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The Acceptability of Reactors in Space

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David Buden

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THE ACCEPTABILITY OF REACTORS IN SPACE*

by

David Buden

ABSTRACT

Reactors are the key to our future expansion into space. However, there has been some confusion in the public as to whether they are a safe and acceptable technology for use in space. The answer to these questions is explored. The US position is that when reactors are the preferred technical choice, that they can be used safely. In fact, it does not appear that reactors add measurably to the risk associated with the Space Transportation System.

I. INTRODUCTION

Energy is the key to man's future development in space. Reactors in turn unlock limitations on energy for large satellites such as proposed for surveillance and communications, orbital transfer vehicles, space stations and lunar settlements. The extension of the planetary exploration program beyond Saturn depends on reactor power. The benefits of reactors in space are high.

*The views presented here are those of the author and do not necessarily represent those of the Los Alamos National Laboratory, the University of California, or the US Department of Energy.

In fact, without reactors space development will be severely limited and crippled.

Safety has always been emphasized in US space reactor programs. The US has flown one space reactor, in 1965. This was not operated until a safe, long-life orbit was achieved. The reactor operated properly and predictably for 43 days until shutdown by a nonpower plant element.

The USSR has flown a series of space reactors at low orbits and then boosted them from low operational orbit to a higher disposal orbit.[1] However, one was not successfully boosted. On January 24, 1978, the USSR's COSMOS 954 became the first space nuclear reactor to reenter the Earth's atmosphere. The reactor disintegrated over Canada's Northwest Territories. COSMOS 954 vividly reopened the question of the safety and acceptability of using reactors in space. It has led to the United Nations establishing a Working Group on the Use of Nuclear Power Sources in Outer Space and the United States Government reviewing the use of nuclear power in space. This paper reviews these recent US and UN studies, proposed reactor safety criteria, as well as the technical aspects related to safety in using reactors in space, and the safety of nuclear reactors launched by the Space Transportation System (STS).

There are two types of nuclear power sources that have been launched into outer space--radioisotopic generators and nuclear reactors:

a. Radioisotopic generators consist of radionuclide fuels surrounded by energy conversion systems. The radioisotope decays spontaneously, emitting ionizing radiation which is absorbed as heat and can be converted into other forms of energy (see Fig. 1A).

b. Nuclear reactors derive their thermal energy from the controlled fission of nuclei, such as fissile uranium 235. The reactor consists of an enriched uranium core with a reflector, producing heat for possible conversion to other forms of energy (see Fig. 1B).

This paper will address only nuclear reactors.

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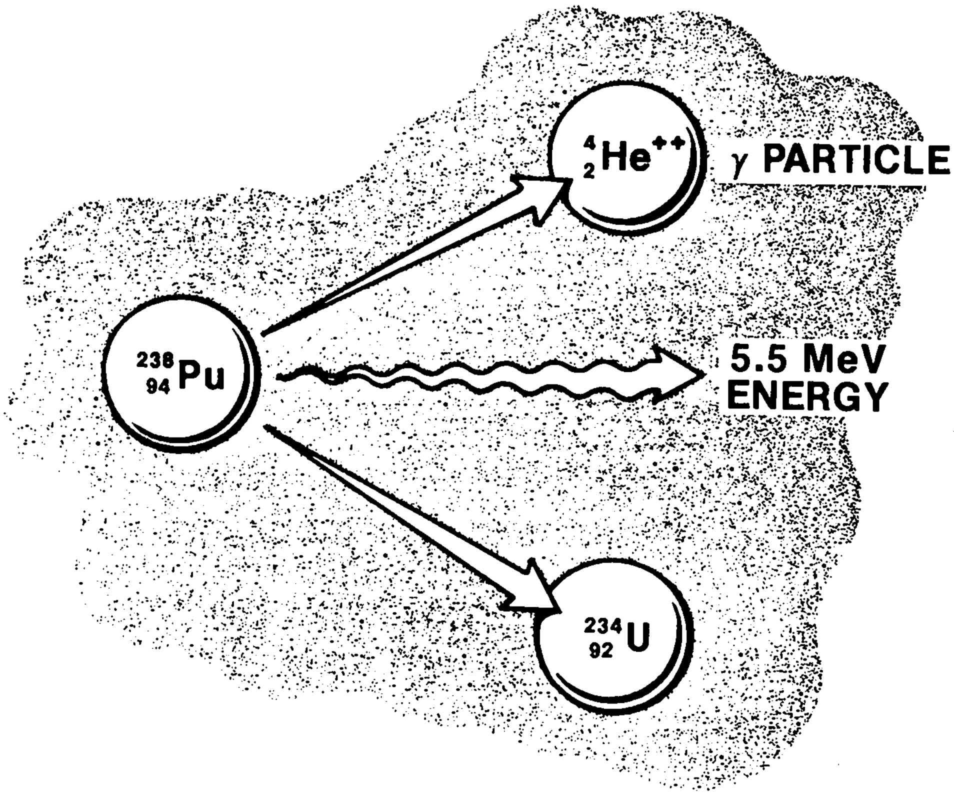
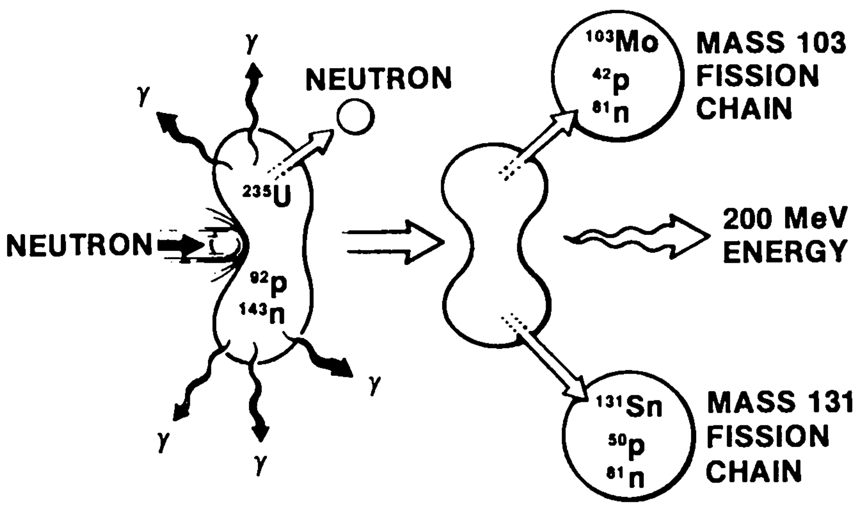
[1]Henry S. Bradsher reported in the Washington Star on January 24, 1978, that this was the 16th satellite in the Russian radar surveillance series that used nuclear power.



1A. Radioactive decay.



1B. Uranium fission.

Fig. 1. Nuclear power sources.

II. CONCLUSIONS

The following conclusions are reached concerning the use of reactors in space:

1. US and UN studies accept the use of reactors when the preferred technical choice provided.

2. Safety is achieved prior to launch and ascent to orbit by maintaining the reactor subcritical (shut-down). A non-operated reactor is safe to handle by flight crew and ground support personnel. Subcriticality is maintained prior to orbit by redundant design and special safety locks, and designing against criticality occurring for either water immersion or ground or water impact.

3. Reactors operated in orbit are safe if they reenter the Earth's biosphere provided fission products are virtually eliminated through the process of natural radioactive decay. This is accomplished by orbits that are on the order of 300 years. Current proposed US missions have orbital lifetimes greater than 300 years.

4. If a mission requires an orbital lifetime of less than 300 years, the reactor can be boosted to a higher orbit after operation either by an on-board boost systems or a boost system delivered by the shuttle. In addition, the reactor can be designed to disintegrate on atmospheric reentry.

5. Reactors do not measurably change the risk associated with Space Transportation System operations.

III. A RECENT US STUDY OF SPACE REACTORS

A high-level study was established by the US Government involving interested elements from the Department of Defense, National Aeronautical and Space Administration, and the Department of Energy to study the desirability of using reactors in space. Their conclusions are reflected in papers given in support of the UN Working Group in 1979 and 1980.

Following are quotations from the January 1980 US paper[2] to the United Nations that defined the US concerns:

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[2] "Studies on Technical Aspects and Safety Measures of Nuclear Power Sources in Outer Space," United States of America working paper to Working Group on the Use of Nuclear Power Sources in Outer Space, UN Committee on the Peaceful Uses of Outer Space, January 23, 1980.

"Exploration and utilization of outer space for the good of mankind will continue to benefit from the application of safe, reliable nuclear power sources. These sources can be used safely if they are developed to meet stringent safety standards designed to protect the earth's population and environment."

"Stringent design and operational measures are required in order to protect both the public and environment under normal and postulated accident conditions. Hence, the primary safety design objective is to minimize the potential interactions of the radioactive materials with the populace and the environment so that exposure levels are within limits established by international standards."

"For reactors, the emphasis should generally be on maintaining a subcritical configuration in all credible accident environments so that no fission products are generated and released through possible core damage. Hence, one safety design philosophy for a reactor system is: to launch an appropriately shielded reactor in a subcritical mode, to design it so as to prevent criticality at or after impact should the subcritical reactor reenter before startup, and to limit startup until the system achieves an earth orbit of sufficient duration to provide time for fission product decay. This would assure minimal interaction of the nuclear material with people and the radiological exposure levels would conform to recommended international standards. These guidelines were included in the criteria applied to the only US launch of a space nuclear reactor in 1965. If reactors are intended for use in short-duration orbits, the safety assessment should include the duration of reactor operation, the duration of the orbit (both of which govern the available fission-product inventory) along with a probabilistic risk analysis of the type of reentry and ultimate disposal."

The above quotation clearly states that the US is generally supportive of the use of reactors in space. It is true that the use must conform to high safety standards to protect the Earth's population. Currently, guidelines are being prepared for the use of reactors in space.

IV. UN STUDY ON USE OF REACTORS IN SPACE

Because any statement by the UN must bear the unanimous approval of the participating members of the Working Group, it further reflects the US views on the use of reactors in space.

In the Conclusions and Recommendations for the 1980 Meeting, the Working Group states[3]:

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[3]"Report of the Working Group on the Use of Nuclear Power Sources in Outer Space on the Work of Its Second Session," United Nations Committee on the Peaceful Uses of Outer Space, A/AC.105/C.1/L.120, February 12, 1980.

"26. On the basis of studies submitted in response to the request in its first report, the Working Group reaffirmed its conclusion that NPS can be used safely in space provided that all necessary safety requirements are met."

The first report stated in its Conclusions and Recommendations[4]:

"39. The Working Group concluded that NPS can be used safely in outer space provided the safety considerations in paragraphs 13, 14, and 15 are met in full. The decision to use NPS in outer space should be based on technical considerations providing safety requirements can be met while satisfying mission requirements."

The pertinent parts of paragraphs 13, 14, and 15 that apply to reactors are quoted below:

"13. The Working Group agreed that appropriate measures for radiation protection during all phases of an orbital mission of a spacecraft with nuclear power sources--launch, parking orbit, operational orbit, or reentry--should be derived principally from the existing, and internationally accepted, basic standards recommended by the International Commission on Radiological Protection (ICRP) in particular ICRP Document No. 26."

"15. The Working Group agreed that the safety of reactor systems did not present any difficulty when they are started and operated in orbits sufficiently high to give time for radioactive materials to decay to a safe level in space after the end of mission. In this way the dose equivalents at the time of reentry could be guaranteed in all circumstances to be within the limits recommended by the ICRP for non-accident conditions. If reactors are intended for use in low orbits where the radioactive materials do not have sufficient time to decay to an acceptable level, safety depends on the start of the operation in orbit and the success of boosting nuclear power sources to a higher orbit after operation is completed. In the event of an unsuccessful boost into higher orbit the system must in all circumstances be capable of dispersing the radioactive material so that when the material reaches the earth the radiological hazard conforms to the recommendations of the ICRP."

Other pertinent paragraphs from this report[4] include:

"7. For certain important space missions nuclear power sources have been the preferred technical choice. Provided the additional risks associated with nuclear power sources are maintained at an acceptably low level, the Working Group considered that the basis of the decision to use a nuclear power source should be technical."

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[4]"Report of the Working Group on the Use of Nuclear Power Sources in Outer Space," United Nations Committee on the Peaceful Uses of Outer Space, A/AC.105/C.1/L.111, 16 February 1979.

"10. For uranium 235 fueled space reactor systems, safety can be assured by delaying the reentry until radioactive materials have decayed to a safe level."

V. TECHNICAL ASPECTS OF MEETING SAFETY STANDARDS

A. Reactor Description

A typical advanced space reactor consists of a fueled region called the core surrounded by a region called a reflector. The fuel is a fissile material used to produce energy--highly enriched in 235-uranium in most cases. The reflector is used to increase the efficiency of the reactor arrangement by returning escaping neutrons to the core. The power level is controlled by means of a material that absorbs neutrons and also by controlling neutron leakage. The relative geometry of this neutron absorption material to the core is used to establish the reactor power level. This device is known as the reactivity control.

B. Safety Design Aspects

The UN and US papers clearly recognize the acceptance of the use of reactors in space with the provision that certain safety standards are met. Our ability to design and launch reactors that meet these safety standards can now be discussed. The UN reports refer to ICRP Document No. 26. This report, as summarized in the 1980 UN Report, states:

"12. With regard to the ICRP recommendation concerning dose limits, the Working Group agreed that, in each case prior to launch, an assessment of the collective and individual dose equivalent commitments must be carried out for all planned phases of a space mission with a NPS. Appropriate guidelines are provided in ICRP publication 26, paragraphs 129 to 132, on exposure of populations. In this connection, the Working Group noted that ICRP publication 26 recommends an annual dose equivalent limit for workers of 50 mSv (5 rem) whole body dose (or equivalent doses to parts of the body) and an annual dose equivalent limit for the most highly exposed members of the public (the critical group) of 5 mSv for all man-made sources. The Working Group recommended that these limits should not be exceeded during any phase of a NPS mission."

The phases associated with a space reactor mission are shown in Fig. 2. The phases of interest to us are:

1. Ground operations
2. Prelaunch and ascent
3. On-orbit operations
4. Descent and postlanding or post operational disposal (deep space or lunar surface)

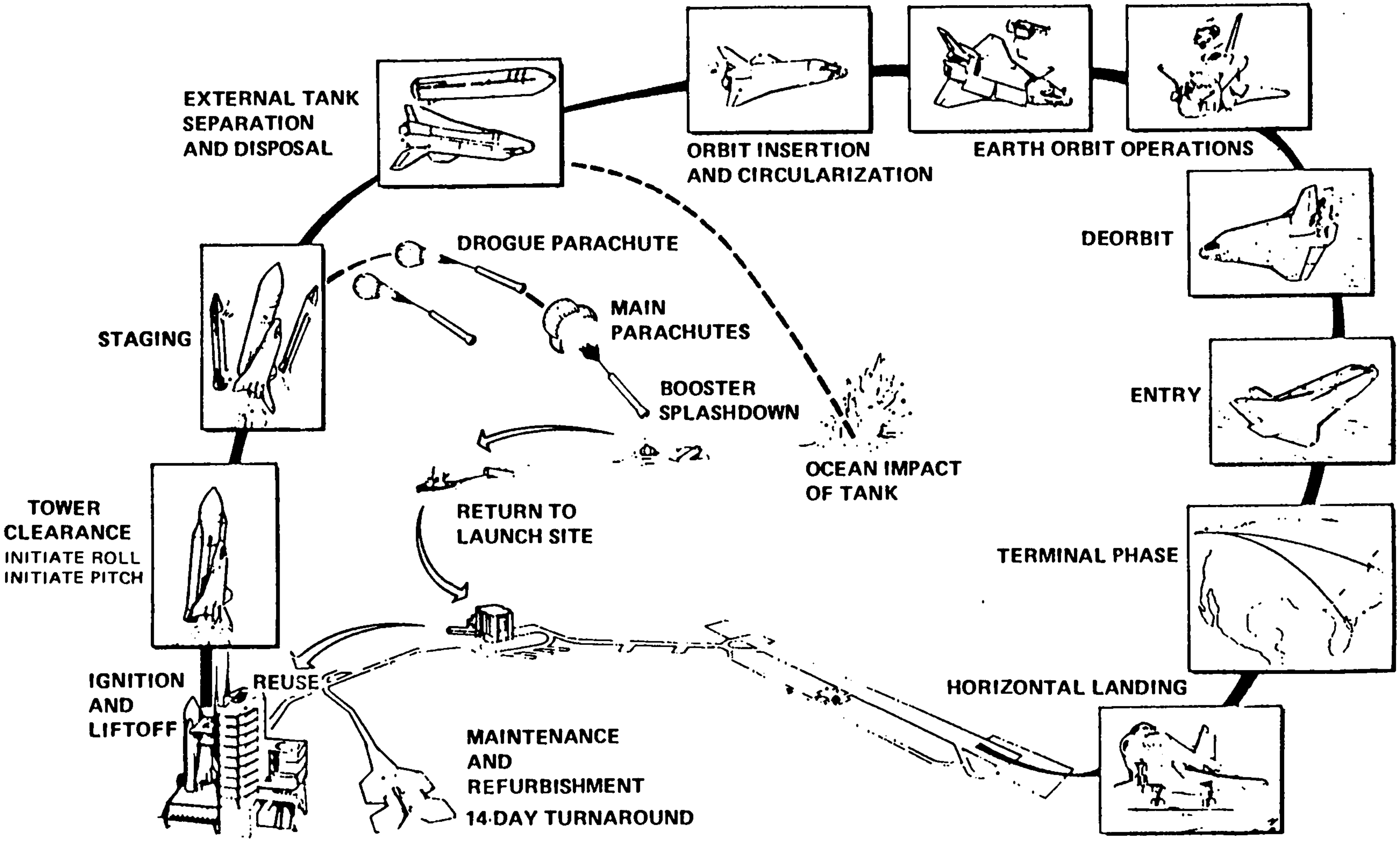

Fig. 2. Space shuttle mission profile.

Though we do not have any operational experience with the Space Transportation System (STS), we can still use past experience to provide some type of guide to the probability of failure during various operational phases. Also, the STS is a manned vehicle and thus the reliability tends to be higher than for other launch vehicles.

Launch Pad Abort. Over the past few years, roughly 1% of launch attempts have terminated in fires or explosion on or in the immediate vicinity of the launch pads.[5] All launch sites have considerable exclusion radii and launch is over sparsely populated areas. Consequently, debris is local and at ground level.

First Stage Success. The first stage solid boosters burn for about 2 minutes and boost the Space Shuttle to about 50 km and a speed of 4300 km per hour.[6] Initial flight is in the troposphere (see Fig. 3). Debris behavior shows a critical altitude about 21 km. Fine debris above this altitude does not appear until the Spring or Fall a year later. The proportion of launch vehicles destroyed below 21 km is taken as 1%.

Second Stage Success. Eight minutes into the mission, the Orbiter's main liquid engines are shut down and its External Tank is jettisoned. This occurs about 115 km. Launch records on other vehicles show about a 2% failure rate.

Orbiter Stage Success. A few seconds after the External Tank separation, the Orbital Maneuvering Subsystem engines are fired.[6] About 2% of launches do not result in attaining orbit because of failures in the third stage or trimming system. However, because of the STS design this may not be analogous here because of "Abort to Orbit" mode or "Abort Once Around" mode.

Though historical data may be pessimistic, one should assume in designing space nuclear reactors that launch vehicle failures can be expected in all phases of the launch and ascent to orbit cycle. Therefore, we shall examine the additional hazards that a reactor might impose in case of a failure. The types of failures are:

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[5] "United Kingdom of Great Britain and Northern Ireland: Working Paper Studies on Technical Aspects and Safety Measures of Nuclear Power Sources in Outer Space," United Nations Working Group on the Use of Nuclear Power Sources in Outer Space, A/AC.105/C.1/WG.V/2.11/Add.1, January 28, 1980.

[6] Marshall H. Kaplan, "Space Shuttle," Aero Publishers, Inc., Fullbrook, CA 1978.

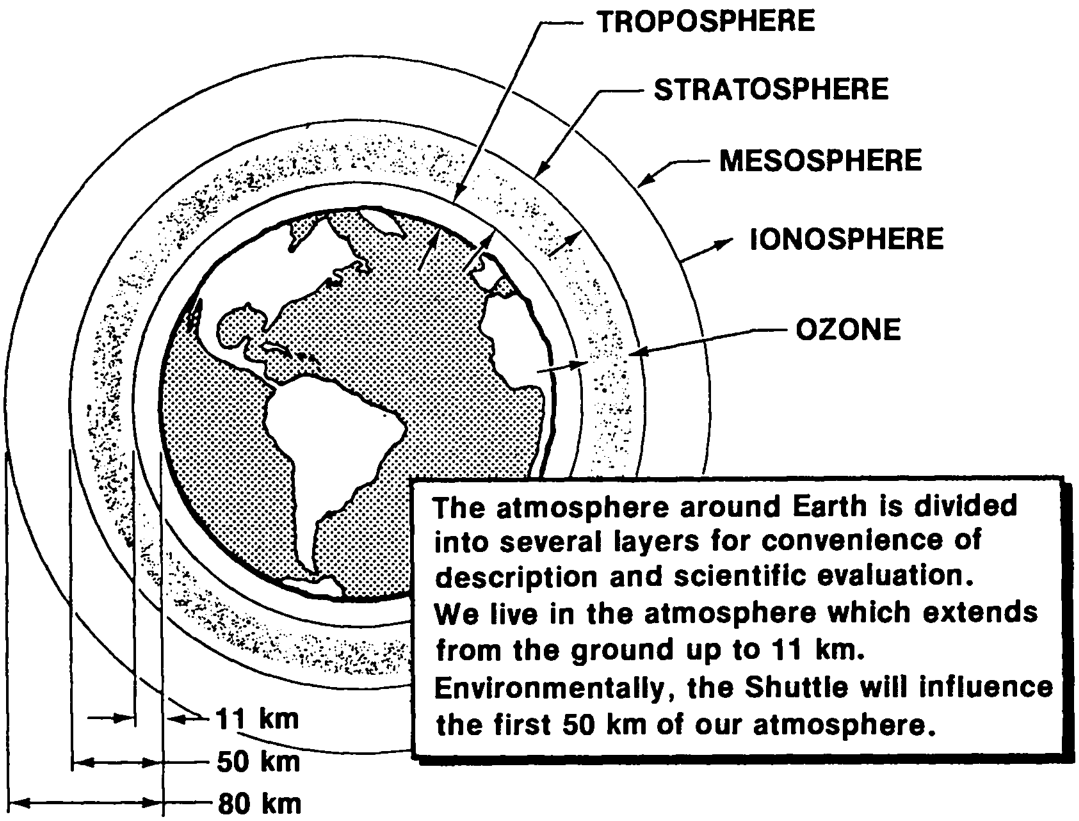


Fig. 3. Atmosphere around Earth.

1. Nuclear, with its associated radiations.
2. Chemical, including toxic substances like Be or BeO.
3. Kinetic (heavy falling object).

1. Nuclear With Its Associate Radiations.

Nuclear hazards can be perceived as (1) being associated with the accumulation of large quantities of a fissile material, such as ^{235}U or (2) the operation of a fissionable reactor (at appreciable power levels).

The accumulation of a large quantity of nuclear material such as in the 100-kW_e Space Power Advanced Reactor (SPAR) design requires around eighty kilograms of highly enriched ^{235}U. The "Engineering Compendium of Radiation Shielding" lists the half-life for the decay of ^{235}U at 7.1×10^8 years (p. 29) and the half-life for spontaneous fission as 1.8×10^{17} years (p. 33). Hence, the decay constants become:

$$\lambda_{\alpha} = 3.1 \times 10^{-17}\ s^{-1} \text{ and } \lambda_{SF} = 1.2 \times 10^{-25}\ s^{-1} .$$

As such, the specific activity per gram of ^{235}U is 2.1×10^{-6} Ci/g for alpha activity and 8.3×10^{-15} Ci/g of spontaneous fission. Now, if the 1200-kW SPAR reactor has 80 kg of ^{235}U, the activity is 0.17 Ci.

To put this in perspective, the radiation is mainly alpha particles which consist of a helium nucleus of two protons and two neutrons with a double positive charge. Alpha radiation is not an external radiation hazard since even a sheet of paper will stop it or several cm of air. In fact, the uranium in the core is surrounded by a layer of molybdenum and 10 cm of beryllium. Therefore, the nonoperated core with enriched uranium is an insignificant biological hazard.

The hazards associated with an operating reactor or one that has been shutdown after appreciable power operation levels are the main radiological concern. Before the reactor has been operated at power, the amount of radioactivity in the core would be negligible. Once at power, the fission products build up fairly rapidly. After the reactor is shutdown, the radioactive fission product inventory decreases through decay. An evaluation of the potential hazards associated with SPAR requires a more detailed specification of the fission product inventory than just the total number of curies. In absorption by the human body some fission products are "bone seekers," some are "thyroid seekers," and some are preferentially absorbed in muscle. Each isotope has a different probable body residence time (biological half-life) and different pathways in the biosphere (ingestion, inhalation). The amount of damage done to tissues and cells will depend on this residence time, the type and energy of ionizing radiation emitted, and so forth. Thus, a fairly detailed inventory of the fission product isotopes are required to analyze the potential effects from a reactor on reentry.

Estimates of the inventories of the various classes of fission products (bone seekers, thyroid seekers, etc.) at the point of shutdown, 24 hours later, and after 300 years are shown in Tables I through V. The reactor operating power and time preceding shutdown is assumed to be 1200 kW_t and 1 year. These tables show that if the reactor reenters the biosphere after 300 years in orbit (this corresponds to around a 400 nmi initial orbit), SPAR would have only:

0.8 Ci of Sr^{90}

0.6 Ci of Cs^{137}

2μCi of Sr^{91}

30μCi of Kr^{85}

of activity after one year of reactor operation. For seven years of reactor operation, Sr^{90} is 4.7 Ci and Cs^{137} is 3.7 Ci.

TABLE I

FISSION PRODUCT INVENTORY - BONE SEEKERS

Radioisotope	Yield (%)	Half Life		Activity in Curies: At Shutdown	24 Hours After Shutdown	300 Years After Shutdown
Sr^{89}	4.8	53	d	40,000	39,400	
Sr^{90}	5.9	23	y	1200	1200	0.8
Y^{90}	5.9	65	h	1200	920	
Sr^{91}	5.9	8.7	y	49,600	7,340	2×10^{-6}
Y^{91} m	2.4	51	m	19,800	0	
Sr^{92}	6.1	2.6	h	51,200	80	
Y^{92}	6.1	3.5	h	51,200	440	
Y^{93}	6.5	10	h	54,600	10,340	
Zr^{95}	6.4	65	d	52,600	52,040	
Zr^{97}	6.2	17	h	52,000	19,540	
Nb^{95} m	0.1	90	h	800	660	
Nb^{95}	6.3	35	d	53,000	51,000	
Nb^{97}	6.2	74	m	52,000	0	
Mo^{99}	6.1	68	h	51,200	40,100	
Ba^{140}	6.3	12.8	d	53,000	50,200	
La^{140}	6.3	40.5	h	53,000	35,160	
La^{141}	6.0	3.7	h	50,400	560	
Ce^{141}	6.0	32.8	d	50,400	49,340	
Ce^{143}	6.2	33	h	52,000	31,400	
Pr^{143}	6.2	13.7	d	52,000	49,400	
Ce^{144}	6.1	290	d	29,800	29,720	
Pr^{144}	6.1	17.5	m	29,800	0	
Nd^{147}	2.6	11.3	d	21,800	20,500	
Pm^{147}	2.6	2.6	y	5,000	5,000	
Nd^{149}	1.3	2	h	11,200	0	
Pm^{149}	1.3	54	h	11,000	8.080	
Pm^{151}	0.5	27.5	h	4,200	2,300	
				894,000	504,720	0.8

TABLE II

FISSION PRODUCT INVENTORY - THYROID SEEKERS

Radioisotope	Yield (%)	Half Life	Activity in Curies: At Shutdown	24 Hours After Shutdown	300 Years After Shutdown
I^{131}	2.9	8 d	24,360	21,680	
I^{132}	4.4	2.4 h	37,000	40	
I^{133}	6.5	20.5 h	54,600	24,260	
I^{134}	6.7	52.5 m	56,800	0	
I^{135}	6.0	6.7 h	50,400	4,200	
			223,160	49,460	0

TABLE III

FISSION PRODUCT INVENTORY - KIDNEY SEEKERS

Radioisotope	Yield (%)	Half Life	Activity in Curies: At Shutdown	24 Hours After Shutdown	300 Years After Shutdown
Ru^{103}	2.9	39.8 d	24,400	24,000	
Ru^{105}	0.9	4.5 h	7,600	200	
Ru^{106}	0.38	1 y	1,600	1,600	
			33,600	25,800	0

TABLE IV

FISSION PRODUCT INVENTORY - INERT GAS CONTRIBUTORS TO EXTERNAL DOSE

Radioisotope	Yield (%)	Half Life	Activity in Curies: At Shutdown	24 Hours After Shutdown	300 Years After Shutdown
Xe^{131} m	0.03	12 d	40	36	
Xe^{133} m	0.16	2.3 d	1,310	970	
Xe^{133}	6.5	5.3 d	53,200	46,680	
Xe^{135}	6.2	9.2 h	52,000	8,520	
Kr^{83} m	0.48	114 m	4,040	∿ 0	
Kr^{85}	1.5	4.4 m	12,600	280	
Kr^{85} m	0.3	10.6 y	10,000	10,000	3.0×10^{-5}
Kr^{87}	2.49	78 m	21,000	0	
Kr^{88}	3.7	2.77 h	31,000	80	
			185,200	66,566	3.0×10^{-5}

TABLE V

FISSION PRODUCT INVENTORY - MUSCLE SEEKERS

Radioisotope	Yield (%)	Half Life	Activity in Curies: At Shutdown	24 Hours After Shutdown	300 Years After Shutdown
Cs^{137}	5.9	27 y	1200	1200	0.6
Ba^{137} m	5.9	26 m	1200	0	—
			2400	1200	0.6

The combined $\gamma + \beta$ activity from fission products becomes smaller than the residual activity due to α decay of the original ^{235}U after about 430 years and is 10% of natural ^{235}U activity after about 520 years.

In summary, when one considers nuclear hazards associated with a reactor, the period of potential biological hazard exists between the time a reactor is operated at an appreciable fissioning power level to the time that the reactor fission products have decayed to an insignificant level. This is a period of about 300 years. From a radiological safety point of view, we take advantage of such safe periods by:

1. not operating the reactor prior to launch or in the ascent mode to orbit;

2. for most missions, selecting the orbit where the reactor is first operated as one whose lifetime exceeds 300 years; and

3. if the desired mission orbit lifetime is less than 300 years, providing a means to boost the reactor after operation to an orbit that has a greater lifetime (or ensuring that a rescue capability exists).

We will discuss orbits in more detail later. Let us now examine the hazards of the various stages to orbit that are potentially presented in addition to the usual risk associated with an STS flight. The major additional risk would be from an unscheduled reactor start. One considers that this risk could be initiated by:

1. an unscheduled increase in reactivity caused by movement of the reactor control elements;
2. water immersion of the core if a Shuttle should crash; or
3. land impact of the reactor in a crash.

Occurrence of the first potential mode to create an unscheduled startup can be eliminated in a manned launch vehicle, like the STS, by using physical interlocks on the control reactivity mechanisms. These interlocks could be removed once the STS achieves orbit, and, thus can provide a fail-safe system. Also, combinations of electrical interlocks with multiredundant arrangements can also be used that would meet the reliability requirements. Thus, by designing for safety, an unscheduled startup involving the reactor control mechanisms can be avoided.

The problem of reactor criticality during water immersion can again be avoided by proper design. Space reactors are designed to remain subcritical in case of accidental immersion in water. For instance, the SNAP-8 incorporated a gadolinium poison for this purpose. This ensures against unscheduled criticality.

The impact problem is concerned with whether the reactor can be distorted in a crash in such a manner as to become critical. The reactor can be designed to assure that such an event can not occur. One feature of a reactor design is that it requires great care to make it sufficiently compact to establish a configuration that will become critical. Distortions will tend to make the system safer.

For the pre-launch, launch, and ascent to orbit, the reactor is kept in a shutdown mode, it requires no cooling and the control elements are locked in a manner ensuring against unscheduled criticality. Thus, negligible nuclear risk is introduced by having the reactor aboard.

Once orbit is achieved, mechanical interlocks on the control mechanisms can be removed. Since there are usually at least twelve control actuators, the interlocks can be removed one at a time and the control element tested independently and without risk to the Orbiter crew. Once the Orbiter has retreated to a safe distance, the reactor can be started employing redundant remote control commands.

Now, let us return to the subject of orbit lifetime and what is the likelihood that a reactor is operating at an orbit that meets the 300-year safety criteria. The orbital lifetime is a function of the ballistic parameter W/C_DA, where W is the weight of the reentry body; A is the drag area which is a function of the flight altitude with respect to the orbital path; and C_D is the drag coefficient which is influenced by the geometric characteristics of the body. Figure 4 shows the orbit decay time as a function of the initial altitude and ballistic parameter. A 300-year orbital lifetime requires an initial altitude of around 500 nmi. If we use figures from the

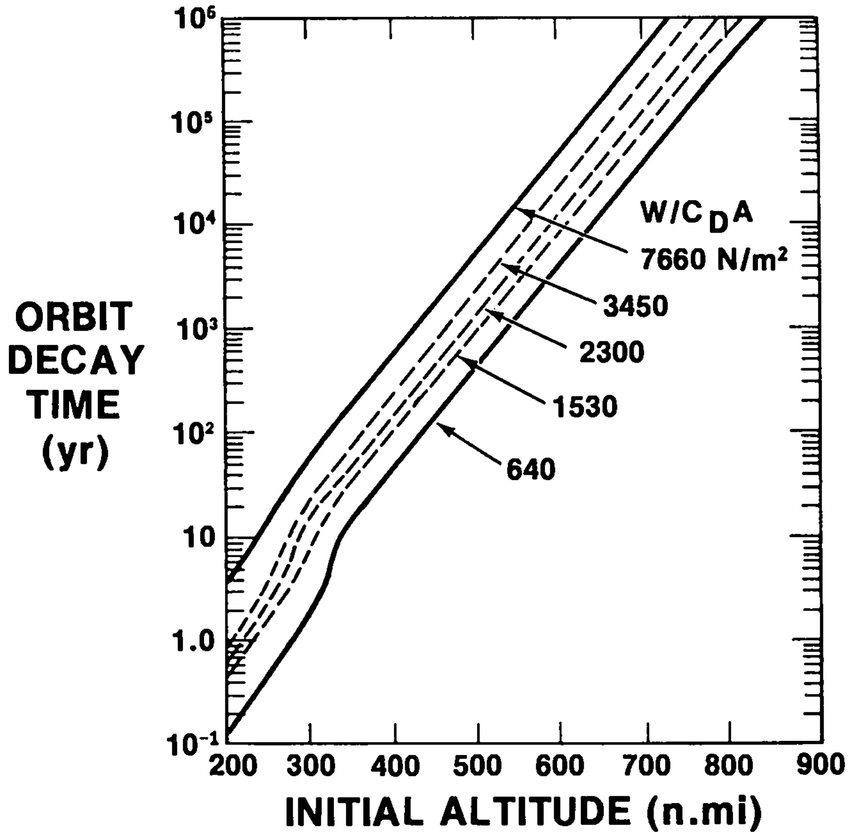
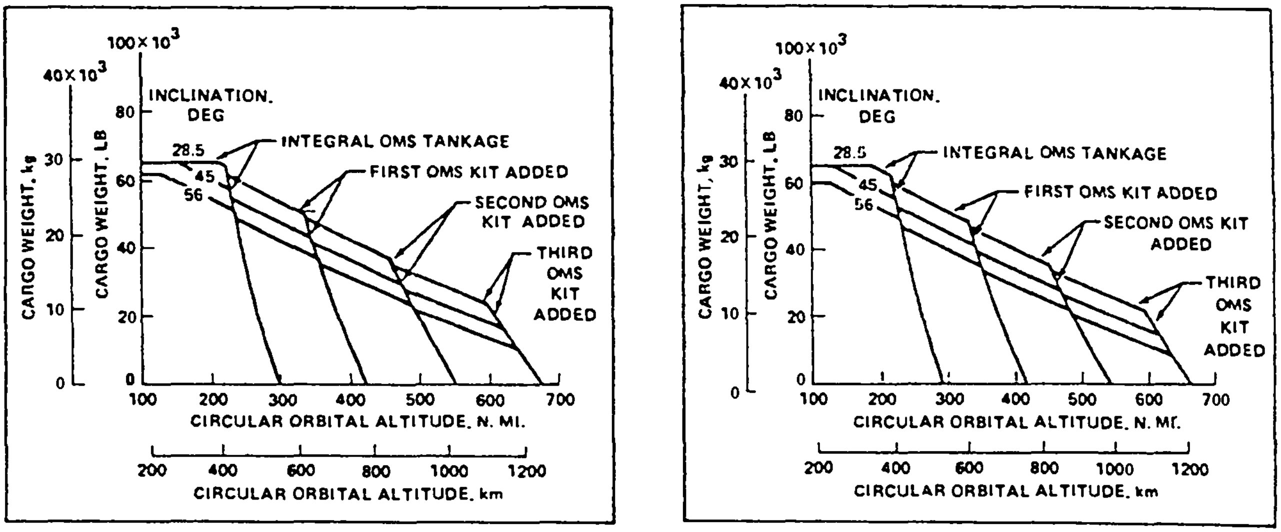


Fig. 4. Minimum orbit decay time.

Space Transportation System User Handbook (Figs. 5 and 6), we see that we can equip the Shuttle with Orbital Maneuvering Subsystem (OMS) kits sufficient to achieve an initial orbit at this altitude. Another observation from examining Fig. 4 is that if we increase the operational altitude of say 700 nmi, we have orbital lifetimes of 10^5 years--a small increase in orbit results in a very large increase in orbital decay time.

However, we should not discard possible missions in orbits below 300 lifetimes if the missions warrant a commitment to nuclear power. We have already mentioned that at the termination of the mission the power plant can be boosted to higher orbit. We have seen the USSR do this successfully many times and experience only one failure--COSMOS 954. We will have an added back-up system once the STS is operational--the ability to rendezvous and push the satellite higher if an on-board boost system fails. This added capability needs to be factored into any planning for lower altitude missions. A feature of the USSR reactor design is to have the core disintegrate into small particles on reentry. If desired, US reactors can be designed in the same



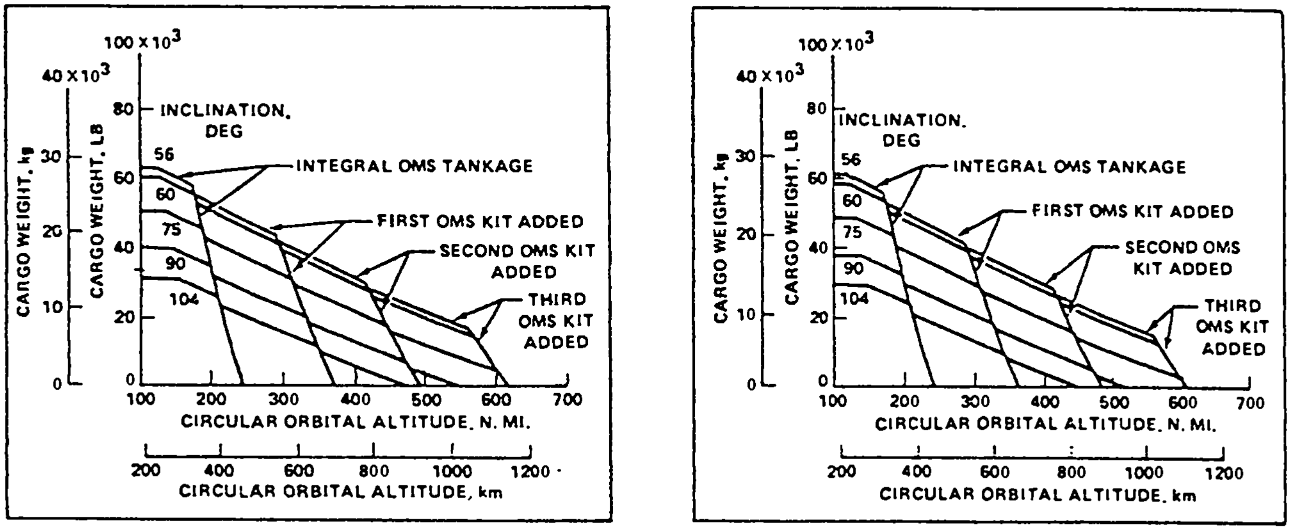
(a) (b)

Fig. 5. (a) Maximum cargo weights at various circular orbital altitudes for flights with delivery only; (b) Maximum cargo weights for delivery and rendezvous flights in circular orbit.

manner. But with disintegration, one must consider interactions with the environment and man and the possibilities of ingestion, inhalation, and external doses through each plausible environmental pathway.

2. Chemical Hazards. The non-nuclear risk must also be considered. The reactor contains such materials as UO_2, Mo, Be, and BeO. In addition to the reactor, the power plant contains a radiation attenuation shield to protect the payload, thermoelectric modules to convert thermal energy to electrical energy, and a reject heat radiator. The shield contains LiH and stainless steel; the thermoelectrics contains SiGe.GaP, Mo, Si, SiO, Al_2O_3, Nb; and the radiator Ti. LiH would probably be the major fire hazard; but compared to the rocket fuel, it would be relatively slow-burning and not very hot. Its ignition temperature is about 590 K and contains 2.7×10^7 J/kg (jet fuel is 4.6×10^7 J/kg). The few hundred kilograms of LiH that is part of the nuclear power plant contributes little to a potential fire compared to the two 590 000 kg (1.3-million pound) solid rocket boosters or 725 000 kg (1.6-million pound) liquid rocket External Tank.

The reflector weighs 160 kg and contains beryllium and beryllium oxide. Beryllium is used as a structural material for some spacecraft and thus its hazards have been evaluated and accepted.



(a) (b)

Fig. 6. (a) Maximum cargo weights at various circular orbital altitudes for flights with delivery only launched from VAFB; (b) Weight limits on delivery and rendezvous flights launched into circular orbit from VAFB.

3. Impact Hazards. The major impact hazards that one considers is whether the core can impact severely enough to collapse the void spaces and form a critical mass. A calculation of the current SPAR 100 kW_e heat pipe reactor shows that reactivity would be increased 5% from a severe impact if the reflector survives intact--the core would still be subcritical.

VI. MISSION CHARACTERIZATION

Typical hazards can be characterized by two parameters as follows:

1. operational mode
   - electricity production alone (by nuclear means)
   - nuclear electric propulsion
   - chemical propulsion following reactor operation, and
2. initial orbit where reactor will operate
   - high orbit
   - low orbit

For the purposes of this classification, a high orbit is defined as greater than 500 nmi. At this altitude the orbit decay time is 300 years, which is needed for the induced fission activity to decay to a negligible level. A low orbit is less than 500 nmi.

In considering the different types of mission, we have selected five classes that we believe characterize the use of reactors in space well enough to identify problem areas and perhaps indicate preferred directions of development.

- Class I: Initial high orbit with nuclear electricity production plus limited station keeping or station-changing capability.

In this class the reactor would not be operated until it was placed in high orbit and the maximum velocity change (Δv) that could be applied by misapplication of available thrust would not be sufficient to move the satellite to a low orbit. Velocity change could be by NEP or chemical means.

- Class II: Initial high orbit with nuclear electricity production and potential velocity change sufficient to cause a change to low orbit.

As in Class I, the reactor would not be operated until it is placed in a high orbit, but the mission requires that the vehicle have a major Δv capability that could lead to a low orbit with potential reentry. Reentry would only occur under abnormal conditions and would not be a planned segment of a mission. Transfer to a low orbit could be a planned mission segment, in which case subsequent mission segments would consider the safety consequences (in effect, it enters Class IV). Transfer to low orbit could also only occur if the available Δv were improperly applied and could not be terminated. There is no intent to make such a transfer.

- Class III: Initial low orbit with electricity production and limited station keeping or changing capability.*

The mission that might characterize Class III is a relatively low-orbit manned space station with perhaps the major power source being nuclear electricity. The space station would probably include a reactor shield with provision for reactor maintenance and repair. Even though this type of mission includes low-orbit reactor operation as a normal procedure, we have rated it as safer than Class IV because we believe that any such mission can assume human control and shuttle-based corrective operations if needed. The capability of such control and intervention radically alters safety questions.

- Class IV: Initial low orbit with nuclear electric propulsion to higher orbit, or to lunar or planetary missions.

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*It is debatable whether Class IV is more hazardous than Class III.

In this class one has to assume that the thrust must be both misapplied and could not be terminated to produce reentry, but the available Δv could potentially lead to even lower orbit or reentry. We note that it is currently projected that such NEP operations would not occur until the spacecraft had been placed in a 300-year orbit by chemical propulsion. The Shuttle has been designed to reach these orbits.

This class is of great importance, since NEP from low orbit is likely to be the only feasible way of executing many missions.

- Class V: Initial and continuing low orbit with lifetime of the order of months.

This class is typified by the COSMOS 954 satellite where a reactor is used for low-orbit surveillance. Disposal at the end of mission is preferably by boost to higher orbit. Design for controlled reentry might also be another option.

Table VI shows how the possible missions can be classified according to these criteria.

Regarding purely technical problems we believe that:

- Those of Class I are intrinsically essentially zero. The reactor would be placed (by nonnuclear means) in a high orbit before startup, and there would be no built-in means of lowering the orbit by any significant amount. The only means of reentry of any active material would be by the highly unlikely and calculable occurrence of impact by a major meteorite. Even this event would lead to general dispersal of the radioactivity rather than return of any major fraction to Earth.

- Those of Class II can also be essentially zero by proper redundant design and operation. This is true because of the multiplicity of independent safeguards that are available, all of which must fail and in the worst manner (with very low probability) before an intrinsically safe orbit is converted to a potentially hazardous orbit. The independent safeguards provide control over reactor power (with NEP), electrical power generation (with NEP), reaction mass flow, and spacecraft altitude.

Nevertheless, since there is some potential for lower orbits, some missions in Class II could have a small additional risk.

- In Class III there must be action taken to ensure that the reactor will not reenter after some relatively short time. This action is to maintain the orbit or to provide for reactor disposal by boost to higher orbit.

TABLE VI
CLASSIFICATION OF POTENTIAL MISSIONS

Best Prospects		Good Candidates		Potential Users	
Defense:	Space-based radar I, IV	Defense:	Advanced strategic surveillance sensor (infrared) I, IV	Defense:	Global logistics information system I, IV
Scientific:	Planetary exploration IV		Space-based weapon systems I, II, III, IV		Navigation grid I, IV
Transportation:	Earth orbit transfer		Deep space backup surveillance I, IV		Far-term RPV control readout I, IV
			DSCS-X I, IV	Civilian:	Disaster communications set I, IV
			G.I. - personal communications I, IV		Urban/police wrist radio I, IV
			Deep space command post I, IV		Personal communications wrist radio I, IV
		Transportation:	Earth orbit tug IV		Electronic mail transmission I, IV
					Advanced T.V. broadcase I, IV
					Voting/polling wrist set I, IV
					National information service I, IV
					3-D holographic teleconferencing I, IV
					Vehicle/package locator I, IV
					Border surveillance I, IV
					Fire detection I, IV
					Burglar alarm/intrusion dectection I, IV
					Energy monitor I, IV
					Nuclear waste disposal I, IV
					Low-orbit space station III
				Lunar Colony:	Power station for 12 men, I, IV

NOTE:

CLASS I High orbit, no re-entry

CLASS II High orbit, potential re-entry

CLASS III Low orbit space station

CLASS IV Low orbit NEP

CLASS V Short-life orbit (months)

However, even if the reactor reenters, it is probable that radiological analysis will show an acceptable risk to the general population. We, therefore, believe that this class of mission will be as acceptable even though the intrinsic hazard is higher than those of Classes I and II. In part, this is because we believe that a low-orbit space station will not be undertaken by the US unless rescue and corrective capability such as that afforded by the Shuttle is available ahead of time. The reactor should be acceptable in these circumstances.

Class IV is similar to Class III, in that again it is necessary to take action to ensure that reentry will not occur prematurely. The action is to ensure proper application of nuclear electric propulsion (NEP) to take the craft to higher orbit. The major concern is misapplication of thrust which reduces orbital lifetimes. It should be noted that the low NEP thrust gives ample time for detection of malfunctions and corrective action. Additionally, there are several independent systems that can be controlled from the ground to terminate the misapplied thrust (reactor power, electric power generation, reaction mass flow, spacecraft altitude).

Thus, as in Class III, even though the intrinsic hazard is higher than in Classes I and II, the risk of a properly designed mission will be acceptable.

Class V risk will always be considered higher because of the relatively short orbital lifetime. Planned disposal could be by boost to higher orbit or possibly controlled reentry. Because positive action is needed to prevent unscheduled reentry and the orbital times are short, we believe these are relatively high-risk missions. The justification would be the great benefit of the mission for national military purposes.

VII. SAFETY ANALYSIS

It is essential at the outset that space nuclear reactors be designed, fabricated, and tested with public health safety as a baseline consideration. The philosophy of safety involving radioactive substances embraces:

a. Confine and Contain.

b. Delay and Decay.

c. Disperse.

The first of these, confine and contain, isolates the radioactive material from the population by barriers.

The second, delay and decay, provides for sufficient isolation time that radioactive levels are reduced to meet radiation safety standards before exposure to the population. This can be accomplished in space missions of long-life orbits on the order of 300 years or more.

The third, dilute and disperse, is used when there is a large medium for dispersal such that elements in the population are not exposed to radiation levels greater than set forth in the radiological standards.

All of the methods can be used to meet the radiological standards, and any of them may be used in meeting different parts of a particular mission. Safety standards are met by operational and design features. Design features include devices that preclude reactor criticality until a satisfactory space orbit is reached and ensure that the reactor will be designed to be subcritical if immersed in water.

The accident environments considered are peculiar to the planned mission. The actual environmental conditions associated with each accident type are determined on the basis of the launch vehicle and mission profile. In general, the following constitute credible accident environments for spaceborne nuclear power sources:

Launch and Ascent

- Explosion overpressure
- Projectile impact
- Land or water impact
- Liquid propellant fire
- Solid propellant
- Sequential combinations

Space/Earth

- Loss of control
- Reentry
- Land or water impact
- Post impact environment (land or water)

For any given mission, detailed event trees such as Figs. 7 and 8 are developed and each event evaluated to insure that nothing is overlooked in protecting the populace. This analyses is documented and reviewed in a series of safety analysis reports, including a Preliminary Safety Analysis Report, after the reactor concept is selected for a particular mission; an Updated Safety Analysis Report after the design freeze; and a Final Safety Analysis Report issued about one year before launch.

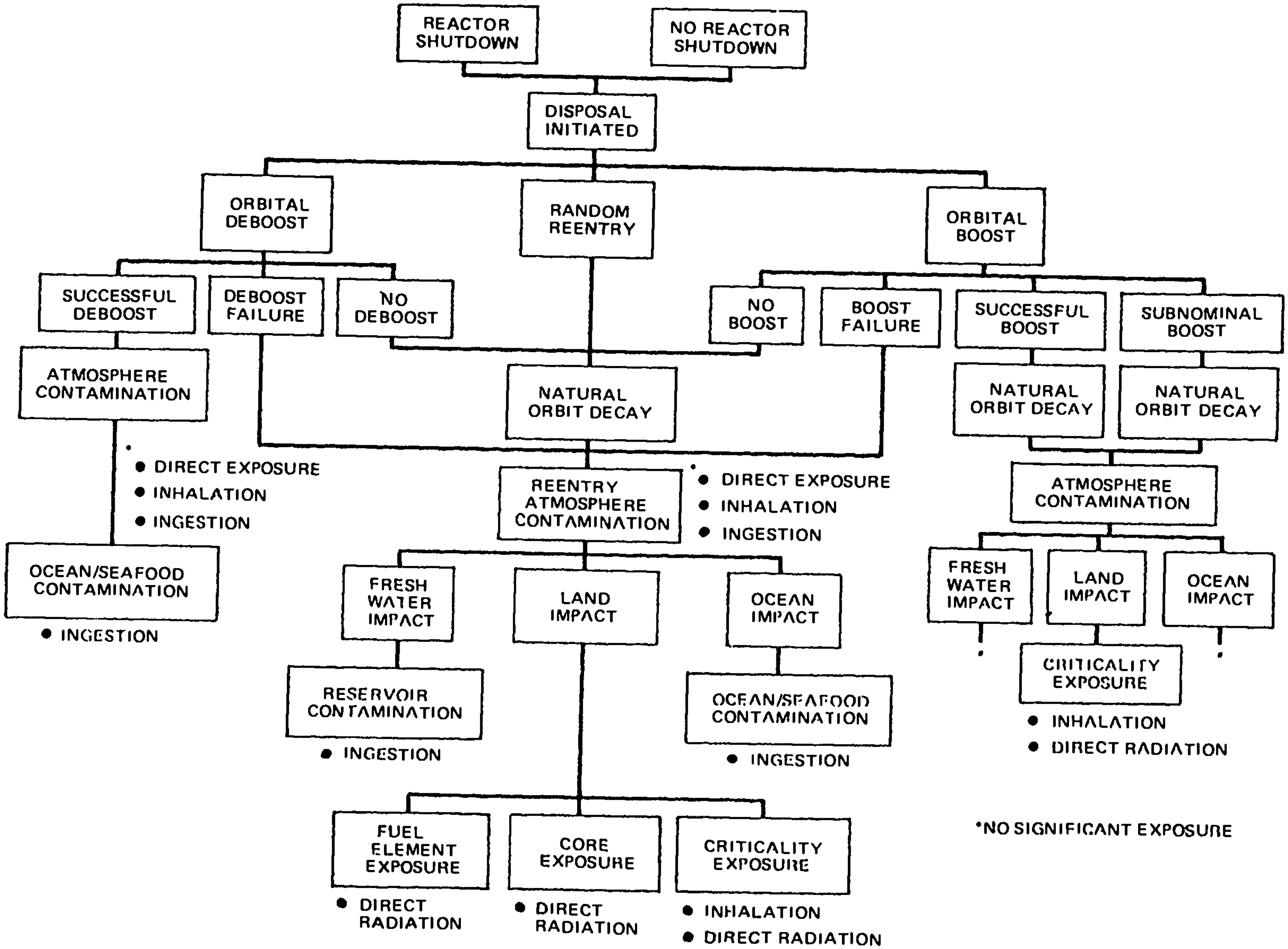

Fig. 7. Events leading to potential exposures for disposal phase.

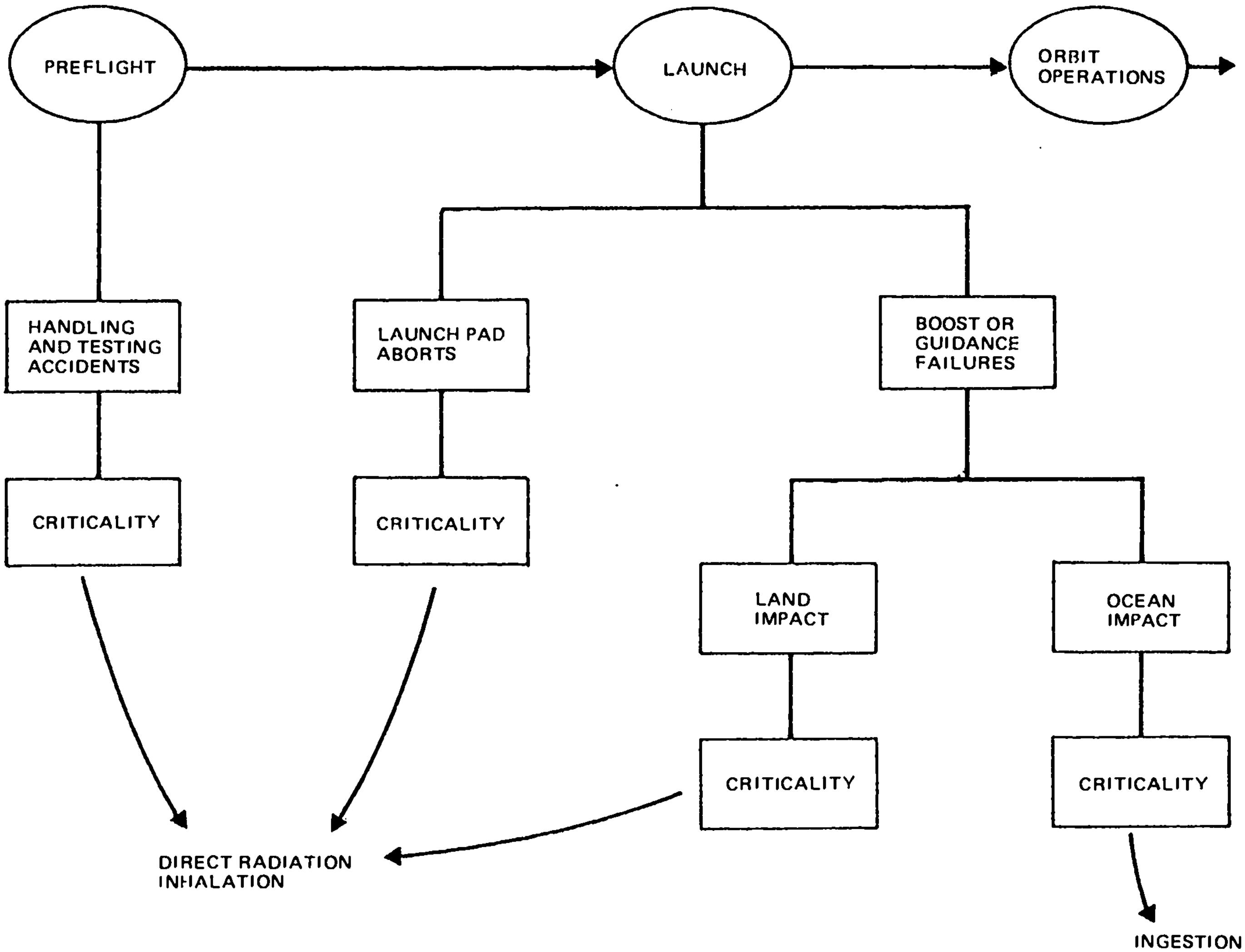

Fig. 8. Events leading to potential exposures during pre-flight to orbit operation.

VIII. SUMMARY

Based on statements made at UN meetings during 1979 and 1980 following the COSMOS 954 incident, the US accepts the use of nuclear reactors in space when technically justified. The UN also recognizes the acceptability of the use of reactors as long as they meet radiological standards set forth in the International Commission on Radiological Protection standards. There does not appear to be any reason using proper design and operation approaches that safety standards cannot be met.

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076-100	8.00	A05	226-250	14.00	A11	376-400	20.00	A17	526-550	26.00	A23
101-125	9.00	A06	251-275	15.00	A12	401-425	21.00	A18	551-575	27.00	A24
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