SPACE APPLICATIONS OF

RADIOACTIVE MATERIALS

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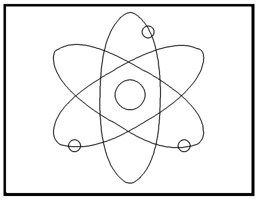
INTRODUCTION



There are a variety of space applications for radioactive materials, both on spacecraft and on launch vehicles. These applications range from power generation to the use of radioactive sources for radiation measurement references, instrument calibration, irradiation experiments, electronic circuit components, or for structural purposes, usually as ballast. The key characteristics of safety interest which differentiate these applications are the types and amounts of radioactive source material they use and the levels of radiation involved.

These materials emit ionizing radiation (as by-products of the process of radioactive decay) of different types and at different rates, according to the type, amount, and usage of the source. This radiation may, therefore, be relatively benign, or may pose a potential health hazard, or may be capable of damaging or affecting the operation of some types of equipment. In the extreme, and in sufficient quantities, certain of these materials can sustain the critical or even super-critical reactions which result in meltdown or detonation.

Applicants for a license to conduct commercial launch activities involving radioactive materials (radionuclides) must comply with regulatory requirements concerning their use. As the regulatory agency assigned the overall responsibility for ensuring public safety from hazards associated with U.S. commercial space launch activities, OCST must oversee that compliance. Licensees using Federal ranges will have to comply with established Range Safety procedures related to both regulatory and safety requirements. If such a launch is to be conducted from a commercial facility, OCST will have to provide more detailed oversight.

As an aid to assessing and preparing for that oversight role, this document addresses:

- A Technical and Terminology Review
- Typical Applications Relevant to Space or Space Launches
- Classifications of Radioactive Sources
- Agencies Involved in the Nuclear Safety Process
- Public Concerns and Issues Raised Regarding Past Launches of Payloads Using Radioactive Materials
- Key Safety Issues, as Perceived by the National Ranges

TECHNICAL AND TERMINOLOGY REVIEW

The following is a brief review of the physical mechanisms and technical terminology associated with the subject, with which the reader may not have maintained currency. While not a detailed primer on nuclear physics, it is intended to address the subject in sufficient depth to convey an understanding of the implications of nuclear materials use in commercial space vehicles.

Atomic Number: the number of protons in the nucleus of an atom of a given chemical element (as listed on the Periodic Chart); its value establishes the basic characteristics of an element.

Atomic Weight: roughly, the total number of protons and neutrons (which are of equal mass) in an element's nucleus;

Isotope: one of several forms of an element, having the same atomic number but slightly different atomic weights;

Nuclear Reaction: a reaction that alters the energy, composition, or structure of an atomic nucleus;

Nuclide: an atomic nucleus specified by atomic number, atomic mass, and energy state; "Radionuclides" are radioactive nuclides;

Nuclear Disintegration: natural or induced transformation of atomic nuclei from a more to a less mas-sive configuration, releasing one or more Ionizing Radiation type: alpha (α) or beta (β) particles and in some cases, gamma (γ) rays. α particles are positively charged helium nuclei, while β are high-speed electrons or positrons; a stream of either type may also be called a ray. γ rays are electro-magnetic radiation of very short wavelength. Of the three types, γ rays pose the most severe hazard, followed by β and α, respectively. The relative penetrating power of each type is shown in Figure 1.

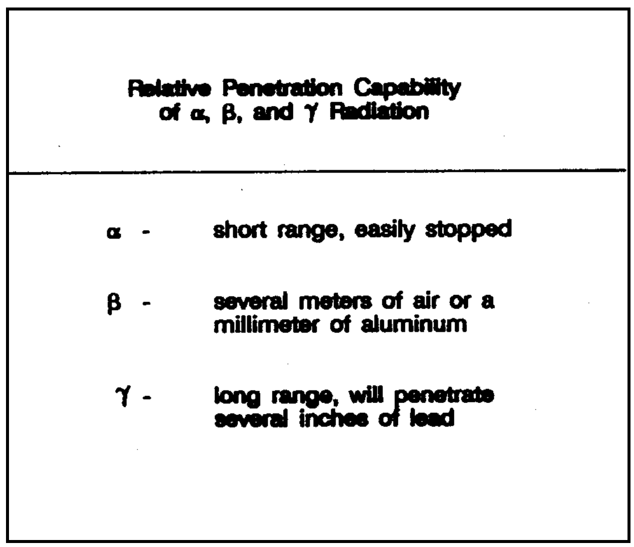


Figure 1. Relative Penetration Capability

Ionizing Radiation: radiation which can produce ions (atoms/groups of atoms with a net negative or positive charge due to gain or loss of an electron) in electrically neutral target material;

Radioactivity: emission and propagation of rays or particles from unstable atomic nuclei (see Radioactive Decay) or as a result of a nuclear reaction; inert materials may become radioactive when exposed to this ionizing radiation.

Radioactive Decay: decrease in the radiation intensity of a radioactive material over time, generally accompanied by emission α or β particles and/or γ radiation;

Radiotoxicity: poisoning effects of exposure to radioactivity; the direct effects on humans, called Radiation Sickness, vary with the intensity and duration of the exposure. They may progress from fatigue, nausea, vomiting, headache, and diarrhea shortly after exposure, to loss of hair and teeth, reduction in both red and white blood cell count, inability to resist infection, hemorrhaging, prostration, sterility, and death. The secondary effects of exposure include increased occurrence of cancer.

The early clinical effects of acute radiation doses, i.e., received within a period of about one day, over the whole body (as they might be in an accident or the explosion of a nuclear weapon) are summarized in Figure 2. Because the effects from a given dose of radiation vary according to the individual and the circumstances, the figure shows five dosage ranges where the effects are somewhat similar. For doses up to about 1,000 rads, the blood-forming system is most affected by radiation; for larger doses, first the gastrointestinal tract and then the central nervous system suffer major damage.[1]

ACUTE DOSE IN RADS	**PROBABLE CLINICAL EFFECT**
0 to 25	No observable effects.
25 to 100	Slight blood changes; no other observable effect
100 to 200	Vomiting in 5 to 50% within 3 hours; fatigue and appetite loss. Moderate blood changes, but otherwise recover within a few weeks.
200 to 600	Vomiting, etc. in 50 to 100% within 3 hours. For doses over 300, effects in 100% within 2 hours. Hair loss after 2 weeks. Severe blood changes, hemorrhaging, infection; death in 0 to 80% within 2 months. Survivors recover in from 1 month to a year.
600 to 1,000	Vomiting within 1 hour. Severe blood changes, hemorrhaging, infection, and loss of hair. Death of 80 to 100% within 2 months; survivors convalescent over a long period.

Figure 2: Early Effects of Acute Whole-Body Radiation Doses

Rad: a unit of absorbed radiation equal to 100 ergs/gram (see Rep);

Radioactive Isotope or Radioisotope: an unstable isotope, produced either naturally or artificially, which is subject to decay by nuclear disintegration, thereby releasing ionizing radiation (particles, rays) and/or energy in the form of heat;

Fission: the splitting of atomic nuclei, usually into two fragments of comparable mass, releasing heat energy and neutrons. It is commonly induced by the impact of slow neutrons, themselves released by fission. Fission produces additional highly active radioisotopes, and if uncontrolled, may reach a super-critical level, leading to a meltdown or nuclear explosion.

Controlled Fission: a self-sustaining chain reaction controlled at some desired level, as to generate heat in a nuclear reactor. The packaging of a reactor incorporates means to both moderate (slow the speed) and control (limit or regulate their numbers) the neutrons released.

Critical Mass: the minimum mass of a given fissionable material needed to achieve a self-sustaining chain reaction;

Units of Measure

Several measures are used to express the quantity of radioactive material (by its mass or weight, usually in metric units) and/or the amount of radiation emanating from it (by the number of nuclear disintegrations per unit time which will yield ionizing radiation):

Curie: that quantity of a radioactive material which will undergo 3.7×10^{10} disintegrations per second. Since this is a very high level of activity, either Millicurie (1/1,000 curie) or Microcurie (1/1,000,000 curie) are more often encountered.

Half-life: the time required for the number of radioactive atoms of an isotope (in a sample) to decay to one-half that number. Each radioisotope has a characteristic, exponential rate of decay, and thus a unique half-life (ranging from milliseconds to many thousands of years for different radioisotopes) which must be considered in safety requirements, especially those for long-term storage. The radioactive decay process produces a radioactive series of isotopes, successively lower in atomic weight, the last or "lightest" of which will be stable.

Specific Activity: the relative intensity of the radioactivity of a source, expressed in curies per gram of the material. For a pure radionuclide, specific activity is inversely proportional to the product of the isotope's* half-life and mass number. The benchmark material for this measurement is Radium ($_{88}Ra^{226}$); its specific activity has been assigned the value of unity[2], as its calculated activity is close to 1.

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* The specific activity may be calculated using the following relationship:

$$\text{Specific Activity} \approx \frac{1.13 \times 10^{13}}{T\ A} \quad \text{(curies/gram)}$$

where T = half-life (years, minutes, seconds, etc.)
and A = atomic mass

Roentgen: that quantity of ionizing radiation (X-rays or γ rays) that will produce one electrostatic unit (esu or statcoulomb) of charge in one cubic centimeter of dry air, at standard temperature and pressure.

Rem (roentgen-equivalent-man): that quantity of radiation which, when absorbed by a human, will produce the same effect as absorption of one roentgen of high-voltage X-rays.

Rep (roentgen-equivalent-physical): measure of the number of ion pairs produced, per unit volume of target material, per unit time. In tissue, one rep is equivalent to the absorption of 93 ergs (energy) per gram of the target material.

SPACE APPLICATIONS OF RADIOACTIVE SOURCES

Radioactive sources have a variety of uses in space, ranging from power generation to instrumentation. The following are examples of typical space applications:

Reactor Power Systems use the heat energy from controlled fission to drive some form of electric power generator. The U.S. flight-tested a reactor in 1965[3], with the launch of the SNAP-10A (Systems for Nuclear Auxiliary Power) device aboard an Atlas-Agena vehicle, the only such launch to date, while the U.S.S.R. has launched over twenty reactors. The SP-100 will be the first test unit under the Multi-Megawatt Reactor program, a joint venture by DOE, DoD, and NASA to develop large reactors for space use.

A new reactor fueled with enriched Uranium-238 remains relatively benign with respect to the production of thermal and ionizing radiation until the fission process is initiated. The requirements for shielding are at their minimums, and the radiation protection and heat dispersion measures will not see their design loads until the vehicle has reached orbit and the reactor is activated. Radiation from the fission process may begin to activate previously inert materials in the structure of the reactor "device" (generally at low levels), and possibly parts of the vehicle in which the device is installed, as well. Given these characteristics, the on-orbit activation is an effective safety measure.

Radioisotope Power Systems, which either use the heat released during radioactive decay (e.g., of Plutonium-238) to generate electric power or convert it directly into electricity, have been used frequently in the U.S. space program, and even more frequently in that of the U.S.S.R. Radioisotope Thermoelectric Generators (RTG) convert heat energy into electricity through thermocouples. The Dynamic Isotope Power Source (DIPS) uses heat in a closed Rankine or Brayton cycle to power a turbine-alternator, operating at higher thermal efficiency than the RTG.

Devices using radioactive decay, rather than fission, as their heat source are active at full thermal output[4] as soon as they are fueled, and both thermal and radiation protective measures must be in effect at the time of fueling. In four accidents or incidents involving U.S. spacecraft carrying RTGs, all safety systems have functioned as designed, and no unplanned releases resulted.

Figure 3 illustrates domains, with respect to required power level and mission duration, where each type of space power source (including non-nuclear sources) seems to best suit requirements. Other factors may influence the choice, including cost and the need for radiation shielding, with possible weight penalties. For a vehicle which has to traverse the Van Allen radiation belt, an environment not conducive to the use of solar panels, or go into deep space, where solar energy flux is of insufficient intensity to permit the use of solar panels, the NPS may be indicated.

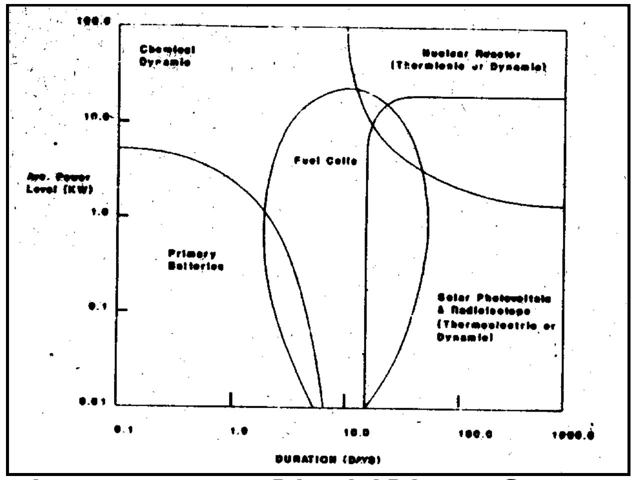

Figure 3. Applicability of Space Electrical Power Systems

The design advantages of the NPS include their compactness and long service life. Selection of a particular type of NPS would be based on the functional mission and both the magnitude and duration of the power requirements; current conceptual designs consider both thermocouples (as on an RTG) and heat cycles with a turbogenerator as the means of converting heat to electricity.

Environmental Heaters utilize the heat from radioactive decay directly, rather than to produce electricity; they are not a type of NPS, and may use either major or minor sources, according to the application. The Light Weight Radioisotopic Heater Unit (LWRHU) is used to provide heat to surrounding equipment on interplanetary spacecraft.

Minor Radioactive Sources, used in applications other than power generation, may involve quantities in the millicurie or microcurie range. One such application is in electronic circuit components such as tubes of a class referred to as "gas" or "gas-filled". This type of tube is used in the "electronic trigger" portions of the engine igniters or flight termination system (FTS) firing circuits on launch vehicles, rather than in payloads. They employ "cold cathode" gas diodes containing a very small amount of radioactive material, used to establish and maintain an initial level of ionization of the gas in the tube.

The Centaur Upper Stage, used with the General Dynamics Atlas Booster, employs two "discharger electron tubes"; one in each of the RL-10 engine ignition circuits. These tubes use a radioisotope of krypton gas (${}_{36}Kr^{85}$)* for gas tube excitation. The FTS circuits on the Exoatmospheric Re-entry Interceptor Subsystem (ERIS) vehicle employ a radioisotope of nickel (${}_{28}Ni^{63}$). The circuit design uses the tubes more as pulse-shaping devices than for the characteristic constant voltage/varying (high) current capabilities of gas diodes.

Larger quantities of radioactive material may be used on space vehicles and still qualify as minor sources. Depleted Uranium-238 (from which the U-235 normally present has been extracted) is often used as ballast; its density is approximately 1.67 times that of lead. Its radioactivity makes no contribution in this application, but it must be treated as a minor source.

Other uses for minor sources are varied, but most involve minute quantities. Radiation measuring instruments frequently employ a sample of known intensity for calibration purposes, or to provide a reference level against which to compare the target radiation. Minor sources may be used in scientific experiments where the thrust is to compare phenomena observed on earth with comparable observations made in the space environment.

As noted previously, the characteristics of safety interest which differentiate power generation applications from other applications are the amounts of radioactive material and the radiation levels involved. Typically, a nuclear power system will contain a "major" source consisting of material which is highly radiotoxic; while a "minor" source for some other use may also be highly toxic, the quantities are smaller, as explained below.

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* General Dynamics Corporation, <u>Application for Launch License to the Office of Commercial Space Transportation</u>

CLASSIFICATIONS OF RADIOACTIVE SOURCES

Two schemes of classification are relevant to space-related applications; the one used by the Nuclear Regulatory Commission (NRC)*, as the basis of its regulatory framework, and that used by the National Aeronautics and Space Council (NASC)** (and followed by the Department of Defense) as the basis for determining safety review and reporting requirements. The NRC regulations address "Special Nuclear Material" (enriched Uranium or Plutonium used for weapons or nuclear power) and "Byproduct Material" yielded or made radioactive when special nuclear materials are produced or used.

In 1970[5], the NASC adopted the International Atomic Energy Agency (IAEA) "Classification of Radioisotopes"[6]. Radioactive materials are grouped according to relative radiotoxicity, a function not only of the activity of the material, but also of the severity and characteristics of the biological effects from exposure to their radiation. Each radioisotope is assigned to one of four Groups; Group I is the most hazardous and Group IV the least. These Groups are based on maximum permissible intake, primarily by way of inhalation (note: this is a different measure from "acute dose").

The NASC classified radioactive sources incorporating 20 or more Ci of material in Radiotoxicity Group I or II, or 200 or more Ci in Group III or IV, as "Major". Any launch of a major source requires Presidential level (or equivalent) approval. These sources are usually for nuclear power system applications. "Minor" sources are those containing Group I through IV materials in smaller amounts than those cited above. While they do not require Presidential approval for launch, minor sources are subject to a set of safety analysis and reporting requirements which are described later in this report. Figure 4 shows where some typical space and non-space applications fit into the NASC classifications.

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* The Atomic Energy Commission (established by the Atomic Energy Act of 1946, as amended by the Atomic Energy Act of 1954) exercised extensive licensing and related regulatory functions. The Energy Reorganization Act of 1974, 42 U.S.C. 5801 *et seq*., abolished the AEC, and established the Nuclear Regulatory Commission (NRC) as an independent regulatory agency, under Congressional oversight and functionally separate from the Executive Branch of the Government.

** The National Aeronautics and Space Council was established by the National Aeronautics and Space Act of 1958, the same Act that established NASA. It was chaired by the Vice President of the U.S., with the Secretaries of Defense and Transportation, the NASA Administrator, and the Chairman of the AEC as members. The council functioned to advise the President on matters pertaining to aeronautics and space activities conducted by U.S. departments and agencies. The NASC was abolished by Reorganization Plan No. 1 of 1973, effective June 30, 1973.

CLASSES	APPLICATIONS	RADIOACTIVE MATERIALS
MAJOR SOURCES		
	POWER REACTORS	ENRICHED URANIUM-238
	RADIOISOTOPE THERMAL GENERATORS	PLUTONIUM-238 CURIUM-242 STRONTIUM-90
	DEEP-SPACE HEATERS	PLUTONIUM-238
MINOR SOURCES		
RADIO-TOXICITY GROUP I	STATIC ELIMINATORS	POLONIUM-210
	BOMB DETECTORS	CALIFORNIUM-250
	CALIBRATION SOURCES	AMERICIUM-241
RADIO-TOXICITY GROUP II	TUMOR IMPLANTS ("GOLD SEEDS")	RADON-222
RADIO-TOXICITY GRP III	ELECTRON TUBES	KRYPTON-85 COBALT-60
	SPARK GAP IRRADIATORS RADIATION THERAPY	COBALT-60
	SELF-LUMINOUS INSTRUMENTS	KRYPTON-85
	COUNTERWEIGHTS (BALLAST), SHIELDING, PHOTOGRAPHIC MATERIALS, FIRE DETECTORS	NATURAL OR DEPLETED URANIUM
	SYNTHETIC PLASTIC RESINS	SCANDIUM-46
RADIO-TOXICITY GROUP IV	ELECTRON TUBES	NICKEL-63 CESIUM-137 PROMETHIUM-147
	MICROWAVE RECEIVER PROTECTOR TUBES	TRITIUM
	SELF-LUMINOUS INSTRUMENT AND WATCH DIALS, MARINE COMPASSES	TRITIUM PROMETHIUM-147
	FLOW METERS	CESIUM-137

FIGURE 4: Example Applications

AGENCIES INVOLVED IN THE NUCLEAR SAFETY PROCESS

NRC Licensing

The NRC licenses and regulates civilian uses of nuclear energy. NRC licenses are required authorization for a variety of activities involving manufacture, production, transfer, receipt, acquisition, and ownership of nuclear materials, including the construction and operation of power utility nuclear reactors[7]. The NRC is charged to protect both public health and safety and the environment, and its decisions are subject to judicial review by the Federal courts.

NRC does not regulate most Department of Energy (DOE) activities, except for licensing of DOE high-level radioactive waste disposal repositories. Special nuclear materials which are produced by DOE for DoD or NASA are exempt from NRC licensing, based on national defense interests. Nor does the NRC regulate DoD nuclear power reactors, such as those used on U.S. Navy ships.

The NRC regulations are contained in CFR 10, Chapter I, Nuclear Regulatory Commission (Parts 0-199). The primary regulations that cover licensed activities are:

- 10 CFR 30 - Rules of General Applicability to Domestic Licensing of Byproduct Material
- 10 CFR 40 - Domestic Licensing of Source Material
- 10 CFR 70 - Domestic Licensing of Special Nuclear Material

Typically, the party responsible for the minor source radioactive material must apply to the NRC for a license (under 10 CFR 30) for possession or use of the material. The application will specify that the source materials will be used in a launch. As they relate to the use of nuclear materials in space, the NRC also controls minor sources and activated materials under the terms of general licenses[4]. Each regulation cited above also lists certain exemptions, based on the use, concentration, or quantity of the radioactive material. For example, 10 CFR 30 exempts electron tubes containing less than 30 microcuries each[*].

NRC guidelines require that re-entering radioactive materials be recovered, if they <u>can</u> be (NRC does not expect or require recovery if the materials impact in deep ocean areas.) Recovered materials must be placed in appropriate containers for shipment to, and then burial at, a licensed radioactive waste disposal facility.

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[*] These tubes, however, must be provided by a licensed manufacturer. The intent of this requirement is to ensure that the quantity limitation is met, rather than to assure safety. The licensing process for manufacturers also addresses disposal concerns.

The Department of Energy (DOE)

The Department of Energy develops major source nuclear systems for weapons and DoD or NASA power sources. DOE is the authority assuring the safety of these systems while under development, but an NRC license is required prior to system operation by the using agency. Major sources in space applications undergo extensive review by the Interagency Nuclear Safety Review Panel, with DOE participation, as described later in this report.

NASC/OSTP Review Process

As introduced earlier, NASC classified radioactive materials for space use into major and minor sources. Major sources are subject to an extensive review process involving the user agency or organization, an Interagency Nuclear Safety Review Panel, and the launch range. NASC defined three Nuclear Safety Review Categories ("A", "B", and "C") of minor source analysis and reporting requirements, and set upper limits for the amounts of material from each Group which would require each Category of safety review, reporting, and approval for launch. These Categories are shown in Figure 5.

NUCLEAR SAFETY REVIEW CATEGORIES	MAXIMUM QUANTITIES OF SOURCE MATERIALS IN CURIES (Ci)			
	Radiotoxicity Group I	**Radiotoxicity Group II**	**Radiotoxicity Group III**	**Radiotoxicity Group IV**
Category A NASC/OSTP Staff Review	≤ 20 Ci	≤ 20 Ci	≤ 200 Ci	≤ 200 Ci
Category B Agency Approv; OSTP Qtrly Rpt	≤ 1.0 mCi	≤ 50 mCi	≤ 3 Ci	≤ 20 Ci
Category C No Reports	[See Appendix A to this report; Category C limits are assigned by individual radionuclide, not by Group]			

Figure 5: Nuclear Safety Review Categories

When the NASC was abolished, its role in the review and reporting process was assumed by the Office of Science and Technology Policy (OSTP). The NASC guidelines for both major and minor source review and approval remain in effect, and are also used in the reviews conducted by the Department of Defense (DoD) ranges for both major source (AFR 122-15[8]) and minor source (AFR 122-16[9]) launches.

The Category A review process is the most extensive of the three, and the review report must be submitted to OSTP for approval. This report consists of a letter or memorandum discussing the purpose, schedule, on-orbit duration, and orbital parameters of the mission; the device(s) containing the nuclear materials, and the quantity and type of materials used; and the conclusions drawn on the safety consequences of any potential problem scenarios (including a launch mission failure or abort), and of the planned re-entry.

In certain cases, the action agency must provide a brief Safety Analysis Summary (SAS) which lists the characteristics of the radioisotope materials, the consequences of an abort or worst-case accident, relevant safety procedures, and the recovery plans, where appropriate. In order for the OSTP staff to accomplish its review, the Category A report should be submitted a minimum of six weeks prior to the planned launch date.

Category B reviews require "user agency" approval, with quarterly reporting to the OSTP; these reports must be submitted a minimum of two weeks before launch. Category B reports list planned launches of nuclear materials (in tabular form), specifying the spacecraft and mission parameters, the launch site and schedule, the number of sources, and types and amounts of radioactive materials contained.

Category C materials are exempt from any reporting requirements outside the user agency. No safety analysis is required, beyond confirmation that good safety practices are in effect and that the cumulative amount of an isotope does not, in fact, exceed Category C limits, even in multiple sources. Appendix A to this report is a listing of radionuclides by Group, showing the maximum quantity (activity) of each for which Category C safety review.

The cumulative quantity determines the appropriate Category for each Radiotoxicity Group. Should there be sources from multiple Groups on a single vehicle, each will be prorated and their sum will determine the Category. In the Centaur example cited earlier, Krypton-85 is a Group III substance, and the total activity in the two tubes is approximately 49.4 microcuries, requiring Category B review for the approximately 0.063 micrograms of material used per tube. The four ERIS tubes total 160 microcuries of a Group IV nickel isotope, requiring Category A review and approval.

The Interagency Nuclear Safety Review Panel (INSRP)

During the 1960's, the Atomic Energy Commission (later changed to DOE), DoD, and NASA developed an informal process for interagency safety review and approval of launches involving nuclear materials. On December 14, 1977, after studies were conducted to develop a consistent and efficient review and approval process, Presidential Directive/National Security Council Action Memorandum 25[10] formalized the interagency review process. This Directive also established a requirement for all launches involving a nuclear power system or other major source to be approved by the President or the Director of the Office of Science and Technology Policy (OSTP).

Upon request of the user agency (historically one of the three INSRP member agencies), an *ad hoc* Interagency Nuclear Safety Review Panel (INSRP) is chartered by OSTP for each planned mission which will involve a spaceborne nuclear power system. The Panel is charged to review and evaluate the risks associated with the launch, operation, and re-entry. An INSRP is chaired by three coordinators: one each from the DOE environmental, safety, and health (ES&H) organization; the Air Force Inspection and Safety Center (AFISC); and from the NASA Headquarters Safety Office. These coordinators establish subpanels of experts in the areas needed. The INSRP may remain involved with a mission through several years of it's evolution.

The INSRP process includes the review of safety analysis products produced under the Air Force Regulations (AFR 122-15), the DOE Overall Safety Manual, and the NASA Basic Safety Manual[11] which are followed by the organization planning the launch. The NRC is invited to send representatives to INSRP meetings; the Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA), and/or other agencies may also participate, as observers or subpanel members of the INSRP.

The INSRP evaluation is based on review of three Safety Analysis Reports [Preliminary (PSAR), Updated (USAR), and Final (FSAR)] developed by or under contract to DOE, and of the documentation packages prepared for the program preliminary and critical design reviews. Contributions concerning the spacecraft, launch vehicle, flight profile, and operations come from organization responsible for the launch. The FSAR is issued approximately one year before launch[4], and is comprehensive. It contains risk analyses for nominal performance and any failure modes or anomalies in or affecting a nuclear power system, as well as hazard predictions over the entire range of operation of the system.

The INSRP performs an independent evaluation of the risks, but does not recommend approval or disapproval of the launch; findings are submitted to the OSTP, with copies to the heads of the three INSRP member agencies, in the form of the FSAR, for their use in the launch approval request process. If the heads of the two supporting agencies concur, the user agency submits a request for launch approval, with a copy of the FSAR, to OSTP[12].

The INSRP must address failure modes for a vehicle, including launch anomalies and on-orbit failures, as well as re-entry and disposition of spent sources. The purpose of these reviews is to ascertain whether the containment provisions for the nuclear fuel can withstand the failure mode and re-entry environments, retaining integrity and preventing any unplanned release, which could pose a potentially severe radiation hazard to any exposed populations.

Figure 6 illustrates the process of Nuclear Safety Review and approval for launches of major or minor nuclear sources.

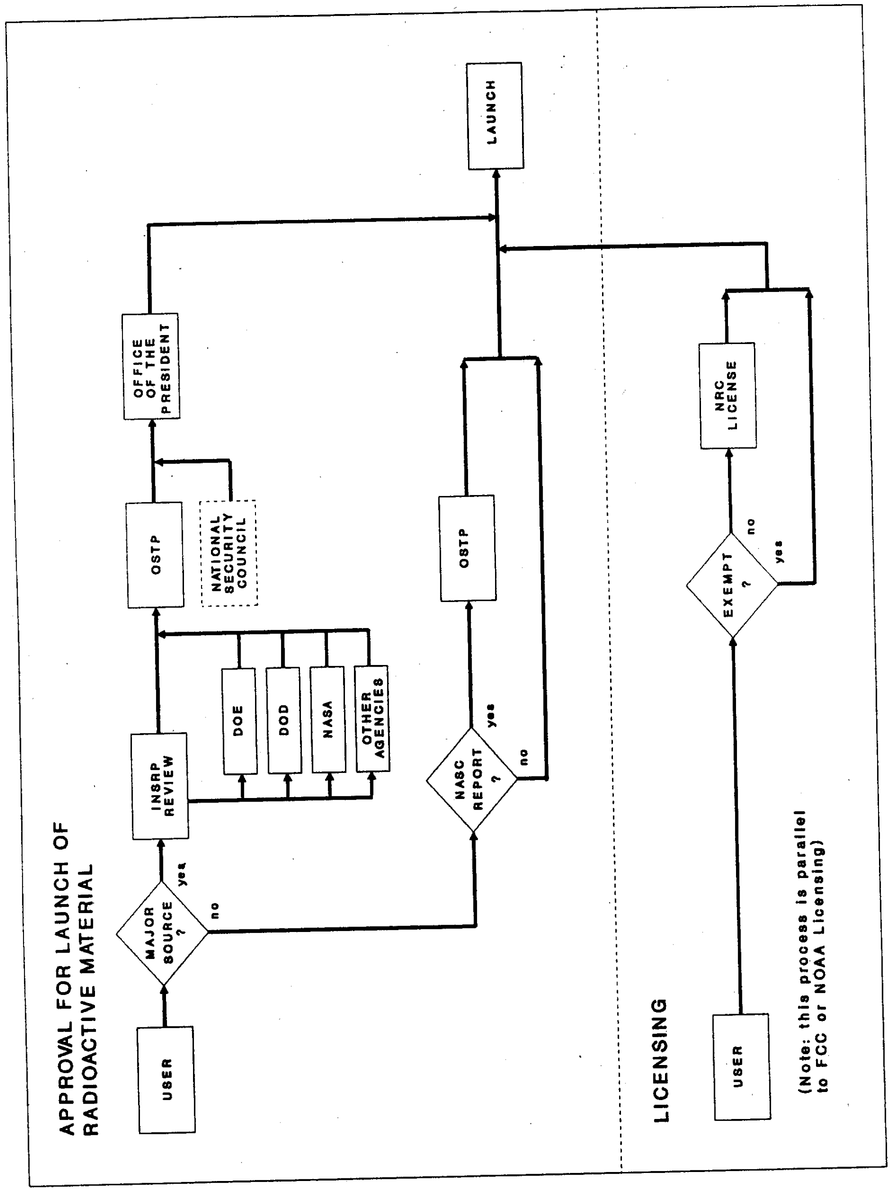

Figure 6: Radioactive Material Safety Review and Approval Process

International Influences

The United States has cooperated and complied with the spirit and letter of international agreements stemming from the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS). The focus of these agreements was on the potential environmental effects of the inadvertent re-entry and subsequent dispersion of radioactive material carried aboard an earth orbiting spacecraft. The documentation[3] listed below constitutes a history of these agreements:

1. United States of America, Uses of Radioactive (Nuclear) Materials by the United States of America for Space Power Generation, working paper submitted to COPUOS, U.N. Document A/AC.105/L.102, United Nations, New York, 15 March 1978

2. United States of America, Use of Nuclear Power Sources in Outer Space, working paper submitted to the Scientific and Technical Subcommittee of COPUOS, United Nations, New York, February 1979

3. United States of America, Criteria for the Use of Nuclear Power Sources (NPS) in Outer Space, working paper submitted to the U.N. Working Group on the Use of Nuclear Power Sources in Outer Space (WGNPS), U.N. Document A/AC.105/C.1/WG.V/L.8, United Nations, 23 January 1980

4. Report of the WGNPS on the Work of Its Third Session, Annex II of Report of Eighteenth Session, U.N. Document A/AC.105/287, 13 February 1981

Presidential Directive/NSC-25 implemented the policy subsequently covered in the U.S. working paper submittals and the U.N report, which forms the basis of international efforts to regulate the launch and orbit of nuclear materials.

PUBLIC CONCERNS/ISSUES WITH THE LAUNCH OF RADIOACTIVE MATERIALS

As mentioned, the United States first launched a SNAP-10A reactor aboard an Atlas-Agena vehicle in 1965. Other major nuclear sources have been launched through the years*, including NASA deep space probes such as the Voyager series launched in 1977. The Soviet Union routinely uses reactors in low earth orbit (LEO) and boosts them to high earth orbit (HEO) after mission completion[13]. There was no extraordinary news coverage or expression of public concern with these events, and no significant protests or demonstrations.

On January 24 1978, Cosmos 954, a reactor-bearing Soviet satellite, re-entered. A considerable amount of material survived re-entry to impact in northern Canada, including radioactive material from the reactor. This event, coupled with press reissue of the details of the re-entry and impact of significant debris from the U.S. Skylab satellite in Australia (which carried no major nuclear sources), served to heighten public awareness of potential impact hazards from re-entering space vehicles, particularly those with nuclear sources. Notwithstanding this publicity, expressions of public concern in this area never approached the intensity of those routinely raised in regard to the potential for accidents within the nuclear power industry.

The events spurred efforts of the U.N. Working Group on the Use of Nuclear Power Sources in Outer Space, which later reaffirmed its conclusion that, provided all safety requirements are met, nuclear power sources can safely be used in space[13]. The government space community was given added impetus to continue to comply with both the spirit and the letter of Presidential Directive/NSC-25, requiring INSRP review of all intended uses of nuclear power sources in space, while the international space community was encouraged to adopt similar measures.

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* Other major sources include: SNAP-27 RTG's employed with the Apollo Lunar Surface Experiment Packages (ALSEP), SNAP-19 RTG's launched with the NASA Pioneer deep space probes and Viking Mars unmanned lander missions, and RTG's for DoD navigation satellites and NASA's Nimbus B weather Satellite (SNAP-3, 9A, 19).

The launch of the Galileo Spacecraft, with twin General Purpose Heat Source Radioisotope Thermoelectric Generators (GPHS-RTG) in October of 1989 was preceded by a flurry of anti-nuclear rhetoric from a spokesman of a Florida protest group, including threats of a "sit-in" to prevent the launch. Although this activity received nationwide press coverage, it did not become a *cause celebre*. NASA spokesmen appeared in public (news) interviews to answer the stated concerns, principally by explaining the extensive safety review to which the mission had been subjected. NASA explained that, in conjunction with DOE, it had spent 10 years and $10 million dollars studying the potential risks.

The Christic Institute and anti-nuclear activists petitioned a Washington, D.C. court to enjoin the launch, based on claims that it was too dangerous because the Jupiter probe contained a nuclear power source[14]. The petition was denied after oral arguments, and the launch was successful.

This protest was the first attempt by a citizen's group to stop a NASA launch by instituting legal proceedings, but the incident may indicate a growing public propensity to protest against the launch of major nuclear sources. The publicity given the results of the investigation into the Challenger (STS-51L) accident may be a contributing factor to this attitude, if it exists.

With minor amounts of radioactive materials, there seems to be no discernable public concern. A popular comparison, frequently used when discussing minor sources at the National Test Ranges, states that most minor sources are not as active as the material used for luminescence on some wristwatch dials. Low hazard levels associated with minor sources are not likely to raise public concern.

KEY SAFETY ISSUES CONCERNING RADIOACTIVE MATERIALS, AS PERCEIVED BY THE NATIONAL TEST RANGES

The Galileo spacecraft, launched aboard the Shuttle Atlantis, carried two GPHS-RTG power systems, which use Plutonium Dioxide

(Pu-238) for fuel. The exact amount of plutonium carried has been treated as sensitive information; however, "Space News[15]" stated it was 48 pounds. If this is the weight of the PuO_2, then the actual weight of the plutonium would be approximately 42.3 pounds.

The most stressing failure mode addressed by the INSRP in their analysis of the safety of the mission concerned an intact impact of the orbiter/ET/booster aggregate, shortly after liftoff. In this scenario, the high order detonation that would result was estimated to have maximum credible yield values from 1 to 2.6 million pounds TNT equivalence. Galileo originally was to use a Centaur stage to boost it to earth escape velocity and then into its trajectory to Jupiter. The contribution of the Centaur to the maximum credible yield is not included in these figures.

Clearly, the INSRP members (and the agencies they represented) were concerned that the RTGs could not withstand the severe over-pressures and thermal stress of such a detonation. NASA, however, decided that the risks to the crew from a Centaur stage [with its cryogenic liquid oxygen (LOX) and liquid hydrogen fuel load] were excessive, and chose to replace the Centaur with an Inertial Upper Stage (IUS) booster.

The INSRP conducted a thorough risk evaluation, including review of the results of tests of RTG mock-ups in a shock tube, where expected overpressures were simulated. The INSRP often helps to define the requirements for such tests. They also conducted a comprehensive study of both the STS-51L (Challenger) and Vandenberg Titan 34D-9 accident data, in order to include as much recent empirical data as was available in their analysis. The INSRP presented its conclusions regarding the probabilities, quantities, and possible health effects of a release due to failure during launch of the Galileo with the IUS.

The considerable work performed by the INSRP reflects the prime concerns of its members, which include representation from the National Test Ranges, that the structural integrity of a nuclear power source be maintained in a worst-case failure scenario. It is important to emphasize from a public safety and health perspective that this concern for the integrity of the RTGs is not based on the notion that they could produce a nuclear explosion and create casualties in that manner, as might be assumed from the discussions of blast and overpressure.

Concerning reactors, DOE's current specifications for the SP-100 reactor require a design that maintains the integrity of its core in launch failure or re-entry modes leading to earth impact. The reactor must be designed to survive a catastrophic explosion during the launch phase or a re-entry and impact, in an essentially intact condition. In the latter scenario, it would bury itself until it could be recovered[13], unless it impacted in the broad ocean area[*].

Two alternatives to re-entry exist for the disposition of spent sources. Again maintaining an intact device, they are to either provide the capability to boost the device into a high earth orbit (thus delaying eventual re-entry for perhaps hundreds of years), or to impart sufficient velocity to the device to achieve an escape trajectory from the earth's gravity. The former alternative poses a problem for future generations, and the latter may be difficult to achieve due to the extra weight (and expense) to provide the thrust necessary to achieve escape velocity. All three schemes, intact impact, HEO, and escape, may involve separation of the nuclear device from the rest of the satellite.

There also exists the potential for on-orbit collision of the satellite and other orbiting satellites or space debris. Relative impact velocities in this circumstance may be extremely high, and the effect of such a collision on the integrity of a nuclear power source may be devastating, creating clouds of nuclear debris that

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[*] Although generally associated with security rather than safety, the possibility of an intact major nuclear source being recovered by parties hostile to the U.S. exists. Consideration of this aspect of space applications of nuclear sources would seem to fall within OCST responsibilities if the launch were conducted from a commercial facility.

would eventually re-enter. NASA, the Air Force, and other users of space are currently researching and analyzing this problem.

Plutonium and the other transuranium elements (except Neptunium) are radiological poisons with high rates of α particle emission and a characteristic of specific absorption by bone marrow. The former makes these elements lethal in minute amounts, and the latter means that the human body cannot get rid of the material, once ingested.

Plutonium is one of the most dangerous poisons known; the worst-case scenario may therefore be a launch vehicle explosion which results in Plutonium being vaporized or otherwise reduced to small particles and released into the environment. The severity of the short-term effects would depend on the timing of the failure. If it occurred early enough in the flight, there could be casualties on the range and/or in the surrounding area. Whether early or later in the flight, a failure of this type over the ocean could result in long-term contamination of the area's food chain.

No commercial space launch vehicle in the current inventory uses an expendable booster which can approach the degree of hazard to which the STS, in failure mode, exposes nuclear power systems. The Centaur aboard the Shuttle was a special case, and analyses would have to be performed of the case at hand, should a proposed launch (e.g., using the Centaur as part of a more conventional commercial Atlas configuration) involve a major source.

SUMMARY

There are two general types of space-related applications for radioactive materials. Major sources are used as heat sources for power systems, while minor sources are used for most non-power applications. Frequent use of minor sources can be expected in future commercial launch vehicles, or their payloads, or both.

For the near term, it appears unlikely that an application for a license to launch a commercial payload would have a nuclear power system as part of the launch configuration. Should the materials processing in space (MPS) area develop to the point where there is sufficient economic return, some MPS experimental or operational payloads might require electric power at levels only available from a reactor or radioisotope power system. Under the current federal regulations, OCST would be directly involved in both the safety and national security aspects of the approval process.

Third party safety concerns are not treated separately from those affecting first or second party safety, either in the NRC safety evaluation requirements for licensing minor sources or those used by DoD for approval to launch them, or in those applied by the INSRP for major sources. Neither mission success nor public safety is given overriding consideration; each set of procedures appears adequate to satisfy OCST concerns for public health and safety.

The INSRP review process was designed to address the launch of all major nuclear sources, when NASA and the Armed Services [now including the Strategic Defense Initiative Organization (SDIO)] were the only proponents of missions incorporating nuclear sources, and either Air Force or NASA vehicles would be used to launch those missions. Should a commercial launch involve nuclear power or some other major source application, and particularly if that launch is to be conducted at a commercial launch facility rather than from a DoD range, it may be advisable for DOT/OCST to seek representation on the INSRP for that launch.

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