# NUCLEAR RADIATION PROBLEMS, UNMANNED THERMIONIC REACTOR
## ION PROPULSION SPACECRAFT[*]

J. F. Mondt,[+] C. D. Sawyer,[#] A. Nakashima[≠]

Jet Propulsion Laboratory
Pasadena, California

*A nuclear thermionic reactor as the electric power source for an electric propulsion spacecraft introduces a nuclear radiation environment. The radiation environment effects the spacecraft configuration, the use and location of electrical insulators and the science experiments. The spacecraft is conceptually configured to minimize the nuclear shield weight by (1) a large length to diameter spacecraft, (2) eliminating piping penetrations through the shield, and (3) using the mercury propellant as gamma shield. The alumina material is damaged by the high nuclear radiation environment in the reactor. For the more ambitious (250 kwe, 30 to 40,000 hour) electric propulsion missions it is desirable to locate the alumina insulator outside the reflector or develop a more radiation resistant insulator. The net spacecraft nuclear environment is now being investigated to determine if there is a problem. It appears some experiments may require local radiation shielding.*

## INTRODUCTION

Some of the nuclear radiation problems which have been, or will be, encountered during the technology development of a thermionic reactor ion propulsion spacecraft (TRIPS) are described. A thermionic reactor ion propulsion spacecraft (Ref. 1) provides an electric propulsion system with the potential for delivering large payloads (Viking class-2000 Kg) to the outer planets. TRIPS consists of an in-core thermionic reactor and mercury bombardment engines configured into a propulsion system. The spacecraft configuration and the reasons for the configuration is explained.

An electrical insulator for in-core thermionic reactors is located in the high nuclear radiation environment. The effects of the nuclear environment on this insulator have been investigated in some detail. The insulator effects, how it relates to the spacecraft, and various solutions which are mission dependent is described.

The nuclear radiation shielding requirements for the power conditioner are discussed. The spacecraft arrangement is such that dual use of the spacecraft propellant is possible. The power conditioner is part of the propulsion system, and has been used as the most sensitive radiation component in designing the nuclear shield. The nuclear radiation shielding requirements also influence the spacecraft arrangement. The shielding requirement and how it affects overall propulsion system weight is also explained.

A preliminary look at the science payload environment and its possible problems are briefly described. The science payload is not well defined at this time; therefore, the environment and problems are just now being investigated.

## DESCRIPTION OF SPACECRAFT

A Nuclear Electric Propulsion (NEP) spacecraft consists of an electric propulsion system, a propellant system, and a net spacecraft. The arrangement of these systems must be such as to increase reliability, reduce the weight, simplify interfaces, and maintain maximum flexibility for scientific information return. An isometric of a NEP spacecraft, identifying the major components, is shown in Fig. 1. This spacecraft configuration has a large length to diameter ratio (L/D) which reduces the nuclear shield weight and the overall propulsion system weight. This configuration also simplifies the thermal interfaces by having the high temperature components (power subsystem) all at one end of the spacecraft. The thrust subsystem and propellant system is in the center of the spacecraft, an intermediate temperature environment, and the low temperature net spacecraft at the other end of the spacecraft. The net spacecraft being at one end also allows maximum field of view, and allows the science equipment to be operational during the thrusting. This side thrust configuration, as shown in Fig. 1, has the thrust perpendicular to the long axis of the spacecraft. Therefore, the mercury propellant used for thrust is expelled away from all spacecraft components.

## PROPULSION SYSTEM

The propulsion system is divided into two subsystems – power and thrust. The power subsystem consists of a primary radiator, a thermionic reactor, electromagnetic (EM) pump and (NaK) liquid metal heat rejection piping. The thrust subsystem consists of power conditioner modules, mercury ion bombardment thrusters and bus bars or power cables. The power distribution for

[+] Group Supervisor          [#] Member Technical Staff          [≠] Senior Engineer
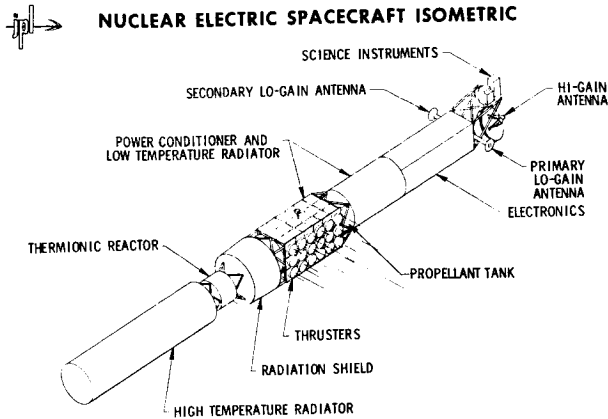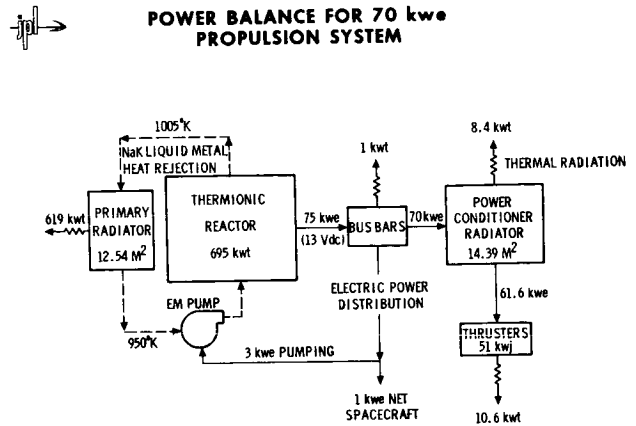
Fig. 1  NEP SIDE-THRUST SPACECRAFT

Fig. 2  70 kwe NEP POWER SCHEMATIC

a 70 kw nuclear electric propulsion system, including all components, is shown in Fig. 2. The dashed lines on the figure indicate liquid metal piping loops. The solid lines indicate electric power distribution. The accordion lines indicate heat rejected to space.

The power subsystem produces 75 kw of electric power at the thermionic reactor terminals. The reactor thermal power level is 695 kw. The thermionic reactor is cooled by liquid metal, sodium potassium (NaK), at a coolant temperature of about 1000°K (730°C). A complete power balance for the propulsion system is also shown by Fig. 2. The overall reactor efficiency is approximately 11%. The efficiency of the power conditioner is approximately 88%. The overall thruster efficiency in converting electrical energy to thrust is approximately 83%. All NEP components include a minimum of 20% redundancy at the beginning of mission life. For instance, the radiator can lose 20% of its effective area and still rejects the 619 kw thermal at design temperatures.

The primary radiator, which cools the thermionic reactor, operates at an average temperature of 700°C, has an area of 12.5 square meters (120 square feet) and rejects approximately 620 kw of thermal power to space. The radiator required to reject the heat from the power conditioner is actually larger in area than the primary radiator. The power conditioner radiator operates at an average temperature of 80°C, rejects 8.4 kw thermal, and has an area of 14.4 meters$^2$ (140 square feet). It is also assumed that 1 kw of electric power is used by the net spacecraft.

SPACECRAFT ARRANGEMENT

The major subsystems and their major components are shown in Fig. 3. The NEP spacecraft is shown located on the Centaur stage of a Titan 3D-Centaur launch vehicle. This configuration allows the three major spacecraft subsystems to be developed independently because of the simple interfaces. The nuclear shield, part of the power subsystem, is located between the power subsystem and the thrust subsystem. The thrusters and mercury propellants are located between the power subsystems and the power conditioner. The power conditioner has nuclear radiation-sensitive components. Radiation-sensitive components are also located in the net spacecraft which is beyond the power conditioner. The mercury propellant is used as gamma shield, as well as propellant.

The nuclear radiation levels can be divided into three main categories within the spacecraft. The power subsystem operates in the highest nuclear radiation environment. The thrust subsystem and electronics must operate in an intermediate nuclear radiation environment. Some specific payload scientific experiments will probably require a very low nuclear radiation environment.

As shown in Fig. 3, the overall length of a 70 kw propulsion system is approximately 50 feet and the spacecraft diameter is about 3 feet. This size spacecraft can be arranged very effectively on the 11-foot diameter Centaur stage. Simple easily defined interfaces between the three major subsystems of the spacecraft allows independent subsystem technology development with prototype configurations.
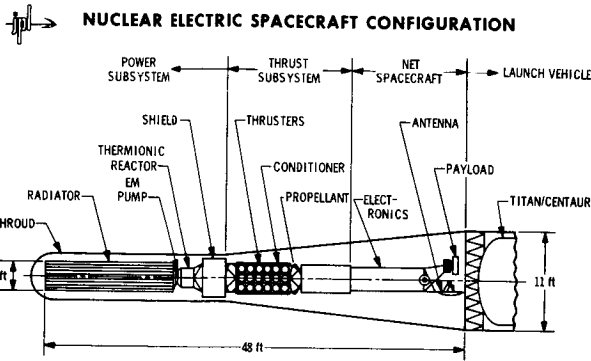
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## NUCLEAR ELECTRIC SPACECRAFT CONFIGURATION

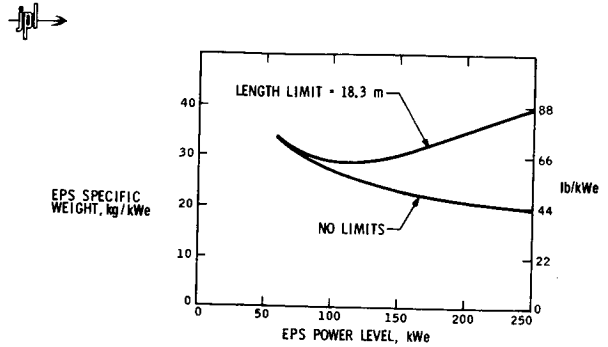FIG. 3  SIDE-THRUST SPACECRAFT ARRANGEMENT

FIG. 4  EFFECT OF POWER LEVEL ON PROPULSION SYSTEM SPECIFIC WEIGHT

The NEP systems weight is very important in the performance of electric propulsion missions. The specific weight variation of this large L/D side thrust spacecraft is shown as a function of electric power output in Fig. 4. The one curve labeled, "NO LIMITS," is the minimum specific weight of the side-thrust propulsion system with no launch vehicle constraints. Given, for example, the constraint of a 60-foot maximum length Titan Centaur shroud or shuttle payload bay, then the weight variation is quite different. The weight variation with a 60-foot length limit is shown by the curve labeled, "LENGTH LIMIT," in Fig. 4. This illustrates the effect on weight of a launch vehicle constraint. The nuclear radiation constraint at the science payload will eventually be another constraint which must be examined.

The propulsion system specific weight with no limits (Fig. 4) is 25 kg/kw at 120 kw power level. With a length limit constraint, the specific weight is 28 kg/kw. An investigation based on possible constraints from radiation at the science equipment will be necessary to determine their effect on the overall propulsion system weight. The weight effect can then be used to determine the effect of science equipment radiation constraints on the overall mission performance.

## POTENTIAL NEP MISSIONS

The incentive for the NEP system is the desire to explore in some detail the outer planets of our solar system. A list of potential missions with projected launch dates, power level ranges and required full power hours (FPH) is shown in Fig. 5. The assumed net spacecraft (science payload) are Viking class payloads of 2,000 to 3,000 kg. The net spacecraft would probably be designed as outer planet circular orbiters with large data return capability. The thrust mode shown in Fig. 5 as "HI" is chemical propulsion and as "LO" is electric propulsion. The full power hours (FPH) are determined by assuming full reactor power during thrust operation and 33% thermal power during coast periods of the mission.

## LIST OF POTENTIAL NEP PLANETARY MISSIONS
### 2000-3000 kg

| MISSION | LAUNCH DATE | THRUST MODE | POWER LEVEL kw | THRUST DURATION DA | FLIGHT TIME DA | FULL POWER HR x 10⁻³ |
|---|---|---|---|---|---|---|
| HALLEY'S COMET AND JUPITER ORBITERS | '83-'85 | HI-LO | 50-150 | 600 | 900 | 17 |
| JUPITER - ORBITERS SATELLITE RENDEZVOUS | '85-'87 | LO-LO | 150-250 | 500 | 900 | 15 |
| SATURN - ORBITERS SATELLITE RENDEZVOUS | '87-'89 | LO-LO | 150-250 | 600 | 1700 | 24 |
| GALACTIC PROBE | '89-'91 | LO- | 150-250 | ~400 | ~1600 | ~20 |
| URANUS - ORBITERS SATELLITE RENDEZVOUS | '89-'91 | LO-LO | 150-250 | 800 | 2800 | 37 |
| JUPITER OR JUPITER SATELLITE SAMPLE RETURN | '90-'92 | LO-LO-LO | 150-250 | ~900 | ~1700 | ~30 |

FIG. 5  POTENTIAL NEP OUTER PLANET MISSIONS

This potential list of missions is thought of as two classes of missions based on propulsion system lifetimes. The first class includes the first four missions and requires a 15,000 to 20,000 FPH propulsion system with from 2-1/2 to 3 years of flight time. This is considered the first class of outer planet missions for which nuclear electric systems would be useful. The second class is the more ambitious mission to the more distant outer planets, and possible sample return missions from Jupiter satellites. These missions required 30,000 to 40,000 FPH propulsion systems and flight times of five to eight years. The second class of missions is considered second generation NEP systems with the capability of operating for longer times.

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## RADIATION EFFECTS ON INSULATOR

One of the nuclear radiation problems for the thermionic reactor ion propulsion system is the need for an electrical insulator in the high radiation environment. The electrical insulator environment and effects have been investigated in some detail. The nuclear radiation environment in the reactor is very high. The electric insulators can be located in basically three locations within the reactor. The radiation flux level is different for different locations and the insulator damage then varies with time at these locations.

The neutron flux at three different locations in a typical fast thermionic reactor is shown for different power levels in Fig. 6. The first location is designated as core center. The core center is the highest neutron flux location within the core. If the insulators are required in core, then insulators at core center receive the highest radiation dose, and are the limiting insulators. The second location is designated center of lead. This location is outside the active core, but inside the reflector. The center of lead location is in an intermediate nuclear radiation environment. The third location is designated outside reflector. The outside reflector location has 3 inches of beryllium oxide (BeO) between it and the active core. A BeO region with a density 50% of theoretical density was assumed.

The calculated flux for a 100 kwe NEP system is then $4.65 \times 10^{13}$ n/cm$^2$ sec > 0.1 mev at core center, $2.12 \times 10^{13}$ n/cm$^2$ sec > 0.1 mev at center of lead, and $0.246 \times 10^{13}$ n/cm$^2$ sec > 0.1 mev outside reflector. The total accumulated neutron fluence with neutron energy ($E_n$) greater than 0.1 mev is the neutron flux times the full power hours.
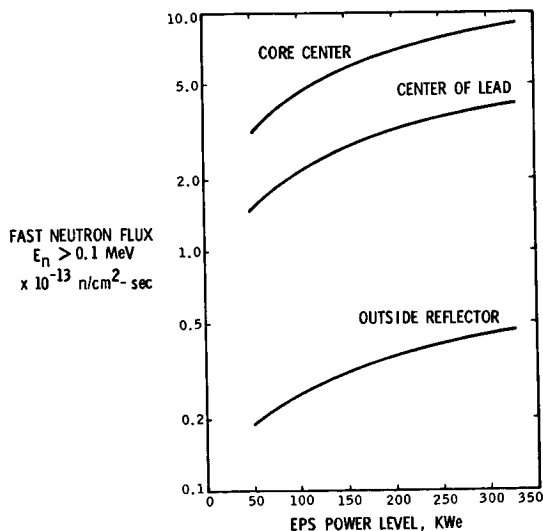
Experimental irradiation damage of electrical insulators has been investigated by Oak Ridge National Labs and Los Alamos Scientific Lab. The insulation irradiation experiments were performed in both a thermal reactor (ETR) and a fast reactor (EBR-2). The results of these experiments are reported in Ref. 2 and 3. A summary of the insulator damage results is shown in Fig. 7. The damage is reported as volume swelling of insulator material as a function of total neutron fluence with neutron energy greater than 0.1 MeV. The percent swelling where insulator cracks are severe enough to cause insulator leaks is shown as a band in Fig. 7. The insulator samples were irradiated at 700°C, which approximates operating temperature of insulators in the thermionic reactor.

The summary of results, Fig. 7, is based on many samples of alumina material and two samples of yttria material. As shown by the figure, the alumina insulators are always leak-tight at a neutron fluence of $4.2 \times 10^{21}$ nvt or less. Therefore, a useful limit for any alumina insulator-seal is $4.2 \times 10^{21}$ nvt.

The two samples of yttria irradiated in the same test reactor as the alumina samples show no swelling at $3 \times 10^{21}$ nvt and very little, if any, swelling at $9.8 \times 10^{21}$ nvt. However, the yttria results are based on two samples and many more samples must be irradiated with similar results in order to gain confidence in these results. Also, the yttria material has lower strength than alumina. The bonding techniques and joining procedures for yttria are not well known and must be developed. The alumina is a well developed material, with well developed bonding techniques and can be reproducibly fabricated today.



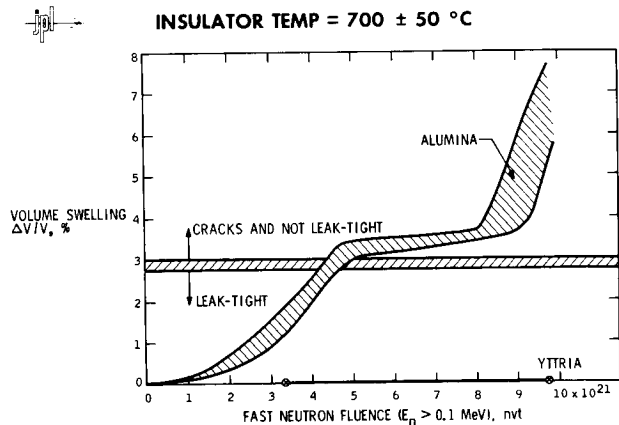FIG. 6  FAST NEUTRON FLUX FOR DIFFERENT REACTOR LOCATIONS



FIG. 7  INSULATOR DAMAGE AT VARIOUS FAST NEUTRON FLUENCES

The useful application limits of the alumina insulator material, based on today's technology, was determined. The insulator damage criteria, the insulator location within the reactor, and the required mission lifetimes were combined. By combining these three factors - insulator damage, mission lifetime and reactor location - the insulator technology status and its usefulness for missions can then be assessed.

The fast neutron fluence at the core center for 10,000, 20,000 and 30,000 FPH is shown in Fig. 8 for various power levels. The alumina leakage limit criteria (seal limit) is shown as a vertical band, from 4.2 to 4.7 x $10^{21}$ nvt > 0.1 mev. So for a 30,000 FPH mission, a fast thermionic reactor with alumina insulator-seals at core center would be limited to a power level of 75 kw electric. A mission requiring 20,000 FPH would be limited to a 150 kwe power level. A 10,000 FPH mission could use alumina insulator-seal at core-center for power levels as high as 350 kw electric.

Also shown in Fig. 8 is the one yttria sample result which would withstand the radiation environment for 30,000 FPH at core center if other properties can be developed. The yttria development requires a joining technology program, investigations of how to live within the low strength properties, and designs to accommodate the low electrical resisivity.
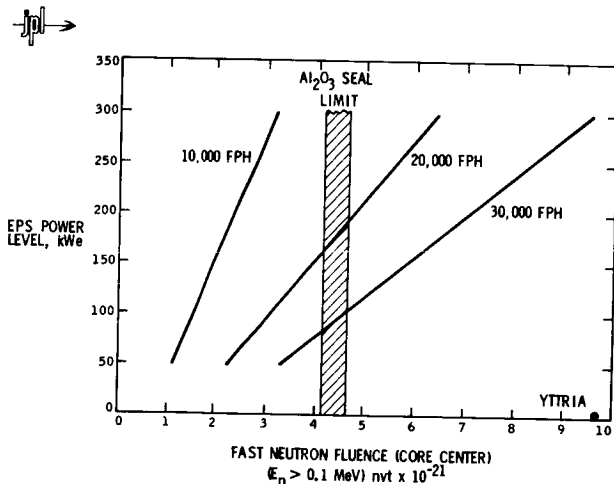
If the alumina insulator seal location is now restricted within the reactor, then the alumina insulator seal usefulness becomes dependent on the location. Figure 9 is a plot of NEP system power level as a function of neutron fluence after 30,000 FPH of reactor operation for three locations within the reactor. An insulator seal at core center is limited to about 75 kw electric, as also shown by the previous figure. If the insulator seal location is limited to the center of lead, then the power level can be raised to 270 kwe for a 30,000 FPH mission. With the insulator seal located outside a 50% dense 3 inch BeO reflector, there is a factor of 10 safety margin for 30,000 FPH missions up to power levels of 350 kwe. This kind of safety margin (factor of 10) is what a user looks for in the early technology phases of any program. The yttria result is still good, but as stated previously, requires a technology effort to make it useful, or to find the limiting criteria for its use.
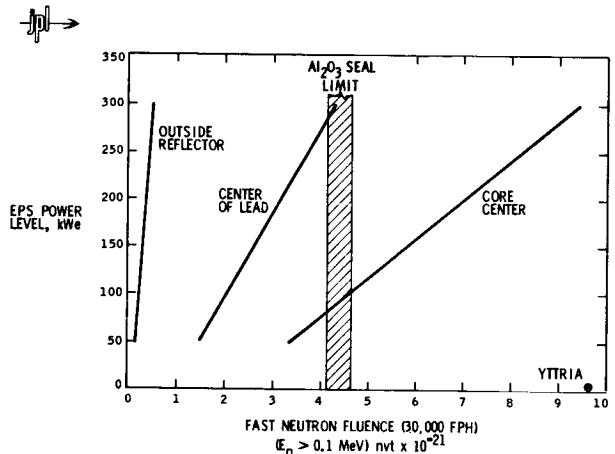


FIG. 9  FAST NEUTRON FLUENCE AT 30,000 FPH FOR DIFFERENT POWER LEVELS



FIG. 8  FAST NEUTRON FLUENCE AT CORE CENTER FOR DIFFERENT POWER LEVELS

## NUCLEAR SHIELD INFLUENCE ON SPACECRAFT

The spacecraft (S/C) arrangement can minimize the shield weight requirement for the power conditioner. This discussion will demonstrate how nuclear radiation imposed requirements influence the spacecraft arrangement and weight. The nuclear shield is designed to limit the nuclear dose to the thrust subsystem power conditioner. The total neutron fluence is limited to $10^{12}$ nvt greater than 1.0 Mev and the total gamma fluence is limited to $10^7$ RAD at the power conditioner at the end-of-mission life. The neutron shield material is lithium hydride (LiH) with 20% allowance for stainless steel structure. The mercury propellant is used as the primary gamma shield. The spacecraft arrangement to shield the closest power conditioner components is shown in Fig. 10.
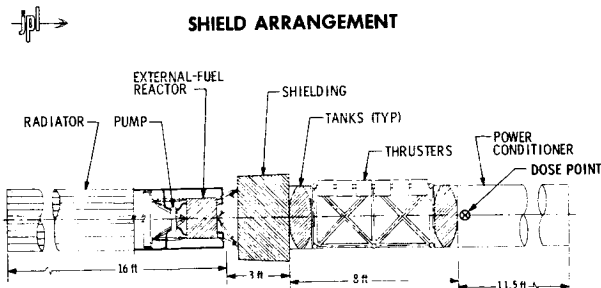
EXTERNAL-FUEL
REACTOR
┌─SHIELDING
RADIATOR─┐ PUMP─┐    ┌─TANKS (TYP)
                              ┌─THRUSTERS   ┌─POWER
                                            │ CONDITIONER
                                            ┌─DOSE POINT

├── 16 ft ──┤├─ 3 ft ─┤├── 8 ft ──┤├──── 11.5 ft ─┤

FIG. 10  SPACECRAFT ARRANGEMENT FOR SHIELDING THE POWER CONDITIONER



FIG. 11  EFFECT OF SHIELD CONFIGURATION AND
NEUTRON FLUENCE ON PROPULSION
SYSTEM WEIGHT

FAST NEUTRON FLUENCE ($E_n > 1.0$ MeV) nvt
AT THE POWER CONDITIONER

The shield (designated shielding and tanks in Fig. 10) is nearly the same diameter as the spacecraft. The shield thickness is fixed by the neutron and gamma fluence limits at the power conditioner, so the diameter of the shield then determines the shield weight. The shield must shadow all the equipment on the power subsystem side from all equipment on the thrust subsystem side of the shield in order to be effective. Any shield penetrations, such as liquid metal piping, will increase the shield weight. The component arrangement shown in Fig. 10 eliminates liquid metal piping penetration and therefore allows a redundant reactor coolant system without increasing the shield weight. The only penetrations through the shield or around the shield is the bus bar required for carrying the electric power from the power subsystem to the thrust subsystem.

The weight savings as a result of no piping penetration and using the mercury propellant for gamma shielding is shown in Fig. 11. The reference propulsion system's relative weight is 1.0 at a fast neutron fluence of $10^{12}$ nvt > 1 Mev for a cylindrical shield with no piping penetrations and mercury as gamma shielding. With a conical shield, including piping penetration and separate gamma shielding, the electric propulsion system weight is increased by 20%.

The effect of total allowable neutron fluence at the power conditioner on propulsion system weight is also shown in Fig. 11. Decreasing the allowable neutron fluence to $10^{11}$ nvt at the power conditioner will increase the propulsion system weight by 5%, while increasing the allowable neutron fluence to $10^{13}$ nvt will reduce the specific weight by 4%. This illustrates one of the radiation shielding problems and its influence on spacecraft configuration and propulsion system weight. All of the nuclear radiation factors must be eventually included before the propulsion system and spacecraft can be developed.
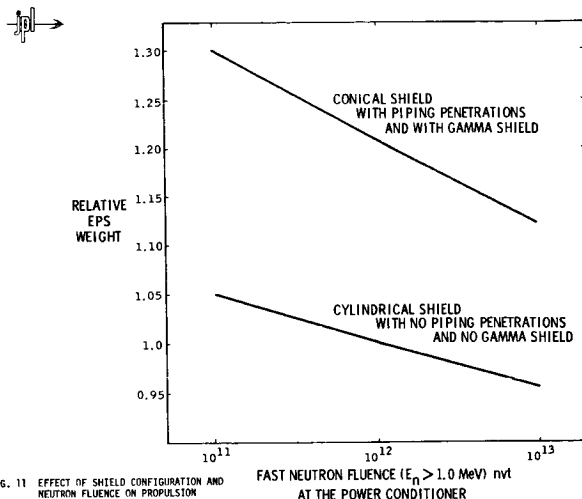
## NET SPACECRAFT ENVIRONMENT

The net spacecraft nuclear environment for the spacecraft arrangement described above is now being defined to see if there is a radiation problem. The nuclear radiation environment must also be defined so that outer planet science experts can evaluate the effect of this radiation environment on their experiments. The neutron flux at three locations within the spacecraft has been calculated. The resultant neutron fluxes with neutron energies greater than a specified neutron energy for three locations are shown in Fig. 12. Since the NEP spacecraft science equipment and experiments cannot be defined this early, it is important to know the flux at various energies. Also, the neutron and gamma spectrum at the payload will be important to the selection of electronic equipment and science experiments.

Based on these initial calculations, the specific experiments that require very low nuclear radiation background will probably be locally shielded. The amount of local shield will be determined by the actual nuclear radiation environment from the thermionic reactor and from space radiation. The total radiation environment is an area which is now being investigated, so the allowable radiation environment from the reactor can be defined.

As shown in Fig. 12, the neutron flux greater than 1 Mev at the power conditioner (location B) is approximately $8 \times 10^3$ neutrons/cm²/sec. This results in a total neutron fluence of 0.86 $\times 10^{12}$ nvt > 1 Mev for a 30,000 FPH mission as designed. The neutron flux greater than 1 Mev at the scientific experiments is then $10^2$ (100) neutrons/cm²/sec, which results in $10^{10}$ nvt> 1 Mev total neutron fluence at the end of a 30,000 FPH mission from the thermionic reactor. If the neutron flux at the science equipment greater than 0.1

Mev is important, then the neutron flux is 7 x $10^2$ (700) neutrons/$cm^2$/sec, and the total nvt > 0.1 Mev would be $10^{11}$ at the end of a 30,000 FPH mission. The limits and radiation problems at the science equipment must be examined in detail. The effects of these limits on the NEP spacecraft and the thermionic reactor ion propulsion system technology will then be determined.

# CONCLUSIONS

The side thrust spacecraft arrangement reduces the nuclear radiation problems by making use of mercury propellant as the gamma shield and eliminating liquid metal piping penetration through the shield. The mercury propellant as a gamma shield improves propulsion system specific weight.

The alumina insulator-seals at core center are leak-tight up to a 75 kw thermionic reactor power level operating for 30,000 FPH. If the alumina insulator-seals can be located outside the axial reflector, then there is a large safety margin for NEP system power levels up to at least 350 kwe for 30,000 FPH. Therefore, the thermionic reactor technology program should investigate ways to eliminate insulator-seals at core center and also investigate new insulator-seal materials.

The neutron radiation environment at the payload is considered low enough not to cause electronic problems, but local shielding requirements for specific experiments must be investigated.



FIG. 12 NEUTRON FLUX AT THREE SPACECRAFT LOCATIONS WITH NEUTRON ENERGIES > A SELECTED ENERGY
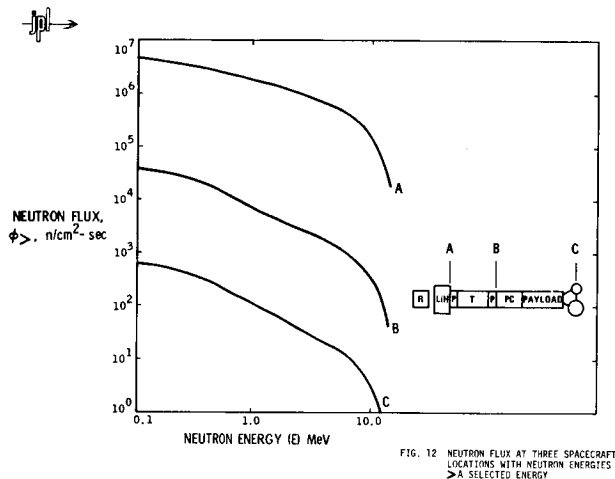
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