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# AEROSPACE NUCLEAR SAFETY: An Introduction and Historical Overview

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# AEROSPACE NUCLEAR SAFETY: An Introduction and Historical Overview

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## Abstract

This paper provides an introduction and overview on the topical area of aerospace nuclear safety. Emphasis is on the history of the use of nuclear power sources in space, operational experience with these nuclear sources, a review of previous accidents associated with both U.S. and Russian launches, and the safety issues associated with the entire life cycle of space reactors. There are several potential missions to include near earth orbit, orbit-raising, lunar bases, and propulsion to such solar system locations as Mars, which are suitable for the use of space reactors. The process by which approval is obtained to launch these nuclear materials to space is also presented as well as the role of nuclear safety policy and requirements in a space program using nuclear power sources. Important differences in safety concerns for the Radioisotope Thermoelectric Generators (RTGs) now used, and space reactors are presented. The role and purpose of independent safety evaluation and assessment in ensuring safe launch and operation is also discussed. In summary, this paper provides the requisite framework in this topical area for the remaining papers of this session.

## Introduction

Both radioisotopes and nuclear reactors have been used to power satellites in space. These systems are significantly different from commercial or research nuclear systems. The environment, power levels, materials used, heat rejection methods are all unique in the space environment. Also, these systems are designed to operate for many years with no opportunity for servicing or repairs. Space reactors tend to have a fast or epithermal spectrum because of size constraints of launch vehicles. Typical space nuclear power systems may deliver (1) tens-to-hundreds of watts using radioisotopes as the heat source and thermoelectrics as the power conversion subsystem or (2) tens-to-hundreds of kilowatts of power using a nuclear reactor as the heat source and thermoelectrics, thermionics, Brayton or Stirling engines as the power conversion system. The payload is protected from harmful radiation by a shadow shield since there is no back scattering from space. Mass and volume constraints become primary design criteria because the power system must be launched on a rocket. The largest current U.S. rocket, the Titan IV, can only deliver 5200 kg to geosynchronous orbit and much less to the far planets. As a result of the mass and volume constraints, reactors that are very compact are favored. These lead to some representative characteristics seen in Table 1. Table 1 also shows the contrast to representative terrestrial power systems.

## History of Nuclear Power Flight Experience

Radioisotope thermoelectric generators (RTGs) and nuclear reactors have been used in space by the U.S. and USSR. Though both countries have flown about the same number of satellites with nuclear power sources on board, the U.S. has concentrated on RTGs while the USSR concentrated on nuclear reactors. The U.S. nuclear powered satellites include 24 with RTGs and one nuclear reactor between 1961 and 1990. Power levels have ranged from 2.7 $W_e$ on SNAP-3A to 500 $W_e$ on SNAP-10A. These flights have demonstrated that nuclear power sources can be safely and reliably launched, despite three aborted missions. The USSR launched 2 satellites with radioisotope generators in 1965 and 33 satellites powered by reactors between 1970 and 1988. Two reactors eventually reentered the atmosphere--Cosmos 954 and 1402--while one flight, Cosmos 1900, malfunctioned, but was successfully boosted to a longer life orbit.

**Table 1.**
**Representative values of space and terrestrial nuclear reactor power plants**

| | Space | Terrestrial |
|---|---|---|
| | | |
| Power output (kWe) | -1000 | 1,000,000 |
| Fuel enrichment (%) | >90 | few (2-4) |
| Outlet temperature (K) | 1400-1800 | 565 - 715 |
| Coolant | Li, NaK | Water |
| Fuel | $UO_2$, $UC_x$, UN | $UO_2$ |
| Power conversion | Thermoelectrics, Thermionics | Steam cycle |
| Neutron energy | Fast | Thermal |
| Heat rejection temp. (K) | 800-1000 | 355 |
| Core height (M) | 0.5 | 3.8 |
| Vessel height (M) | none | 13-22 |
| Containment vessel | none | yes |
| Servicing and repairs | none | extensive |
| Siting | highly mobile | fixed |

The U.S. has launched just one reactor into space (in 1965). The Snapshot spacecraft was designed as an experimental testing platform for the SNAP-10A reactor power system. The SNAP-10A was a fission reactor with a NaK heat transfer loop coupled to a thermoelectric conversion subsystem. The fuel consisted of uranium-zirconium hydride with the uranium-235 enriched to 93%. The fuel had a mass of 61 kg, the amount of uranium-235 was 4.93 kg. The fuel was contained with 37 hastalloy-N clad fuel elements. A beryllium reflector surrounded the core to reflect neutrons back into the core. A core pressure vessel which surrounded the fuel elements was 316 stainless steel. The reactor operated at 34 kilowatts-thermal and delivered 500 watts of electrical power because of the low conversion efficiency of the thermoelectric conversion devices of the day.

SNAP-10A, the only U.S. reactor now in space, was designed to burnup upon reentry into the Earth's atmosphere following orbital decay. One of the characteristics of putting satellites into Earth orbit is that eventually the orbit decays and the satellites reenter the atmosphere. It is estimated that the orbital lifetime of SNAP-10A is 3800 years. Its radioisotope nuclear inventory will be very low when it finally reenters several millennia from now. This source term is computed to be 0.026 Ci.

Of the USSR nuclear reactor powered spacecraft, except for Cosmos 1818 and 1867, the spacecraft appear to be ocean reconnaissance satellites. These generally operated 2-4 months in low Earth orbit at an altitude of 250-280 km, with an inclination of 65 degrees. At the end of the missions, the reactor power supply is boosted to a longer lived orbit - an orbit that permits the fission product inventory to decay. Since 1978, this "parking" orbit has typically been on the order of 1000 km (which corresponds to an approximate 600-year lifetime). This disposal orbit will allow the fission products to decay to less than 0.1 Ci at the time of atmospheric reentry.

The reactor in the Soviet ocean reconnaissance satellites, RORSATs, has a fast-neutron spectrum with core containing 37 cylindrical fuel elements surrounded by a beryllium reflector. Stainless steel is used as a structural material in the reactor. The fuel loading of the active core is 30 kg of 90% enriched uranium-235. The reactor is cooled using liquid metals. Power conversion is by thermoelectric devices with an electric power output of about 5 $kW_e$.

Cosmos 1818 and 1867 were satellites powered by a new generation of Russian space reactors designed for use on their military satellites. These reactors were called TOPAZ I reactors, which were designed and built by the "Red Star" Association in Russia. These reactors employed an in-core thermionic power conversion approach and produced about 5 Kw(e) of power. These reactors were tested in orbits that had about a 600-year lifetime so that when these reactors reenter the earth's atmosphere, the radioactive inventory of the core will have decayed to a negligible potential biosphere dose.

## Space Reactor Safety Design Philosophy

Reactors that move and have no containment building present unique challenges to the designer to prevent exposure of the earth's biosphere to potentially harmful radiation. In many cases, the potential safety issues for these space reactors are different from their terrestrial brothers, and these differences are highlighted in this section.

Therefore, the primary safety design objectives for U.S. space reactors are to minimize the potential accidental interaction of radioactive materials with the Earth's population and environment and to maintain a subcritical reactor configuration in all conceivable accident scenarios. This prevents the generation of fission products and their subsequent environmental release in the event of core damage.[1] This fundamental aerospace nuclear safety philosophy is consistent with the conclusions of the United Nations Working Group.[2][3] The United Nations Working Group was established by Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) following the accidental reentry of a Soviet satellite over Canada--Cosmos 954. The Working Group's charter is to consider technical aspects and safety measures relating to the use of nuclear power sources in outer space. Its membership concluded that the radiation dose equivalents at the time of reentry should be within the limits recommended by the International Commission on Radiological Protection (ICRP) for conditions that exist without accident.

Philosophical safety differences are recognized for reactors intended for use in low Earth orbits. In this regard, reactor powered spacecraft should be boosted into a higher orbit after their operations are completed. If boosting to higher orbit fails, then the core material should be dispersed or reenter intact to minimize local dose levels in the biosphere.

Reentry safety philosophy, similar to radioisotope generators, continue to evolve. Analysis of safety risk for the SP-100 space reactor power plants led to the use of a safety criteria specifying that the reactor shall remain intact following atmospheric reentry.[4] Intact reentry, especially with ground or water burial, provides less radiological risk than high-altitude aerosolization and, for some proposed SP-100 missions, provides a significant advantage over partial disruption or low-altitude aerosolization. Also, it is very difficult to design a refractory metal reactor system with high confidence to completely aerosolize at high altitudes while the technology for intact reentry has been demonstrated.[5]

The primary safety design objective is to minimize the potential interactions of the radioactive materials with the populace and the environments so that exposure levels are within limits established by international standards.[2][3] To meet these objectives, a number of design and mission requirements may be delineated. For illustrative purposes we include the safety requirements for nuclear propulsion during exploration type missions [6] :

(1) The reactor should be designed to remain shut down prior to the system achieving its planned orbit.

(2) The reactor shall not be operated prior to space deployment except for low power testing on the ground, for which negligible radioactivity is produced.

(3) Inadvertent criticality shall be precluded for both normal and credible accident conditions.

(4) Routine Operations and Expected Occurrences: ... Radiological releases from the spacecraft shall have no significant effect on earth.

(5) Accidents: The probability of accidents involving radiological release affecting the immediate or long term health of the crew shall be extremely low...

(6) Disposal: ... Adequate and reliable cooling, control and protection for the reactor system shall be provided for all normal and credible accident conditions to prevent reactor system disruption or degradation that could preclude safe disposal.

(7) Entry: ... For inadvertent entry through an atmosphere, the reactor shall be essentially intact, or, alternatively, shall result in essentially full dispersion of radioactivity at high altitude.

(8) Safeguards: Positive measures shall be provided to control and protect the nuclear system and its special nuclear materials (SNM) from theft, diversion, loss or sabotage...

Some of the effects of these safety requirements on the design and operation of space reactors will be discussed in other papers of this session.

## The Safety Review Process

The United States, per Presidential Directive [7], requires an analysis of each space mission involving nuclear material to assess the potential radiological risk to the biosphere [8]. The safety review process, as summarized in Figure 1, begins when the space mission is defined and the nuclear power source (NPS) design is conceived [9]. It continues throughout the design, development, and testing cycles of the NPS. The INSRP process addresses each of these phases. Major emphasis to date has been on launch safety and proper disposal. Space nuclear power system on-orbit operational safety has not been a major safety program driver.

The most important consideration for the entire safety process is that designer/developer of the nuclear power source (NPS) is responsible for performing the nuclear safety analysis for the system. This point cannot be overemphasized. The system designer must be made to feel directly responsible for the safety of the system. Only, if the designer has this kinship with safety will the NPS be designed with safety built-in from the start.

The Safety Review Process and resulting documentation is extensive both for the ground handling and testing of the NPS as well as the flight safety portions of the mission.[8] The required planning and analysis covers a wide range of requirements from overall safety program planning to Safety Analysis Reports for Packaging (SARP). The latter is required by the Department of Energy prior to transporting potential radiological hazards. Flight safety analyses are prepared and updated at least three times during the development cycle. These documents include a Preliminary Safety Analysis Report (PSAR), an Updated Safety Analysis Report (USAR), and a Final Safety Analysis Report (FSAR).

The Preliminary Safety Analysis Report is scheduled to be issued 120 days after a design concept is selected. It contains a description of the design, a preliminary description of the mission that uses the nuclear power source to include the launch vehicle and site, a failure modes and effects analysis (FMEA), and a preliminary probabilistic risk assessment (PRA) for the mission to include a scoping estimate of the potential dose consequences from normal and off-normal mission events. It is important to develop this preliminary PRA so, that if design changes are necessary for the nuclear power source to reduce potential consequences, these changes can be accomplished early in the safety review process. While mission data may not be complete at this phase, and the nuclear power source design may be changing, a wealth of data from previous radioisotope thermal electric generators (RTGs) and reactor launches is available to aid the safety analysis.

The Updated Safety Analysis Report is issued 90 days after the design freeze and is similar in format to the preliminary report. Additional requirements include (1) a complete description of the mission on which the system is to be used, (2) an evaluation of the differences between the specific mission environments and those established by the guideline, and (3) an update of the PRA using data from the developmental tests performed to freeze the design.

The Final Safety Analysis Report (FSAR) is issued approximately one year before the scheduled launch and is similar in format to the earlier reports. This report provides final system, mission, and safety assessment data factoring in the results of the verification and qualification test programs. Thus, the final assessment is based on the actual expected mission environments. From the FSAR, an evaluation can be made on the benefits versus risk of this mission for a specific nuclear power source.

The Interagency Nuclear Safety Review Panel (INSRP) is responsible for review of the safety analysis reports at each step of the development process. DOE, NASA and DoD have a co-equal status on the INSRP. The respective agencies appoint their INSRP voting member called coordinators. The coordinators are appointed by their respective agency's top management, from within their agency's oversight, Inspector General, or Safety Office. Thus, they are independent of their agency's programmatic mission involvement and have the freedom, as well as the authority, to candidly raise and confront issues at any level with their organizations.

The representatives from NASA and DOE are typically civilian employees of the government, while the DoD representative is usually an Air Force colonel from the Inspector General's Directorate of Nuclear Surety. These coordinators are supported with detailed technical assistance from within their parent organizations. For example, the DoD representative to the INSRP is supported by the Nuclear Safety Group of the Air Force Phillips Laboratory.

It is of interest to those acquainted with nuclear safety that the Nuclear Regulatory Commission (NRC) does not have a formal role in the approval of NPSs. The NRC, Environmental Protection Agency (EPA), and National Oceanic and Atmospheric Administration (NOAA) are among other government agencies that are invited to participate with the INSRP as interested observers. Their advice is invaluable in the safety review process, though they do not have a formal role in the final INSRP recommendations. Of course, the ultimate purpose of the INSRP and its supporting casts is to ensure that the risks associated with using an NPS in space are acceptable in terms of the benefits to be gained from the mission requiring the NPS.

The subpanels to the INSRP are composed of a cadre of independent technical experts drawn from academia, industry, national laboratories, and government. These subpanels provide specialized technical and analytical support to INSRP. Specifically, they are responsible for performing technical nuclear safety/risk evaluations in six subpanel areas, such as launch abort, metrology, power system, etc. This safety review process is geared to characterize the risk based on probabilistic risk assessment methodology.[10]

The end results of the INSRP process is the Safety Evaluation Report (SER). The SER is the independent risk assessment of the INSRP, not a reissue of the FSAR of the NPS developer. In addition to the information provided in the FSAR, the SER also contains analyses and tests performed by many technical people from various government agencies, laboratories, and universities. The SER evaluates potential human exposures to radiation and the possibilities of exposures during all phases of the mission. The INSRP submits the SER to the heads of the DOE, NASA, and DoD for their review with the INSRP recommendations/conclusions about the safety of the NPS as well as its recommendations as to the benefits/risks of the mission.

The key concept is that the INSRP recommends and does not make any final decisions. The head of the agency which wishes to fly the NPS then must request launch approval from the President through the Office of Science and Technology Policy (OSTP). The heads of the other two agencies represented on the INSRP may choose to support the user agency with formal statements. In any case, the head of the OSTP will review the user agency request and may send the request to the National Security Council for review. The head of OSTP with the concurrence of the President will issue formal launch approval. The ultimate authority for launch and use of the NPS lies with the President of the United States.

These procedures do not require public review of the safety of the NPS. However, except for the most classified of military missions, public opinion or the concern about public opinion, will be a major factor in the approval of these nuclear power sources. The Galileo and Ulysses launches are recent examples of such public involvement. It should also be noted that these approval procedures are accepted by the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space.

The INSRP process, as with any triagency committee, is complex and requires continual close coordination to make the process effective. It does have, however, several major advantages:

(1) First, the INSRP process is efficient in that it takes advantage of the specialized expertise found in several agencies. For example, the DOE has many experts in nuclear safety analysis; the DoD has technical expertise in the aerodynamics of reentry bodies needed for safety analysis of NPS reentry scenarios; and NASA has the experts in spacecraft design and shuttle safety requirements.

(2) Second, the structure of the INSRP usually ensures that one of the three agencies is not a sponsor of the mission requiring the NPS. This means that at least one agency will not be so closely associated with a mission that it will not be able to independently and objectively assess the safety of the NPS. Let us examine the recent Galileo and Ulysses as an example. The mission sponsor was NASA and the DOE was the developer of the mission essential 500 watt, radioisotope thermoelectric generator (RTG) nuclear power source. The DoD independently and carefully evaluated the risks and safety of this nuclear power source. Since the DoD has no vested interests in these missions, it provided the independence and objectivity needed to assure the President that this mission should be flown. The triagency structure of the INSRP ensures that almost every NPS mission should have at least one such disinterested party.

(3) Third, in this rather complex INSRP process there is a rich diversity that helps ensure a viable safety analysis. A typical INSRP subpanel (e.g., the launch abort subpanel) are composed of engineers and scientists with a great variety of experiences and points of view. The reviews and deliberations of these subpanels will be conducted over a period of years with technical input from numerous outside organizations. It is extremely doubtful that major safety problems with a particular NPS would not be identified and analyzed prior to launch.

Also, the three agencies represented on the INSRP conduct extensive safety reviews within their respective agencies, resulting in many technical differences that will have to be resolved. The classic example of this process came in the various agency reviews of the safety of the SNAP-27 RTG that was to provide power for the Apollo-13 mission to the moon. During a safety review, the question was raised as to what would happen to the SNAP-27 if the RTG was not left on the Moon, but had to return on a super-orbital reentry to the Earth's biosphere. It was quickly discovered that a super-orbital reentry could result in an unwanted dispersion of the plutonium in the RTG. To achieve the high safety standards desired, the decision was made to augment the protective aeroshell around the RTG prior to the Apollo-13 flight*. The results of this decision are public knowledge. The Apollo spacecraft was damaged by an explosion on the way to the Moon after a successful launch on April 11, 1970. The lunar module with the RTG then had to reenter the Earth's atmosphere over the South Pacific. The RTG fuel cask survived ocean impact and is now in the 6-km deep Tongas Trench. Subsequent radiological surveys demonstrated that the aeroshell has indeed performed as designed and protected the biosphere. The significant fact is that as a result of the diverse safety reviews and analyses of the SNAP-27 aeroshell, it was redesigned. The previous aeroshell design could have ruptured on an Apollo-13 type reentry and released plutonium to the biosphere. This was avoided when the real-life situation occurred.

*[private communication with Lou Cropp, Sandia National Laboratories, 1983]

## Summary

This paper has outlined the requirements and unique issues associated with the design, development and employment of space nuclear reactors. The unique characteristics of space reactors as well as the unique safety challenges have been emphasized. The process by which the safe use of space nuclear reactors is ensured, and the approval to launch is obtained, has been described as well as the characteristics of this rich process that have led to repeated success in safe launches. A brief history of the use of space nuclear power sources, both RTG's and reactors, was also presented. Based on a history of safe use of these nuclear power sources, on the existence of a well-developed safety approval process, and on the inherent safe characteristics of the nuclear power sources and its mission uses, we propose that space nuclear reactors can be used safely to enhance both military and civilian missions.

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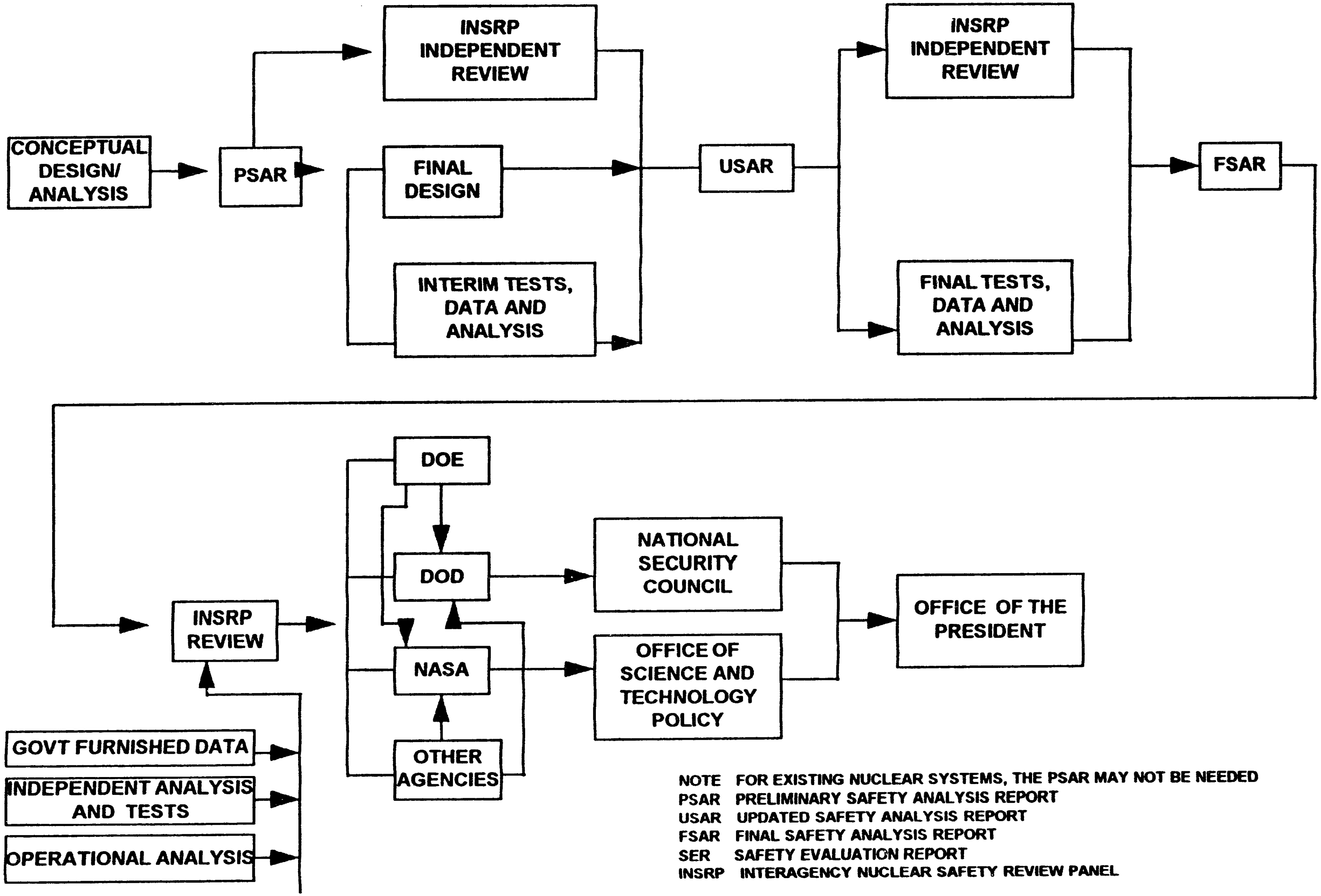
# FIGURE 1



| | |
|---|---|
| NOTE | FOR EXISTING NUCLEAR SYSTEMS, THE PSAR MAY NOT BE NEEDED |
| PSAR | PRELIMINARY SAFETY ANALYSIS REPORT |
| USAR | UPDATED SAFETY ANALYSIS REPORT |
| FSAR | FINAL SAFETY ANALYSIS REPORT |
| SER | SAFETY EVALUATION REPORT |
| INSRP | INTERAGENCY NUCLEAR SAFETY REVIEW PANEL |

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