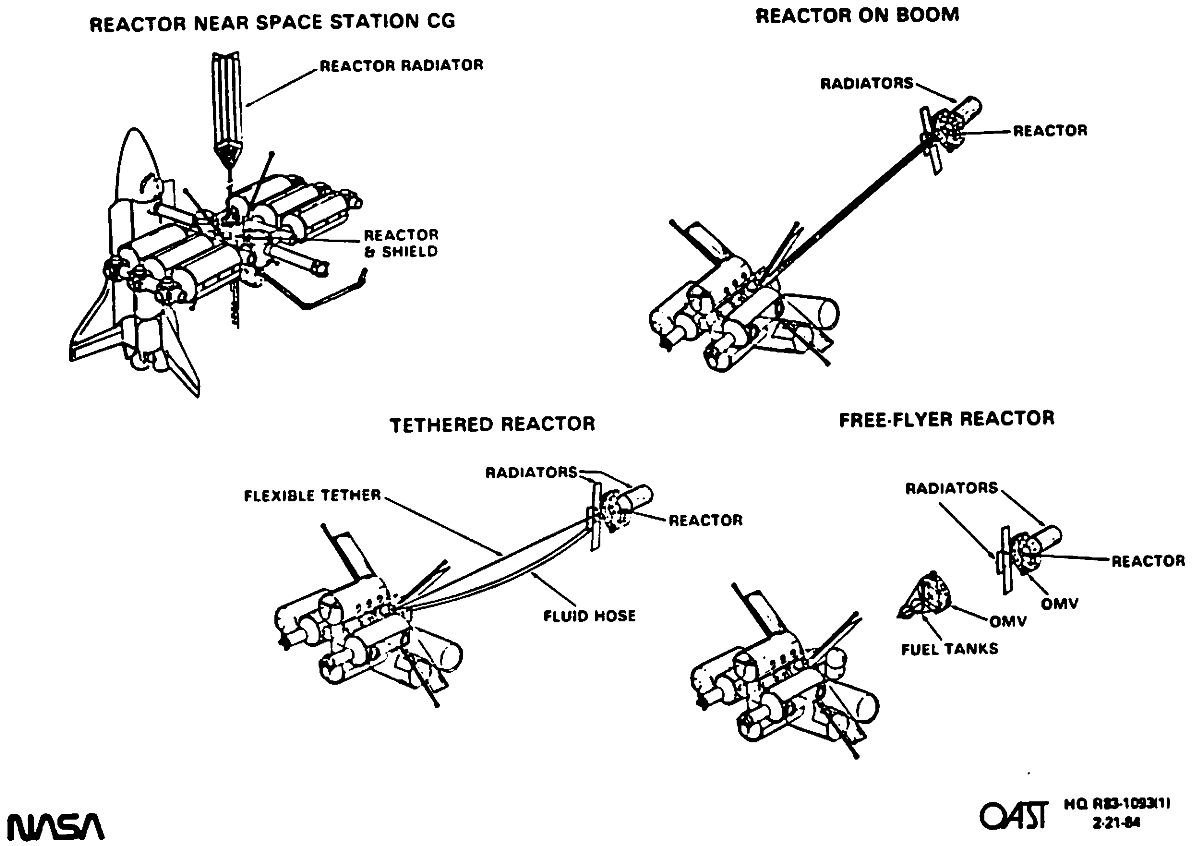
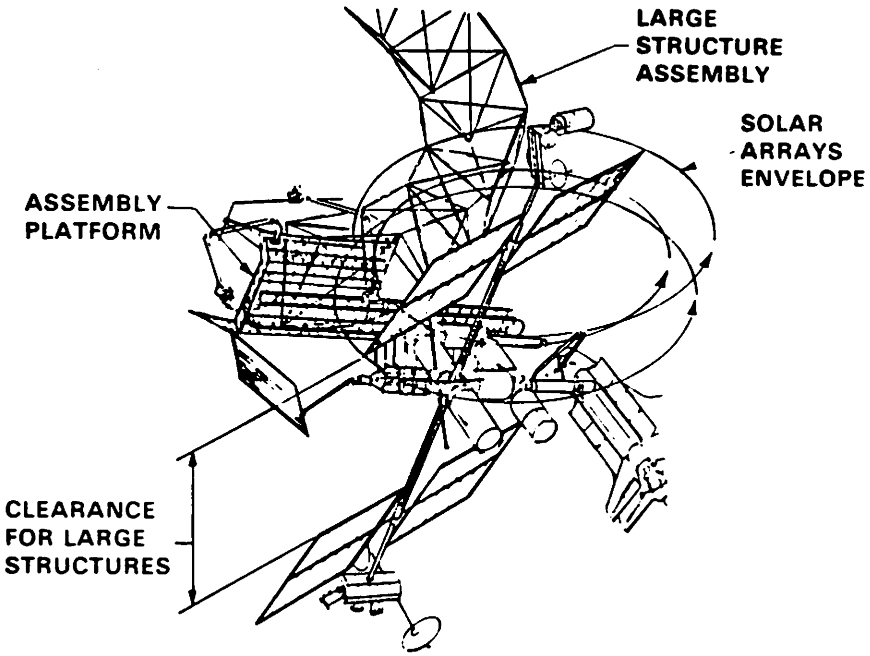


Fig. 12. Space Station Nuclear Options



REFERENCE
BOEING STUDY ON APPLICABILITY OF 100 kw CLASS OF SPACE REACTOR POWER SYSTEMS TO MANNED SPACE STATIONS. NOV 1983

NASA OAST NASA HQ RM84 1138(1)
2 29 84

Fig. 14. Exclusion Areas Around Space Station.

CONCLUSIONS

Nuclear power offers many advantages beyond those implied by direct consideration of mass or specific mass. Nuclear power systems that will produce tens of kilowatts are lighter than alternative systems. For continuous power at the hundreds of kilowatts and megawatt levels, nuclear power systems are necessary. The use of NEP can triple the payloads (power supply plus balance-of-payload) to GEO for a single Shuttle launch. Or, examining the balance-of-payload package separately from the power supply, a factor increase of 5 is obtainable. Though 3-4 months are added to the transfer times from LEO to GEO, the total mission schedule may not be impacted when one considers that several Shuttle launches and matings in space are eliminated.

Three-hundred-year life orbits can be used to allow most of the fission and activation products to decay before a reactor reenters the biosphere. Enough radioactive materials remain, however, with very long lifetimes to make it desirable to design the reactor to fragment into large pieces or disperse as small particles upon reentry. If the reactor is designed for reentry dispersal, little additional risk to the biosphere is introduced by initiating NEP operations from 300-km, especially if a 300-kWe power plant is used with 1000-s specific impluse electric propulsion devices.

Space station shielding for nuclear reactors is a manageable problem. One Shuttle can deliver the reactor and a 4-person-rated shield with the reactor located at the end of a boom on a tether or in a freeflying configuration. Shielding can be stockpiled from volume-limited payloads if the reactor is to be located in the center of the space station.

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