Process to Launch Nuclear Power Sources into Space

An overview of the process necessary to choose and launch Nuclear Power Sources into space.

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The launch of the Cassini spacecraft on October 15, 1997.[1,2]

Introduction

On October 15, 1997 NASA launched the Cassini space probe on a seven-year mission to study the planet Saturn. Onboard the spacecraft were three Radioisotope Thermoelectric Generators (RTG) carrying over 72 pounds of Plutonium to power the electric generators for its seven-year mission. This was the most Plutonium ever launched into space at one time for either the US or the Former Soviet Union. [2]

Although this mission gained much attention for launching a large amount of plutonium into space, it was hardly the first time radioactive material was launched into space. The first launch of radioactive material into space to power a spacecraft was in June 1961. [3] Since then, the US and Former Soviet Union have launched over 70 various nuclear power sources into space, with some of these listed in Table 1. [4,5] With so many nuclear powered missions launched into space, people must wonder if there is a procedure to launch nuclear material into space. The answer is that there is a procedure to launch nuclear power sources into space. Each of the Nuclear Power Systems the US has flown underwent extensive safety review.

With each Nuclear Power Source (NPS), testing has been carried out to provide safety to not only human population but to the environment as well. The Department of Energy (then the Atomic Energy Commission, AEC) with the cooperation of the Department of Defense (DOD) carried out safety reviews before the launches of the first two NPS flown. As was the case for terrestrial uses of Nuclear Power, a safety analysis report was assessed before the launch of these systems. Approval of the launch involved the Department of State (now the State Department) and the White House. [6]

With guidance from the former National Aerospace and Space Council (now the National Aeronautics and Space Administration, NASA) in conjunction under presidential directives, studies were performed to allow a more consistent and efficient safety review and launch approval status. AEC, NASA and DOD then formed a formal safety review panel before the launch of NPS into space, which wrote many papers on the subject of NPS launch review process.[6] The review panel became known as the Interagency Nuclear Safety Review Panel. The details of the review panel will be discussed forthwith, but before going into the details of launching a NPS into space, lets first review why an agency would use a NPS in space. Once this is done, a short review of the two general types of NPS that can be flown will be discussed. Following that is the launch and safety review process including a discussion of the safety analysis.

Number of Launches	Number of RTG's	Mission	Launch Date
4	4	Transit (Navigational)	1961-4 & 1972
1	1	Transit (Satellite failed to orbit)	1964
1	2	Nimbus (Vehicle destroyed during Launch)	1968
1	2	Nimbus (Meteorological)	1969
6	6	Apollo	1969-1972
1	1	Apollo 13 (Mission aborted en-route to the moon)	1970
2	8	Pioneer 10, 11 (Interplanetary)	1972-3
2	4	Viking 1, 2 (Mars)	1975
2	4	LES (Communication)	1976
2	6	Voyager 1, 2(Interplanetary)	1977
1	2	Galileo (Jupiter)	1989
1	1	Ulysses (Sun)	1990
1	3	Cassini (Saturn)	1997
25	44	Totals	1964-1997

Table 1
Launches of RTG's by the United States.[4,5]

One of the primary reasons for using NPS in space has been for long duration space flight missions. Several of the missions, Pioneer 10/11 and Voyager I/II, were launched almost thirty years ago and scientists are still receiving data from them. The radioactive material used to power the RTG is an isotope of plutonium that has an 87-year half-life. [3] What this means is that even after forty years, the RTG power source will still be producing about half the power it did when it was launched with little or no degradation in performance of the heat generation capability.

Another feature of using an RTG is the scalability for different power needs. [3] Up to 10 kW, an RTG could be utilized for a variety of missions. Beyond this power range, a nuclear reactor could be employed for power. Again, like the RTG, a nuclear reactor can be modified to fit a mission's power requirements, allow for a long lifetime mission and operate in a safe manner throughout the spacecrafts lifetime. [7]

The environment of space is harsh in which to operate. The use of NPS alleviates some of the concerns with the possibility of a power failure resulting from intense radiation encountered during travel through our solar system. In addition, by using a NPS, the size of the spacecraft is minimized thereby reducing the risk of a meteoroid collision. This increases the reliability of not only the power source but of the entire spacecraft by decreasing the risks associated with the loss of power or damage to the spacecraft by hostile environments found in space. [8]

Two General Types of Nuclear Power Sources

Above is mentioned some of the reasons why NPS are used in space but it does not address the type of NPS that are possible for use in space. There have many designs of possible systems utilizing nuclear power but they are one of two general types. The first is the RTG and the other is a nuclear reactor. These will be briefly described below to familiarize the reader with the differences and similarities between the two NPS systems.

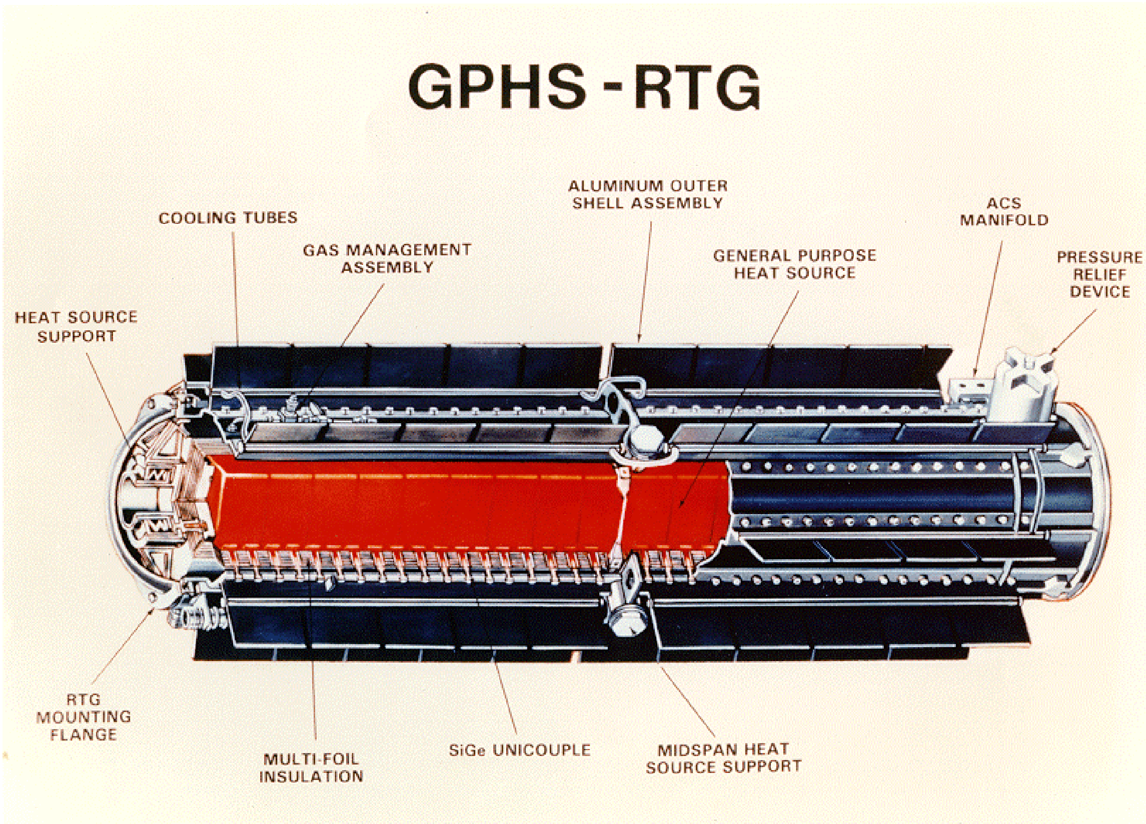

Figure 1
Typical RTG configuration.[7]

An example of a typical RTG configuration is shown above in figure 1. Most of the RTG units launched by the US have contained Plutonium-238 is the heat source.[4] The advantage of using a nuclear-fueled RTG is that it is a static unit and has no moving parts to break. It also is a very stable power supply in the harsh environment of space. Another benefit of using an RTG is their proven performance on missions like the

Cassini, Galileo, Voyager I/II, and Pioneer 10/11.[2] Although an RTG has many advantages, it does have several disadvantages. RTG units are very inefficient and thus have a low value of power generated per kilogram mass launched. In addition, an RTG is generating heat at all times, even while on the pad. This necessitates the removal of heat while the spacecraft is sitting on the pad ready to be launched into space.[3]

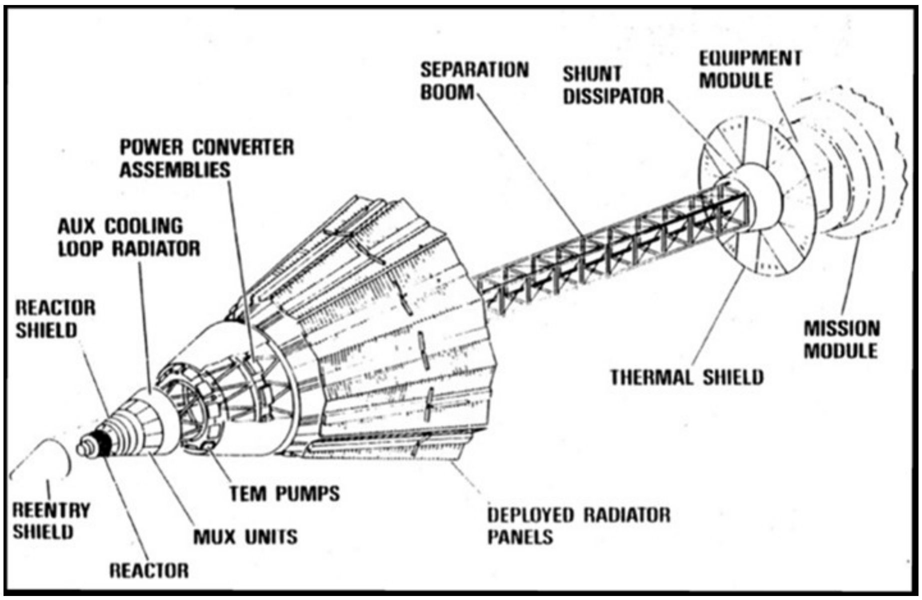

Figure 2
SP-100 space nuclear reactor system.[7]

There have been many launches of RTG units, only one launch of a space reactor by the US has occurred. The only reactor launched by the US was done so in April 1965 aboard an experimental satellite to test the reactor system in a space environment. The mission proved that a nuclear reactor could operate in space even though it experienced a shutdown after only 43 days of operation due to an electrical malfunction.[8] The nuclear reactor is a design that could be scaled up or down, much like an RTG could. However, unlike the RTG, a nuclear reactor can achieve very high amount power generated per kilogram of mass launched.[7] With these benefits, there comes a drawback. It is an increase in long-lived radioactivity from fission products within the nuclear reactor, once it commences operation in space. There is also the disadvantage of more shielding due to the neutrons and gamma radiation from a nuclear reactor and its associated decay products. A recent nuclear reactor concept for use in space is the SP-100 reactor program. The SP-100 was developed through the mid-eighties and early nineties and was variable in power from 10-100 kilowatts of electricity.[7] A SP-100 type reactor design is shown in figure 2 above.

Safety Analysis Report

The types of NPS described above are two of many different types utilizing nuclear power for space exploration. By no means is it to be a complete list but to give an indication of their strengths and weaknesses of the basic systems. Once either of these systems is chosen for use in space, the first thing worked up about the NPS is called a Preliminary Safety Analysis Report (PSAR). Before explaining what is and is not in a PSAR, let us first look at what is contained in a general Safety Analysis Report (SAR).

The SAR consists of two volumes in the PSAR and Updated Safety Analysis Report (USAR) but has three volumes for the Final Safety Analysis Report (FSAR). The volumes common to all three versions are the Reference Design Document and the Accident Model Document. The third volume is the Nuclear Risk Analysis Document. In the Reference Design Document, the characteristics described are as follows: the mission/flight system summary, NPS description, spacecraft/launch vehicle trajectory description and the launch site/range safety radiological safety data. This document will change as the spacecraft continues to be modified for flight by the addition and/or removal of components and the trajectory changed to optimize the path taken to reach its destination. The Accident Model Document will cover models/data on the various accident scenarios, event tree analysis, and nuclear power source response. The Nuclear Risk Analysis Document contains probabilistic description of risk. [8]

In general, all three of the SAR will consider the following types of accident scenarios. These are typically categorized by the mission phase that the spacecraft is in. When the spacecraft is in its prelaunch/launch/ascent phases, the typical scenarios investigated are: explosion, projectile impact, land or water impact, liquid fuel fire, solid fuel fire, and any sequential combinations of the above. Another phase that is considered is the orbit/flight trajectory phase. The scenarios considered at this point are: reentry, land or water impact, and post impact environment. On-orbit contingencies are considered but would depend upon the mission type, whether or not the NPS has been operated, and at what distance the failure occurs from earth. [6]

As mentioned previously, there are several updated versions of the SAR that are published as the review process continues and changes are made to the spacecraft and NPS system. The PSAR comes out after an initial design is selected for a mission. It includes a description of the NPS and some preliminary risk assessments. The USAR is released soon after a design freeze is placed upon the NPS. More failure modes are discussed within this SAR and it includes results of safety tests performed to date. The FSAR contains the final design for the mission and is typically released a year before the mission is flown. It will have the final results of the safety analysis tests and includes radiological safety analysis as well. [8]

Interagency Nuclear Safety Review Panel

Lets now look at what happens once a SAR has been finished and is ready to be reviewed. It is sent to a review panel to establish the risk/benefits derived from the use of a NPS on the mission. The review panel is called the Interagency Nuclear Safety Review Panel (INSRP). The INSRP was provided for under Presidential Directive NSC/25[6] and is chaired by three coordinators appointed by the Secretary of the Department of Defense (DOD), the administrator of NASA, and the Secretary of the Department of Energy (DOE). The reason for including DOD and NASA is that they have great resources upon which to evaluate the launch process, spacecraft systems, and both have used NPS many times in the past and have a proven safety record in these areas. The DOE has the responsibility of the safety of the NPS, which it designs, and produces for use in outer space. The Nuclear Regulatory Commission (NRC), the Environmental Protection Agency (EPA), and the National Oceanic and Atmospheric Administration (NOAA) participate in the review panel as well. Figure 3 shows the structure of the INSRP and administrative review process.[8]

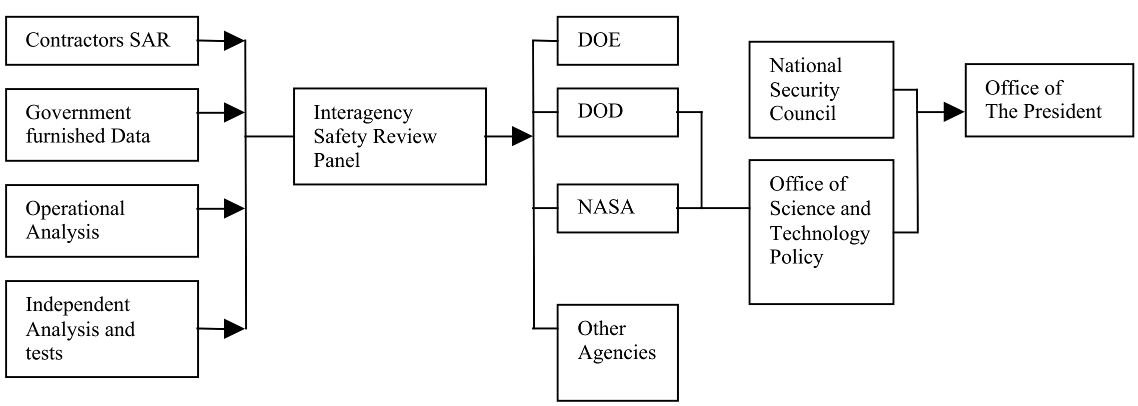

Figure 3
INSRP structure and launch approval process.[8]

There are several advantages of having an independent review panel. The process of having an INSRP was initiated back in the early 1960's to provide a review process of launches of nuclear material into space and has worked quite successfully to date. One of the main advantages of the review panel has been that it neither recommends launch approval nor disapproval but only provides an independent risk evaluation that can be used effectively by government leaders as to whether or not the launch of a NPS is worth the potential risks.[6] It also has the advantage of using common expertise that a specific agency has on hand, can be made available to other agencies. This can reduce the possibility of duplication of work and a savings in cost. At least one coordinator will not be involved from the agency sponsoring the mission. This will allow an objective approach and allow the review to be independent of the sponsoring agency. The review panel allows an environment that will allow the free and timely flow of communication between various parties, regardless of their affiliation. The INSRP will also provide a unified nuclear risk assessment of the mission approval process and allow one joint approval from the three agencies providing the review that is necessary for the leadership of the country to evaluate the potential risks from this launch.[8]

The risks that are evaluated are looked at in depth. For each of the various phases of the mission where a potential risk could occur, a sub-panel within the INSRP is created. Some of the sub-panels within the INSRP that look at these potential risks are: launch abort, re-entry, oceanography, meteorology, and the Biomedical and Environmental Aspects. Although there are other sub-panels within the INSRP, these are the primary ones concerning the potential risks from an accident occurring and what would happen to the environment and society should one occur.[9]

The safety review process kicks off with the submission of the PSAR by the Department of Energy Nuclear Power Source in Space program office to the INSRP. The following INSRP review is a three-stage process, much like that of the SAR. The INSRP meets and has three formal reviews following the release of the PSAR, USAR, and the FSAR. A reason for having three separate reviews of the SAR by the INSRP allows the members of the INSRP to increase their knowledge of the NPS and how the NPS is integrated into the spacecraft. This increased knowledge will allow them to provide input on what they would like to see on the next SAR and allow changes to be made to the spacecraft to improve reliability and safety.[6]

Not only does the INSRP collect information regarding the NPS, it also gathers information regarding the launch vehicle and launch site, which is typically provided by the DOE. Tests and analysis will be done as needed and areas of further testing will be recommended as necessary. The role of the INSRP is to analyze the data and provide assistance to help other personnel to understand the safety concerns and avoid any duplication of work within the constituent agencies in order to reduce the overall cost of the mission.[6]

Once the FSAR has been reviewed, the INSRP writes a report called a Safety Evaluation Review (SER). This document contains their independent assessment of the risks of launching the NPS from the particular launch site and aboard the launch vehicle described within the FSAR. The SER is then passed along to the heads of the DOE, DOD, and NASA for their use in the launch request process. When the user agency that is launching the NPS has obtained written notification from the other two agencies with their approval of the NPS and associated risks, the user agency will submit a letter and a copy of the SER to the Office of Science and Technology Program (OSTP) requesting launch approval. The director of OSTP can approve a launch, however, consultation with and deferment to the President can also occur. The status of whether or not a flight will fly or not will come from the US Government based upon the risk-benefit evaluation given in the SER.[6]

International Agreements

The INSRP writes the SER so that the US government can review the NPS and its associated risk/benefits before it is allowed to be launched. Although the process is internal to the US there are guidelines a country must follow if it is to launch nuclear material onboard a NPS into space. The United Nations looked at the technical aspects and safety measures related to the use of NPS in space following the reentry of Cosmos 954 in January 1978.[6]

Within the Scientific and Technical Subcommittee, the UN Committee on the Peaceful Uses of Outer Space (COPUOS), a Working Group on the use of Nuclear Power Sources (WGNPS) in Outer Space was established on November 10, 1978. The WGNPS met three times beginning in 1979 and issued its final report in 1981 that still is in use today. The US was a member of this working group and submitted several papers for consideration by the WGNPS.[6]

One important note about the COPUOS is that it operates on a consensus basis. This means, there can be no disagreement with the text of the report issued from it. The reports it issued are not binding agreements in the sense of treaties but are recommendations. The US is party to several treaties and conventions concerning the use of NPS in space and the exploration of space in general, which are followed regardless if the mission is nuclear or non-nuclear.[6]

The first of these treaties and conventions is the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies. The US, United Kingdom (UK) and the Former Soviet Union (FSU) and other countries ratified the treaty in 1967. What this treaty states is that each country is responsible for any damage caused by its spacecraft, that the countries should avoid harmful contamination of outer space, and that the countries government that launched the vehicle will be responsible for it no matter if it is a private or government sponsored launch.[10]

Another treaty the US is party to is the Agreement on the Rescue of Astronauts, the return of Astronauts and the Return of Objects Launched into Outer Space. This treaty was ratified by the US, UK, and FSU in 1968. The purpose of this treaty was to enable the launching country to be responsible for any material that might land on another country's land and assist in recovery of the radioactive material, whether it be nuclear or non-nuclear. The treaty also enabled other country's to help another country's astronauts if they were in need of assistance, whether or not they landed on the high seas or in a foreign country.[11]

The UN ratified the Convention on International Liability for Damage Caused by Space objects in 1973. This particular treaty allowed a country to obtain financial reimbursement if an object from space crashed onto their countries territory causing damage. It described the process in which a country goes about getting compensation from another country that launched the spacecraft or object that crashed on the prior country.[12]

The UN ratified the Convention on the Registration of Objects Launched into Outer Space in 1976. The treaty allowed the countries of the world to know what objects were in space and their general purpose. It also provided information regarding the initial orbit of the spacecraft and gave objects a reference number for countries to track.[13]

Two additional conventions cover the use of NPS in space following the Chernobyl accident in the FSU in 1986. These two treaties are the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. In the first treaty, it was written so that those in other countries would be told of a problem involving nuclear materials. The information covered in the event of an early notification would be to notify the UN with the time, the amount of release, the location and other information essential to determining the situation.[14] The second treaty allows for a country to request assistance in the case of a radiological or nuclear accident occurring within its borders. Assistance is provided by other countries based upon whether they can send aid that the requesting country needs. The International Atomic Energy Agency (IAEA) coordinates the activities of the countries as well as provides information and services.[15]

The reason for many of these treaties and conventions is that many in the world countries do not have the resources to draw upon in the event of a NPS onboard a spacecraft lands in their country. The country that launched the vehicle will be liable for damages but it also allows countries that are able to help to do so under the various conventions. By having these treaties and conventions, other non-nuclear countries can have the some level of protection of their environment and citizens as those nuclear-countries that are better equipped to handle these types of emergencies.

Although these conventions and treaties cover the use of NPS in space if an accident occurs, the choice of using NPS was brought up in the Working Group. The Working Group noted that there is a choice generally between using solar cells, fuel cells, and chemical batteries as well as NPS onboard spacecraft. The selection of the choice of a power system has been a complex technical issue and in general, conventional power sources are used in more spacecraft, owing to their less complex workings. However, the choice of using NPS has been in missions where a long life, the ability to operate without the use of sunlight for extended periods of time and their compactness has proved them to be very successful. The Working Group considers the use of NPS should be based upon technical merits, if the risks associated with their use are low level.[6]

The Working Group also looked at the safety of the use of RTG and nuclear reactors in space. In several of the reports published by the WGNPS, they listed two classes of accidents: the first being a probable scenario and the other an improbable scenario. The probable scenario is those with a probability of occurring greater than 10^{-3} per individual mission. The improbable scenarios are those in which remote failure probabilities and many highly unlikely events where the dose limits are greater than those listed by the ICRP may be exceeded or even greatly exceeded. The way in which these scenarios are determined is described next.[6]

Safety Analysis

The objective throughout the review process to launch NPS into space has been one to protect the environment and public health under normal conditions and postulated accident scenarios. The safety objective utilized for all launches with nuclear materials onboard has been to minimize the risk of the radioactive materials interacting with the environment.[6,8] In the case of launching RTG's, the primary concern has been to contain, immobilize, and recover the radioactive material. This has been accomplished by safety in depth with the radioactive sources being in a container within a container philosophy. In order to immobilize the radioactive material, the typical fuel utilized has been a ceramic, which has a high melting point, which can prevent the plutonium from becoming airborne. As for recovery of the NPS and its associated radioactive materials, this can be accomplished a number of ways, depending upon where the NPS and radioactive material is located.[6]

The launching of a nuclear reactor into space brings with it similar safety objectives. The first of these safety objectives is not to operate the reactor for any long periods before launching occurs in order to minimize fission products in the core in the event an accident occurs during the launch/ascent phase. This also means not operating the nuclear reactor at any large amounts of power before launching the satellite into a safe orbit. The second is to provide enough neutron poison material in the core to prevent any type of criticality accident from occurring during the launch and ascent phase until a high enough orbit has been achieved. Typically this is accomplished by the utilization of additional control rods in the core to prevent any accident from occurring, including the total immersion of the core in water and other postulated accidents.[3,6,7,8]

No matter what the choice of a NPS, whether it is a RTG or a nuclear reactor, the NPS must be contained should it ever reach earth from an accident occurring. No matter how well planned or how well built the spacecraft is, there exists a small probability that something could go wrong and cause an accident. This is the focus of the INSRP as discussed earlier, but now lets look at the risk analysis in depth to understand how the risk is being minimized.

Risk analysis is a "quantitative assessment of the potential for human exposure to radiation resulting from the use of a NPS in a space application."[8] The basic analysis consists of three steps. The first is determining the events that could lead to human exposure to radiation and their probabilistic occurrence. The second is the determination of those events in terms of the number of persons exposed to various levels of radiation. The last step is to evaluate the NPS on the basis of the results obtained from steps one and two.[6]

In determining the events, which could lead to human exposure from an accident resulting from a NPS in space applications, analysist starts with an analysis of abort or failure modes. The objective of this is to identify potential single or multiple point malfunctions, which could affect the NPS from completing its mission as designed. An example of a failure and abort sequence tree is shown below in figure 4. In the event of an accident, the sequence tree contains information regarding the condition of the spacecraft after that failure and the occurrence probability for this to occur. For each scenario, a sequence of events is obtained and a probability assessment is determined for each event that is then is added to the probability of arriving there from the previous events. Thus, by following through the various events listed on a sequence tree, one is able to obtain whether or not human exposure to radiation will occur. By analyzing the route in which events transpire for an exposure to humans, modifications can be made at the failure points in order to reduce the chance of a failure.[8]

To evaluate the above results identification of the source terms must be made. A source term is a quantity of fuel, which may be uncontrolled. In describing an accident in which a source term is mentioned, care must be taken to describe the source terms state (size of the particle, chemical form and how much has been released) as well as its location (high altitude, on land, water, latitude and longitude, or random deposition during reentry from a specific orbit). These types of tests have been performed at the Los Alamos National Laboratory and Sandia National Laboratory.[8] After analysis of the events leading up to the occurrence of a source term, the consequences of a release can now be examined.

In order to determine the effects on human exposure following the events listed below, models must be used to determine these effects and those to the environmental dispersion. These models are described more in the *Overall Safety Manual*[15], which has models to analyze environmental dispersion and doses to humans. The models incorporate meteorological, geographical and Earth surface data.[6] By combining these sets of data with the events transpiring to get a particular release from previous calculations, the approximate number of people exposed to a certain radiation dose can be calculated.[8] Because of these postulated exposures, it will list a probability with the particular exposure and number of people exposed.[6]

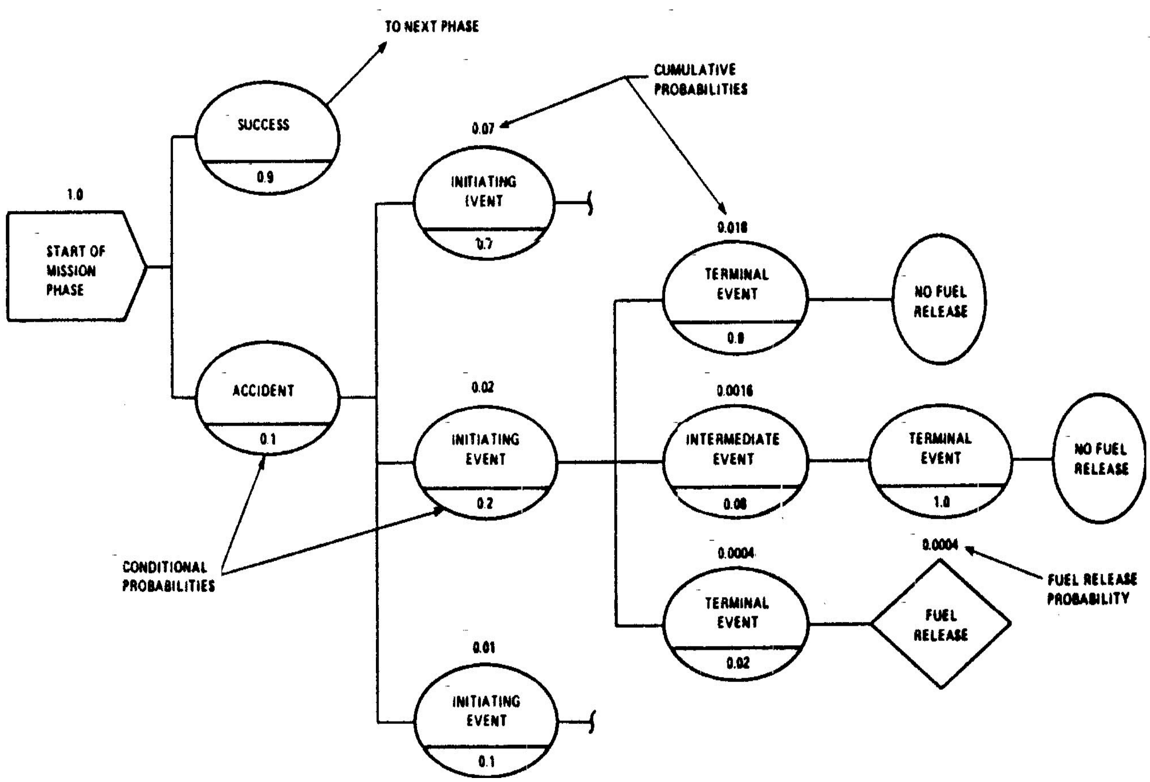

Figure 4
An example of a sequence tree construction and features.[6]

With the results from steps one and two in hand, the assessment of the potential risks for a mission can be developed. The occurrence probability and the probable number of persons exposed with a given dose are used in equation 1 to determine the risk of human exposure for each phase of the mission. The values calculated from these values are the expected number of people to be exposed at a dose level or greater.[6] The formula used for this calculation is shown below.

$$\langle N\rangle_k, Dref = \_\ P_i\ \_\ (P_{j/i}\ N_{j/i})\ D_{ref} \qquad (1)$$

where $\langle N\rangle_k, D_{ref}$ is the expected number of persons exposed at a dose level D_{ref} or greater for the k-th mission phase, P_i is the probability of occurrence of the i-th potential exposure event during phase k, $P_{j/i}$ is the frequency of occurrence of the j-th set of environmental dispersion characteristics that may occur to the i-th potential exposure event, and $N_{j/i}$ is the number of persons exposed to a dose level D_{ref} or above as a result of the j-th set of environmental dispersion characteristics following the i-th potential exposure event.[8] For each of the mission phases, values for $<N>_{k},D_{ref}$ will be determined. The overall risk can be determined from weighting the various consequences for the entire mission.[6]

Some of the risks that are modeled are the eventual re-entry of the NPS. Although it is not something that is expected to happen for a long period of time, one only has to look at the re-entries of the SNAP-9A in 1964, which burned up in the atmosphere, SNAP-19 in 1968 and the unexpected shutdown of the SNAP-10A in 1965.[3,6,8] Each of these particular missions utilized a concept that was modeled before the NPS was launched. Although these re-entries will be discussed, there have been other re-entries of NPS but these ones discussed illustrate the different techniques used to keep the risk of human exposure to radiation low.

The first NPS launched by the US that re-entered the Earth's atmosphere did so on April 21, 1964.[6] The SNAP-9A RTG was onboard a Transit-5BN-3 Navigational satellite. During launch a problem involving the guidance controller malfunctioned, which then did not allow the satellite to be inserted into orbit correctly. It re-entered the atmosphere and the NPS burned up in the atmosphere as designed.[3] The risks associated with the source burning up during re-entry were minimized by dilution and dispersion.[6] The radioactive material was allowed to be dispersed easily upon re-entry, which then would allow it to become diluted by the atmosphere. Having the small amount of radioactive material diluted before humans could be exposed to it lessened the risk to human exposure. This was found not to be an acceptable risk after the NPS re-entered. It was then proposed to encase the NPS for intact recovery should another re-entry occur.[8]

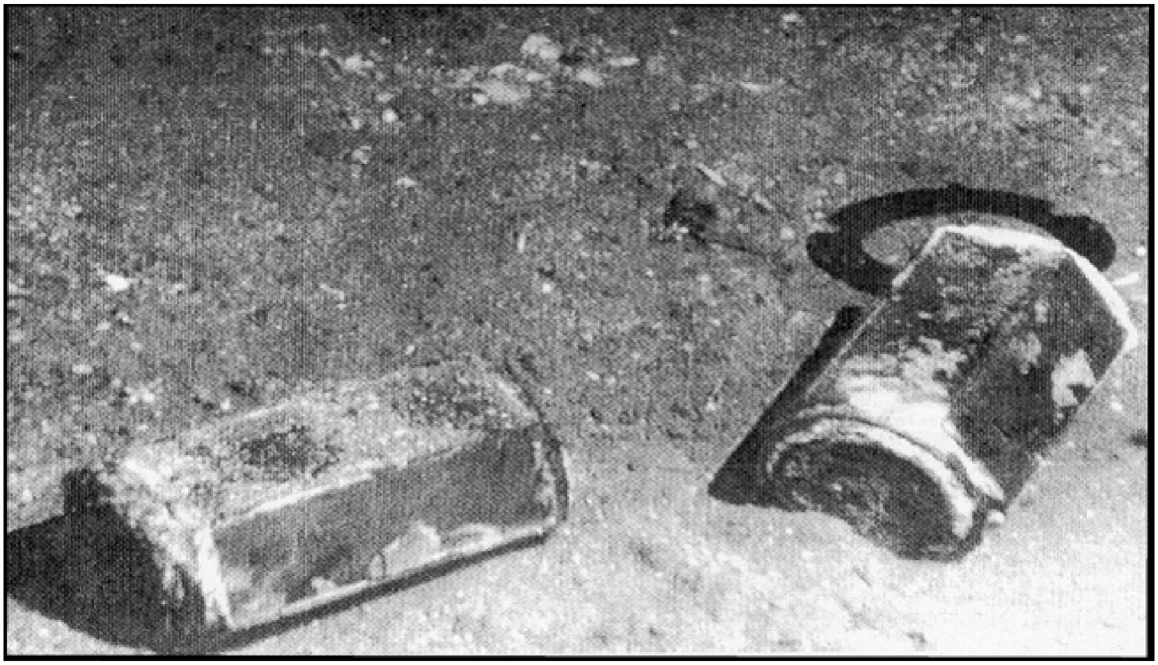

Figure 5
Underwater recovery of the RTG fuel cells from the SNAP-19 NPS.[2]

Following the change mentioned above, the US modified its policy on re-entry risks associated from using NPS in space. This was put to the test on May 18, 1968 when the Nimbus B-1 meteorological satellite was destroyed during ascent. The destruction of the rocket was due to erratic behavior of the launch vehicle and the range safety officer used the self-destruct on the rocket to protect society.[6] The satellite remains were tracked to a point 90 miles of the coast of California. No radioactive material was found in the atmosphere following the destruction of the rocket. In fact, five months after the ascent abort, the RTG fuel capsules were recovered and were later recycled for later use onboard another RTG later. Below is a picture of the RTG fuel cells during the underwater recovery operation.[8]

The third method to reduce the risk to human exposure of radiation is the delay and decay method. When the SNAP-10A nuclear reactor was launched by the US on April 3, 1965, the delay and decay method was used for controlling the amount of radioactive material that could re-enter the atmosphere.[6] Before the reactor was operated at full power, the experimental spacecraft was placed into a 4,000-year lifetime orbit. When the reactor shut down unexpectedly after 43 days of operation, there were several thousand curies of radioactive material present in the reactor core. Since the satellite is in such a long-lived orbit, by the time the satellite re-enters the earths atmosphere, the radioactive inventory within the core will be negligible. Even if something were to happen to the core after 100 years in space, the radioactive inventory upon re-entry will be less than 0.1 Curies.[8]

Conclusions

The process in which to launch a NPS into space is indeed a detailed process. From the first launch of a NPS in June 1961 to the launch of Cassini in October 1997, there has been an extensive safety review of a NPS before being launched into space. The US can be proud of the safety record the space community has had in launching 44 RTGs, 1 nuclear reactor and numerous radioisotope-heating units into space over thirty years with only a handful of re-entries of these systems.

With so many launches, there have been some problems. However, when one takes into account that in every instance of a US NPS re-entering the earth's atmosphere, the NPS has performed exactly as it designed to do so. From the SNAP-9A burning up in the atmosphere to the SNAP-19 after re-entry through the atmosphere to sit in water for five months, the record of accomplishment is very good. Although there have been concerns raised by a small but vocal groups, the safety of NPS remains very high, no matter what choice is made for a NPS.

With the choice of a NPS, it is good to know there is a procedure to follow in order to launch these systems. The process in place has been used for over 30 years with no sign unsatisfactory results. Actually, the process has been able to adapt to concerns within society concerning the dilution and dispersal method. After these changes have been made to spacecraft, the spacecraft have held up well under tests and actual re-entry conditions.

If a US launched NPS is to re-enter the earth's atmosphere, the world's population can be very confidant that the NPS will operate as designed. The tests and analysis the NPS undergoes in the event of re-entry, is very exhaustive. The INSRP undergoes not one review of the NPS but at a minimum of three different times as the NPS evolves and changes before the launch. This allows the reviewers from DOE, DOD, and NASA to be able to obtain information that is vital to them and their analysis of the NPS. With the input of the INSRP from the NPS inception, concerns of the review panel can be addressed in the next SAR. By having the INSRP be part of the process from the beginning, a more thorough understanding of the reasoning for using a NPS for the mission and its associated risks can be laid from the inception of the NPS design.

The review of the SAR for risks is very detailed. The sequence tree shown previously in figure 4 shows the level at which the analysis is made. By tracing through the various malfunctions, the analysis can then determine the probability that an exposure would occur to society. From this probability, a number of people exposed to a certain dose rate can be calculated. With this done, the risk to society can be weighed against the overall return of information from the spacecraft during its mission. If however, there are a high number of people exposed to a dose from a specific malfunction, the designer has the ability to go back and rework the design to improve the safety of the spacecraft. This new level is such that the exposure previously calculated is not reached but is lower.

Once the INSRP reviews the FSAR, it then writes the SER. The SER is then sent to the executive branch of the government. The decision to launch the spacecraft containing the NPS has to be made at the highest levels of the government. With various treaties and conventions holding the government financially responsible and making them available in case of an accident, the agency launching the mission wants to make sure the government is aware of the risks versus benefits of initiating the mission.

Although there are benefits and risks are inherent to launching a NPS, the safety concerns raised by a few vocal anti-nuclear advocates have been addressed. Many of the anti-nuclear advocates fears center on the use of plutonium aboard the spacecraft powering the RTG. The concerns about the fear of plutonium being spread over the globe have been taking into account by building the RTG with safeguards in depth. Even if one barrier is broken by the RTG re-entry, there are others designed to minimize the spread of the radioactive material. The other concerns about the spacecraft being destroyed during ascent have been addressed and, unfortunately, tested safely with the SNAP-19 RTG.

The use of NPS on spacecraft has been demonstrated to be safe. The review process has been shown to be flexible to accommodate the change in society of preventing dilution and dispersion of radioactive material. The INSRP has the ability to identify possible risks or systems that could affect the safety of society early in the design phase to incorporate needed changes and fixes.

The need for using NPS is going to be increasing in the future. As more launches occur with NPS systems, society can rest assured that the process necessary to launch them into space is adequate. As it has been shown, the process is detailed, open to change, and has worked for over 30 years successfully. The future of launching NPS into space has a great review process, which does not require any modifications to continue to provide adequate safety for the foreseeable future.

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