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SPP-SRS-0002
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Page 1

The Manager
Schenectady Naval Reactors Office
United States Department of Energy
Schenectady, New York

Subject: Request for Naval Reactors Comment on Proposed PROMETHEUS Space Flight Nuclear Reactor High Tier Reactor Safety Requirements and for Naval Reactors Approval to Transmit These Requirements to Jet Propulsion Laboratory

References:
1. Nuclear Safety Policy Working Group Recommendations on Nuclear Propulsion Safety for the Space Exploration Initiative, September 27, 1991.
2. DOE OSNP-1, Nuclear Safety Criteria and Specifications for Space Nuclear Reactors, August 1982.
3. Applied Physics Laboratory, Nuclear Space Power Safety and Facility Guidelines Study, September 1995.
4. Lockheed Martin GPHS-RTGs in support of the Cassini Mission, Final Safety Report (FSAR), May 30, 1997.
5. DOE/SF/12209—T1 TI86 026240, SP-100 Surety Evaluation Interim Report, June 1985.
6. DOE-STD-3009-94, "Preparation Guide for U.S Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses", July 1994.

Dear Sir:

The purpose of this letter is to request Naval Reactors comments on the nuclear reactor high tier requirements for the PROMETHEUS space flight reactor design, pre-launch operations, launch, ascent, operation, and disposal, and to request Naval Reactors approval to transmit these requirements to Jet Propulsion Laboratory to ensure consistency between the reactor safety requirements and the spacecraft safety requirements.

The proposed PROMETHEUS nuclear reactor high tier safety requirements are consistent with the long standing safety culture of the Naval Reactors Program and its commitment to protecting the health and safety of the public and the environment. In addition, the philosophy on which these requirements are based is consistent with the Nuclear Safety Policy Working Group recommendations on space nuclear propulsion safety (Reference 1), DOE Nuclear Safety Criteria and Specifications for Space Nuclear Reactors (Reference 2), the Nuclear Space Power Safety and Facility Guidelines Study of the Applied Physics Laboratory

(Reference 3), and the safety approach of previous space exploration missions and projects, such as Cassini (Reference 4) and SP-100 (Reference 5).

I. DISCUSSION

A. Space Reactor Safety Requirements

Consistent with Naval Reactors program philosophy, the cornerstone of the PROMETHEUS nuclear reactor safety approach is that no undue risk to the health and safety of workers, the public, or adverse effects to the environment should result from activities associated with the nuclear reactor of the PROMETHEUS project.

A three-tier approach has been used in the development of the PROMETHEUS space reactor safety requirements. The first tier requirements are of general nature, and are consistent with the reactor safety philosophy for the PROMETHEUS project. They apply to all PROMETHEUS reactors, including land-based test / prototype reactors, space-based test / prototype reactors, and flight reactors that will power specific space exploration missions (e.g., the Jupiter Icy Moons Orbiter (JIMO)) throughout their life-cycle from fabrication through disposal.

The Tier 2 requirements discussed below are qualitative in nature. They are applicable specifically to flight reactors from receipt at the launch site through launch and subsequent operations. They address reactor safety considerations associated with pre-launch operations, launch, ascent, operation, and disposal of the PROMETHEUS flight reactors.

This letter contains Tier-1 requirements for all PROMETHEUS reactors and Tier-2 requirements for the PROMETHEUS flight reactors. The detailed, quantitative, mission-specific (e.g., PROMETHEUS-1) Tier-3 reactor safety requirements will be submitted for NR approval under a separate cover. Tier-2 and Tier-3 safety requirements for operations at core vendor facilities, ground based nuclear test facilities, and disposal facilities are anticipated to be generally similar to those invoked for other Naval Reactors program reactors and any required changes to those requirements or differences in implementation will also be addressed separately.

A.1 PROMETHEUS Project Tier 1 Reactor Safety Requirements

In order to achieve the safety philosophy above, the health and safety of the public and the environment must be protected from the hazards due to all activities related to the PROMETHEUS project. However, it is recognized that some increase in risk is inevitable. It should be a high tier requirement that the increase in risk due to PROMETHEUS project activities be reduced to a level that is insignificant by comparison to the overall risk that is associated with other human activities and is normally accepted (i.e., driving a car, flying on an airplane, etc.)

1. ***Construction, transportation and operation of a flight reactor, flight prototypes and ground based prototype reactors will not result in a significant increase in risk to the health and safety of the public and to the environment relative to the risk associated with normal human activity.***

The term "significant increase in risk" will be defined as part of the Tier 3 requirements.

A.2 PROMETHEUS Flight Reactors Tier 2 Reactor Safety Requirements

As shown on Table 1, the typical space reactor flight unit safety issues naturally fall into three categories:

1. Protection of the public and the environment from energy and radiation due to criticality of the reactor: The risk to the public either due to the energy released by criticality, due to exposure to direct radiation produced by fission or due to dispersion of fission products should be acceptably small.

2. Protection of the public and the environment from accidental dispersion of hazardous materials: The risk to the health of the public due to dispersal of hazardous materials associated with the Prometheus reactor (e.g., uranium, beryllium) should be acceptably small.

3. Ensuring control of the special nuclear material (e.g., highly enriched uranium) to minimize the potential that such material will come under the possession of persons or organizations that would be inclined to use it for illicit purposes such as terrorism or extortion: The risk associated with potential loss of control of special nuclear material (e.g., highly enriched uranium) should be acceptably small.

As can be noticed from Table 1, each of these three issues could arise as a result of a number of initiating events during several phases of operations that start with delivery of the reactor to the launch site and include launch, ascent, operation, and disposal. The following section provides a safety approach to address the concerns listed in Table 1. The discussion is organized into sections along the three main categories of safety issues (radiological and criticality safety, special nuclear material safeguards, and protection from toxic material exposure), and further subdivided into operational phases, where applicable.

<u>1. Radiological and Criticality Safety</u>

<u>Pre-Launch Phase</u>

The PROMETHEUS reactors should not contain any significant amount of fission products prior to planned startup following launch. Therefore, with the exception of testing for a short period of time in order to ensure that it is manufactured according to specifications and that it will perform as expected, startup and operation of the reactor, either intentional or accidental, should not be allowed and should be precluded. This requirement may be expressed as follows:

1.1 The risk to the health and safety of the public due to operation or inadvertent startup of a PROMETHEUS reactor prior to launch (including assembly and pre-launch operations at the launch site) shall be reduced to an acceptable level by a combination of design features, detailed procedures, and rigorous training and oversight.

Launch and Ascent Phase

The launch and ascent of the spacecraft to orbit is a crucial evolution. An accident during launch, such as a launch vehicle explosion, could subject the reactor to high stresses, shock, and potential impacts with components of the launch vehicle and with the ground. An accident during ascent could prevent the spacecraft from achieving earth orbit. The reactor would impact the earth at high velocity, suffer distortion, be surrounded with reflective materials such as sand, or be flooded and surrounded with water. These events have the potential of resulting in a critical configuration and the release of significant amounts of energy and radioactivity. It is imperative that the health and safety of the public be protected from the consequences of such an event. Therefore both aspects of risk, the probability and the potential consequences of criticality, under such conditions should be minimized. This leads to the following requirement:

1.2 The PROMETHEUS flight reactor design shall include features to reduce to an acceptable level the risk to the public due to inadvertent criticality as a result of an accident during launch and ascent to earth orbit.

Operation Phase

For a time after departure from earth orbit, it is possible that an accident could damage the reactor, terminate or re-orient thrust, and place the spacecraft and its damaged reactor on a trajectory from which it could re-enter Earth's atmosphere. Because the reactor would have been operating for a while, it would contain fission products, which could be dispersed in the atmosphere. Therefore, the potential of such an event should be minimized. This leads to the following requirement:

1.3 Earth re-entry of a reactor after power operation shall be precluded for all normal conditions and credible accident conditions by a combination of planning, operational controls and design features.

2. Environmental Protection

Long before protection of the environment became a prevalent endeavor among the general public, it was a high priority in the Naval Reactors Program. The Program maintains the same rigorous attitude towards the control of radioactivity and protection of the environment as it does toward reactor design, testing, operation, and servicing. The same rigorous attitude towards protection of the environment shall be applied to all activities associated with the space reactor program. This ensures that the environmental record of nuclear powered spaceships will be equal to the well documented record which demonstrates the absence of environmental effect from the operation of U.S. nuclear powered ships.

The environmental concern associated with the PROMETHEUS flight reactors is that, without proper design and operation, toxic and/or radioactive materials could be released in the atmosphere or in a region of space near earth.

The nuclear reactor system could include toxic materials (e.g., beryllium). These materials could ablate during re-entry and be dispersed into the atmosphere. The amount of toxic material that could be dispersed under such conditions should be minimized so as not to present a risk to the health of the public. This may be expressed as

2.1 The PROMETHEUS flight nuclear systems shall be designed with positive measures or features to reduce to an acceptable level the amount of toxic and radioactive materials that could be dispersed during credible launch/ascent or reentry accidents.

After the mission has been completed, the reactor must be disposed of in such a manner as to reduce the potential that it could contaminate a region of space or the surface of a planet or a moon with radioactive or otherwise hazardous materials and thus impact future missions.

2.2 Mission planning for PROMETHEUS flight reactor systems shall include disposal in a manner that avoids unacceptable impact on extraterrestrial environments.

3. Special Nuclear Materials Security and Safeguards

Safeguarding the special nuclear material of the reactor to preclude its use by persons, governments, or organizations with the intent to harm and terrorize the public and harm the interest of the United States is of paramount importance. The reactor system should be designed such that, in the event of an accident during launch and ascent to orbit that would result in the reactor and its special nuclear material crashing to Earth, the special nuclear material can be quickly recovered. This requirement may be expressed as follows:

3.1 Positive features shall be provided to aid in the recovery of the special nuclear material in the event of an accident during launch, ascent to earth orbit, or accidental re-entry.

The security and special material safeguards requirements during ground operations, (e.g., reactor core manufacturing, testing, assembly, transportation) will be developed and will be submitted to NR at a later time.

III. ALTERNATIVE APPROACHES CONSIDERED

Several alternative space reactor safety approaches and corresponding reactor safety requirements to those described above were considered. They are presented here for completeness and Naval Reactors information, but are not recommended. These include the following:

A. *The overall PROMETHEUS project reactor safety philosophy (Tier 1) should be based on traditional Naval Reactors philosophy that emphasizes the safety culture of the Naval reactors program and the "defense-in-depth" and the "As Low As Reasonably Achievable (ALARA)" principles.*

The corresponding Tier 1 reactor safety requirements proposed were:

1. ***The primary emphasis of the design, construction, testing, operation, and disposal of space reactor plants (and land-based prototypes) shall be the highest level of reliability and safety.***

2. ***A defense-in-depth approach shall be used to develop and verify the nuclear technology that will be the power source for space reactor plants.***

3. ***Personnel radiation exposure as a result of the operation of a space reactor plant (or land-based prototype) shall be reduced to the lowest level that is reasonably achievable.***

These requirements are not recommended as Tier 1 requirements because they either redundant with the recommended Tier 1 requirement, or they are "implementation strategies" to ensure that the public and the environment are protected. In addition, the ALARA principle by itself is not a requirement; rather, it is a goal, or an objective to "do better" than the minimum required.

B. The reactor safety requirements should focus on ensuring that the PROMETHEUS flight reactors will not result in ***undue risk*** *to the heath and safety of the public and the environment.*

This approach was not recommended because of the difficulty in defining "undue risk" in the context of a discretionary activity. It depends, largely, on an individual's assessment of the value of the activity.

C. The reactor safety approach for the PROMETHEUS flight reactors (Tier 2) should be consistent with the traditional, deterministic approach of the Naval Reactors program.

This approach led to a proposed requirement that criticality be precluded for all accidents assuming a single failure of the protective system.

The deterministic approach is not recommended for the PROMETHEUS flight reactors. The number of accident scenarios that could be postulated is extremely large. Most of these scenarios would be extremely unlikely. With a strictly deterministic approach, all of these would have to be analyzed, and acceptable performance would have to be demonstrated regardless of the probability of occurrence. This is judged to be impractical (because of the large number of possible scenarios), undesirable (because analysis of low probability scenarios will divert resources from analyses of other, higher probability scenarios), and unnecessary (because an acceptable alternative – a probabilistic approach - is available. A probabilistic approach has been used in the safety analyses of past space exploration missions which used RTG power sources, e.g., the Cassini mission. The Interagency Nuclear Safety Review Panel is more familiar with and likely to expect a probabilistic approach).

D. The approach of the tier 2 requirements should focus on ensuring that events that could place the public and the environment at risk are "implausible".

This approach resulted in the following Tier-2 requirements

1.1 Plant design features and procedural controls shall be implemented such that an intentional or inadvertent startup of a PROMETHEUS flight reactor prior to launch (including assembly and pre-launch operations), other than for test purposes, is implausible.

1.2 The PROMETHEUS flight reactor design shall include features such that an inadvertent criticality as a result of an accident during launch and ascent to earth orbit is implausible.

1.3 The PROMETHEUS flight reactor design shall include features such that the dispersion of fission products or toxic material in the Earth atmosphere is implausible.

1.4 The PROMETHEUS flight reactors shall be designed for all normal conditions and credible accident conditions such that the re-entry of a damaged reactor and the dispersion of fission products and toxic materials in the Earth atmosphere is implausible.

This approach is not recommended, because it focuses on probability, rather than risk (i.e., probability times consequences). Instead, the recommended Tier-2 requirements focus on minimization of risk. This allows for specific limits of probability and consequences to be defined as part of the Tier-3 requirements. In addition, a single, specific, universally accepted definition of "implausible" is not available.

E. The reactor safety requirements should include acceptance criteria, which provide clearly defined risk-based absolute criteria, or criteria that represents goals. The establishment of safety requirements as currently recommended is a qualitative approach to ensure adequate safety. The objective is to assure that the risks to the public and the environment are acceptable. Without an acceptance criteria proposed with the safety requirements, no real method exists to ensure that the safety requirements are being met and ultimately the minimization of risk to the public is assured.

Implementing quantitative acceptance criteria, based on estimates of measurable risk, would allow measurable and defendable risk metrics. For example, criterion 2.1 could be modified as follows,

> **"The PROMETHEUS flight nuclear systems shall be designed with positive measures or features such that the amount of toxic material released and the subsequent environmental contamination will be below the maximum allowable concentrations established by the EPA or appropriate governing body."**

In an analogous manner, similar acceptance criteria could be incorporated into all of the other safety requirements.

One advantage to this approach is that the design community has concrete agreed upon rules that, if met, would ensure reactor safety and minimization of risk to the public. A disadvantage to this approach is that the establishment of quantitative criterion at this early development stage may be premature, and some quantitative requirements may have to be revised in the future.

IV. SUMMARY

The proposed high tier reactor safety requirements for the PROMETHEUS project and for the PROMETHEUS flight reactors are presented. The focus of the PROMETHEUS nuclear reactor safety philosophy and objectives is the protection of the heath and safety of the public and the environment from the hazards associated with the construction, transportation and operation of a flight reactor, flight prototypes and ground based prototype reactors. These hazards include radiological hazards, potential loss and misuse of the special nuclear materials, and dispersion of toxic materials. The reactor safety requirements for the PROMETHEUS flight reactors focus on the protection of the heath and safety of the public and the environment during launch preparations, launch and ascent to earth orbit, operation, and disposal. The proposed reactor safety high tier requirements for the PROMETHEUS project (tier 1 requirements) and for the flight reactor (tier 2 requirements) are summarized in Tables 2 and 3.

V. NAVAL REACTORS ACTION REQUESTED

NR comments are requested on the proposed tier-1 reactor safety requirements for the PROMETHEUS project, and the tier-2 nuclear reactor safety requirements for the PROMETHEUS flight nuclear reactor design, pre-launch operations, launch, ascent to earth orbit, operation, and disposal. NR approval is requested to transmit these requirements, following incorporation of NR comments, to the Jet Propulsion Laboratory to ensure consistency between the reactor safety requirements and the spacecraft safety requirements.

VI. CONCURRENCE

The Managers, Reactor Safety Engineering, KAPL (Dietershagen), MER Reactor Safety, Bettis (Lawson), Space Power Program (Wollman), and Space Engineering (Eshelman, for Zika) concurred with this recommendation in their respective areas of cognizance.

Very truly yours

Dimitrios Kokkinos

Dimitrios Kokkinos, Advisory Engineer
Space Reactor Safety
NRPCT

Table 1: PROMETHEUS Flight Reactor Safety Issues

Safety Issue	Initiating Event Category	Concern	Safety Issue
Uncontrolled Criticality Protection	Pre-Launch Accident during Processing, Transport, or Handling at the Launch Site	Uncontrolled criticality due to core distortion, reactivity control devices repositioning to critical configuration, reactor flooding, or other means by which neutron leakage or moderation occurs	Energy or radiation release
	Launch Vehicle Accident	Uncontrolled criticality as a result of geometric distortion by shock wave	Energy or radiation release
	Reactivity Control Device Failure	Uncontrolled criticality due to neutron leakage decrease or moderation	Energy or radiation release
	Inadvertent Reactor Startup		
	Propulsion Failure	Uncontrolled criticality due to reactor impact on earth, core distortion, sliders repositioning to critical configuration, reactor flooding, burial in dry or wet sand	Energy release, radiation release, fission product dispersal
	Guidance Failure		
	Range Safety Destruct		
	Orbital Maneuvering Failure		
	Uncontrolled Reentry Intact		
Protection from exposure to toxic and radioactive material	Uncontrolled reentry and breakup during launch and ascent	Heat-up, ablation, and dispersion of toxic and radioactive material due to friction with atmosphere and upon earth impact.	Dispersion of toxic and radioactive material
	Uncontrolled reentry and breakup from earth orbit after reactor startup	Heat-up and ablation of toxic and radioactive material due to friction with atmosphere; widespread dispersion.	Dispersion of toxic and radioactive material
	Accidental release of fission products during reactor operation	Reactor accident damages the reactor and releases fission products in an important region of space (e.g., near earth or near another planet of interest), thus making that region of space unusable for future missions	
	Uncontrolled reentry or release of fission products and other hazardous materials in a region of space or on the surface of a planet or a moon of interest (e.g. Europa) after completion of the mission.	Dispersion of radioactive and other hazardous materials contaminating a region of space or the surface of the planet/moon and impacting future missions.	Dispersion of radioactive and other hazardous material

Safety Issue	**Initiating Event Category**	**Concern**	**Safety Issue**
Special Nuclear Material Protection	Theft/diversion of Special Nuclear Material	Deliberate acts designed to take control of Special Nuclear Material	Terrorism, Nuclear proliferation
	Sabotage		
	Launch Vehicle Accident, Fire or Explosion	Control of Special Nuclear Material lost due to accident	
	Range Safety Destruct		
	Propulsion Failure		
	Guidance Failure		
	Uncontrolled Reentry Intact		

Table 2: PROMETHEUS Project: Reactor Safety Tier-1 Requirements

Tier 1 Requirements
1. Construction, transportation and operation of a flight reactor, flight prototypes and ground based prototype reactors will not result in a significant increase in risk to the health and safety of the public and to the environment relative to the risk associated with normal human activity.

Table 3: PROMETHEUS Flight Reactors: Reactor Safety Tier-2 Requirements

Tier 2 Requirements
Radiological and Criticality Safety
Pre-Launch Phase
1.1 The risk to the health and safety of the public due to operation or inadvertent startup of a PROMETHEUS reactor prior to launch (including assembly and pre-launch operations at the launch site) shall be reduced to an acceptable level by a combination of design features, detailed procedures, and rigorous training and oversight.
Launch, Ascent, and Reentry Phase
1.2 The PROMETHEUS flight reactor design shall include features to reduce to an acceptable level the risk to the public due to inadvertent criticality as a result of an accident during launch and ascent to earth orbit.
Operation Phase
1.3 Earth re-entry of a reactor after power operation shall be precluded for all normal conditions and credible accident conditions by a combination of planning, operational controls and design features.

Tier 2 Requirements

Environmental Protection

2.1. ***The PROMETHEUS flight nuclear systems shall be designed with positive measures or features to reduce to an acceptable level the amount of toxic and radioactive materials that could be dispersed during credible launch/ascent or reentry accidents.***

2.2. ***Mission planning for PROMETHEUS flight reactor systems shall include disposal in a manner that avoids unacceptable impact on extraterrestrial environments.***

Special Nuclear Materials Safeguards

Requirements

3.1. ***Positive features shall be provided to aid in the recovery of the special nuclear material in the event of an accident during launch, ascent to earth orbit, or accidental re-entry.***

CONCURRENCE/DESIGN CHECK FORM FOR DOCUMENT NO. SPP-SRS-0002 **Date:** 4/28/05

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