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Tutorial on Nuclear Thermal Propulsion Safety for Mars

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TUTORIAL ON NUCLEAR THERMAL PROPULSION SAFETY FOR MARS

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Abstract

Safety is the prime design requirement for nuclear thermal propulsion (NTP)! It must be built in at the initiation of the design process. An understanding of safety concerns is fundamental to the development of nuclear rockets for manned missions to Mars and many other applications that will be enabled or greatly enhanced by the use of nuclear propulsion. To provide an understanding of the basic issues, a tutorial has been prepared. This tutorial covers a range of topics including safety requirements and approaches to meet these requirements, risk and safety analysis methodology, NERVA reliability and safety approach, and life cycle risk assessments.

I. Introduction

The highest priority is given to ensuring safety. However, there is more to the prime design goal than just safety. The paramount objective (i.e., equivalent to the prime design goal) of the Space Exploration Initiative Nuclear Propulsion Program is to safely develop and utilize the required technologies and the necessary components, subsystems, and facilities needed to provide qualified, safe, space nuclear propulsion systems and their associated ground test systems. Recognizing that safety is the prime design goal of nuclear thermal propulsion, it is essential to understand what is meant by this. First of all, the Earth's population and environment must be protected from harmful radioactive materials and radiation. In addition to not significantly effecting the safety of the Earth's population and environment, space nuclear propulsion systems should not significantly adversely effect non-terrestrial environments such as space and the environments of other celestial bodies such as the moon and Mars. This includes cradle to grave protection.

The crew of manned space missions must be protected. Nuclear thermal propulsion is critical for successful human Mars exploration.[1] The safety of the crew is greatly enhanced by shorter trip times enabled by nuclear thermal propulsion. This has the effect of reducing the crew exposure to high levels of galactic radiation, reducing the time that solar flares will be a problem, lowering psychological stresses of long periods in confined environments and reducing the time the crew is subjected to possible equipment malfunctions. In addition, NTP rocket engines have many fewer moving parts than the chemical rockets which they replace and should, therefore, be more reliable. There is no need for an oxidizer system. Launch windows for departing Earth and for returning from Mars are significantly wider. Also, there are more opportunities to go to Mars, providing schedule flexibility and reducing the need for potentially hazardous decisions to meet limited Mars opportunities. In addition, with nuclear thermal rockets performing two to three times better than chemical rockets less (or no) assembly is needed in Earth orbit. This makes the spacecraft more reliable, less costly and easier to meet its schedule. In fact, the mass in low Earth orbit will be one-third to one-half that of a chemical rocket mission configuration.

II. Safety Requirements and Approaches

Safety goals and approaches to achieve safety are given in Table 1. From these, safety requirements can be summarized as:

- prevent unplanned nuclear reactor criticality;
- maintain thrust as needed to assure safe return of crew;
- maintain core integrity (except possibly on planned dispersal on atmospheric re-entry);
- provide for radiological safety in case of random impact location from a launch abort;
- provide for safe reactor disposal;

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SAFETY GOALS AND APPROACHES

Goals	Reasons	Design Approaches
Radiation levels sufficiently low prior to launch to avoid special handling precautions	Protect workers and astronauts	Not operate reactor (except for zero power testing) until a stable orbit or flight path is achieved
		Independent systems to reduce reactivity to subcritical state
		Unirradiated fuel that poses no significant environmental hazard
Prevent inadvertent criticality	Ensure public not exposed to levels of radiation that exceed established standards	Subcritical if immersed in water or other fluid.
	Protect crews	Significant negative temperature coefficient
		Subcritical on Earth impact accident
		Independent reactor safety systems
		Quality assurance standards
		Positive coded telemetry for reactor startup
		Redundant control and safety systems
		Independent sources of electric power for reactor control, protection. and communication systems
		Continuous status monitoring
Avoid unplanned core destruction	Protect space investments and avoid contamination of space environment	Independent shutdown systems
		Independent decay heat removal
	Protect crews	Fault detection for reactor
		Positive coded signal to operator
Avoid release of radioactivity by-products in concentrations that exceed radiological standards	Ensure public not exposed to radiation levels that exceed standards and protect biosphere against concentration of radioactive elements above safety standards	Design fuel elements to meet standards
		Orbital boost system for short-live orbits
		Design reactor for dispersal or intact reentry if boosters fail
Avoid contamination of biosphere	Ensure public not exposed to radiation levels that exceed standards and protect biosphere against concentration of radioactive elements above safety standards	Engine command destruct system
		Disposal in deep space

Table 1

- prevention of reentry into the biosphere after operation;
- reduce radioactive levels of the exhaust plume to acceptable levels for the environment and spacecraft;
- protect the crew against unacceptable radiation levels;
- provide independent, high reliable, and redundant operational and safety systems; and
- meet spacecraft safety goals such as in case of certain number of failures the mission can be completed and after that the crew is protected.

Table 2 summarizes the crew dose standards and potential hazards from natural radiation. Exposure to solar flares exposes the crew to the highest potential radiation hazard levels; however, these are anomalous events, and crews can be protected by use of shielded storm cellars. The major radiation risk to the crews is from galactic radiation. These exposures are continuous and, due to the high energy levels, are very difficult to shield against. The best solution is to shorten trip times to Mars.

RADIATION LEVELS

•RADIATION LIMITS (NCRP#98)

TIME PERIOD	BLOOD FORMING ORGANS (BFO) REM
30 Day	25
Annual	50
Career	100–400*

Based on 3% lifetime cancer mortality risk, age and gender dependent, BFO @ 5 CM depth

•RADIATION SOURCES

SOURCE	BFO
Galactic Cosmic Radiation	
Solar Minimum	60 REM/Year
Solar Maximum	22 REM/Year
Solar Flares	
Ordinary Event	13 REM
Anomalous Event	431 REM

*Assumes 3 G/CM2 Aluminum Shielding and BFO @ 5 CM Depth

Table 2

III. Risk and Safety Analysis Methodology

Safety analysis can use deductive or inductive methods. The former looks at specific information and draws general conclusions. An example is Fault Tree Analysis, where one assumes the system being analyzed is in a failed state and determines how it can occur. Inductive logic examines what happens "if"; it evaluates many cases where components are assumed to have failed and then draws conclusions as to the effects. Failure Mode Analysis is an example--it assumes components in a failed state and determines what happens to the system. Approaches to failure analysis used in safety evaluations are summarized in Table 3.

Failure Mode Analysis is used to illustrate the steps in a typical safety analysis such as was used in the NERVA program.

1. Obtain the functional and physical description of the design to be analyzed.

2. Define the functional and physical boundaries, i.e., those items to include in this FMA as opposed to those which must be evaluated by other component or system FMA's.

3. Obtain or define probabilistically the input and output requirements.

4. List the Component Mode of Failure, the operating conditions, the condition of success, the general design analysis that will be required, and the reliability allocated to this failure mode.

5. List the Component Mechanism (s) of Failure stemming from the success-failure condition, causes, and interactions; give the probability equation; perform the probability analysis (or assess by an acceptable method such as analytical estimation, direct measurement, historical data, or engineering judgement); show the principal distributions; and report the assessed reliability.

APPROACHES TO FAILURE TO ANALYSIS

Type	Purpose	Methodology
Preliminary Hazards Analysis	Initial assessment of potential hazards during early design phases	Identify hazards Determine consequences Classify effects Evaluate appropriate corrective actions
Fault Tree Analysis	Top down approach Evaluate detailed designs and integrate with mission	Start with system failure or accidents Determine events that can lead to failure or accidents Construct path from basic causes Determine failure probabilities for causes Computer probability of system failure or accident
Failure Modes and Effects Analysis	Bottom up approach Evaluate detailed designs and integrate with missions	Start with cause Establish failure probabilities Calculate probability of consequences occurring
Event Tree Analysis	Multi-event, bottom up analysis Evaluate detailed designs and integrate with missions	Identify initiating events Perform failure modes and effects analysis on consequences Integrate effects into tree Compute system success and failures

Table 3

6. Determine how the mechanisms relate to one another (e.g., dependently or independently); and combine the individual assessments to find the probability of success (reliability) under the failure mode.

IV. NERVA Experience[2]

The NERVA program provides an excellent data base for developing NTP engines. The value of much of the work was not the numbers generated, but the forced attention to design details and the recognition of uncertainty. It forced designers to consider every aspect of safety from the initiation of the design process.

Table 4 summarizes the NERVA safety plan. All of the potential flight failure accidents were examined in the NERVA program, and design and operational solutions developed.

Accidental insertions of reactivity could occur from either: (1) a control system malfunction, (2) water flooding, or (3) core compaction on impact. The energy release, if an accident supercritical condition occurred, depends upon (1) the amount of reactivity inserted, (2) the rate of insertion, (3) the initial state of the reactor (e.g., hot or cold), and (4) the quenching or shutdown mechanism. Rapid insertions of large amounts of reactivity would be accompanied by releases of kinetic energy, which physically disrupt the reactor. A test called KIWI-TNT was conducted to demonstrate the effects of large and

NERVA SAFETY REQUIREMENTS

- The means for preventing the inadvertent attainment of reactor criticality through any credible combination of failures, malfunctions, or operations during all ground, launch, flight, and space operations.
- A destruct system during launch and ascent to assure sufficient dispersion of the reactor fuel upon earth impact to prevent nuclear criticality with the fuel fully immersed in water.
- The means for preventing credible core vaporization or disintegration or violation of the thrust-load path to the payload.
- Diagnostic instrumentation adequate to detect the approach of a failure or an event that could injure the crew or damage the spacecraft and the provisions to preclude such an event.
- The capability for remote override of the engine programmer by the crew and ground control as well as for remote shutdown independent of the engine program.
- An engine control system capability to preclude excessive or damaging deviations from programmed power and ramp rates.
- Provide an emergency mode on the order of 30,000 lb-thrust, 500s specific impulse and 10^8 lb-sec total impulse.

Table 4

rapid reactivity insertion. Special actuators were used to achieve the desired reactivity rates. The excursion released 10,000 MW(s) of energy and completely dismantled the core in a mechanical (not nuclear) explosion.

The planned nuclear rocket engine stage was a modified Saturn vehicle, with the nuclear upper stage replacing the S-IVB. The potential energy releases of the booster propellants as a result of booster failure was a predominant factor in range safety. The Saturn booster fueled with liquid oxygen and RP-1 included 2,180,000 kg (4,800,00 lb) of propellants and the S-II stage fueled with liquid oxygen and liquid hydrogen included 386,000 kg (850,000 lb) of propellants. In case of a destruct, it was calculated that 10 percent of the Saturn booster and 60 percent of the S-II stage kinetic energy, or the equivalent of 218,000 kg (480,000 lb) of TNT from the former and 231,000 kg (510,000 lb) of TNT from the latter, needed to be considered in kinetic energy release. The nuclear stage included a destruct system that was integrated with the booster destruct system. In addition, an engine destruct system was tied to the nuclear stage destruct system. Therefore, if vehicle or nuclear stage destruct action was necessary, the reactor would also be safely destroyed. An ordinance destruct system would fragment the reactor into particles small enough to remain aloft as aerosols to be burned up upon reentry into the Earth's atmosphere or with so little activity upon reaching the Earth's surface that they would not present a hazard.

The development of neutron poison systems to "safe" the reactor during its transport to the missile test site, during ground handling, and possibly during the early stages of launch was a primary thrust of the nuclear safety program. A redundant poison approach was pursued in which poisons could be inserted and reinserted into the core through the nozzle opening and reactor control elements could be locked. Therefore, if the control elements are inadvertently withdrawn, the core poisons could override the resultant reactivity insertion. Conversely, if the core poisons were withdrawn, the locked control system alone could safe the reactor.

A number of advanced countermeasures were also considered. Propulsion guidance interlocks were considered to interlock the propulsion and guidance systems in a manner to activate thrust termination in the event of guidance failures during orbital start-up or re-start to preclude prompt re-entry. Retrosystems for inducing downrange impact in the event of late nuclear stage aborts during orbital injection to preclude random re-entry was another idea. Also, retrosystems for inducing orbital departure and impact in pre-determined marine disposal areas to counter random re-entry were under investigation. Satellite interceptions might utilize ground-to-air or air-to-air missile systems to intercept and destroy nuclear rocket reactors or induce their impact into pre-determined marine disposal areas. Another idea considered was the use of auxiliary rockets to carry the nuclear rocket into orbit in case of late pre-orbital injection thrust failures or to transfer the nuclear stage to orbits of higher perigee in case of orbital start-up failures. This would provide additional decay time and also preclude prompt random re-entry. Automatic malfunction sensors and countermeasure initiators using on-board malfunction sensors in the nuclear stage (to detect guidance, thrust, or propellant malfunctions connected to automatic on-board initiators which execute destruct or countermeasure action, if necessary) were also being evaluated.

The NERVA Safety Plan established many requirements for flight safety.[3] It stated, for example, that a maximum effort was to be directed toward eliminating from the engine design those single failures or credible combinations of errors and failures which could endanger mission completion, the flight crew, the launch crew, or the general public. If this effort proved impossible or resulted in an excessive penalty, redundancies internal to the component in question were to be considered. If this alternate approach also proved ineffective, ways in which other components could compensate were to be investigated. Where no practical solutions were found in inherent design and where credible single or multiple failures could jeopardize crew or population safety, countermeasures or techniques such as maintainability and alternative operating modes were to be explored. Further, if the planned mission was to be abandoned because of an engine failure, provisions were to be made for engine operation in an emergency mode to affect safe crew return and to prevent danger to the Earth's population. Operation in the emergency mode was to allow optimum use of remaining propellant commensurate with the failure and, at a minimum provide engine performance on the order of 30,000-thrust and 500-sec specific impulse. In addition, the engine was to be capable of delivering a minimum controllable total impact of 10^8 lb-sec, including the impulse derived from the cooldown propellant. This total impulse was to be obtainable in a single thrust cycle with the powered-operation portion of the cycle at or above the specified thrust and specific-impulse minimums. This goal was to be obtainable from all operating phases of the engine operation, and provision was to be made for coolant up to five hours prior to entering the emergency mode. Final cooling was to preclude engine disintegration and - if possible at no addition risk to population, passengers, or crew - was to preserve the engine in a restartable condition.

Additional NERVA safety design requirements were to have the engine incorporate the following features:

1. The means for preventing the inadvertent attainment of reactor criticality through any credible combination of failures, malfunctions, or operations during all ground, launch, flight, and space operations.

2. A destruct system during launch and ascent to assure sufficient dispersion of the reactor fuel upon Earth impact to prevent nuclear criticality with the fuel fully immersed in water.

3. The means for preventing credible core vaporization or disintegration or violation of the thrust-load path to the payload.

4. Diagnostic instrumentation adequate to detect the approach of a failure or an event that could injure the crew or damage the spacecraft and the provisions to preclude such an event.

5. The capability for remote override of the engine programmer by the crew and ground control as

well as for remote shutdown independent of the engine program.

6. An engine control system capability to preclude excessive or damaging deviations from programmed power and temperature ramp rates.

Because of these safety concerns and the often indistinguishable relationship between safety and reliability, the NERVA reliability program was a significant adjunct to the safety program. The reliability goal for the NERVA power plan was 0.995.[4] This goal was in line with the NERVA design philosophy established by its director, Mr. Milton Klein:[5]

> The major design criteria for the NERVA engine development program shall be reliability and the achievement of the highest probability of mission success. Next in the order of importance must be performance as measured in terms of specific impulse. Then the engine design should attempt to keep the overall weight as low as possible within the bounds allowed by funds available for development. While there are interrelations between these criteria in design, I can see no basis for altering their order of importance.

Flight safety analysis was divided into three parts: malfunction analyses, fault tree analyses, and contingency analyses. Malfunction analyses were performed with a computer model and depict all the system effects of the failure of components. Fault tree analysis used the deductive process by which an undesirable event was postulated and possible malfunctions which caused the event were systematically analyzed. Contingency analyses addressed component failures and how they were detected, system consequences of the failures, contingency actions required, and the time in which the contingency action must be performed.[6]

Analysis of component failures indicates about 3 failure probabilities per 1000 engine cycles for catastrophic failures. (Analysis was only performed on the non-nuclear engine components, but a review of the nuclear subsystem led to this overall number.)[7]

Designers had primary responsibility to prove that a component met specifications. The technique chosen to ensure that the reliability goal would be met was Failure Mode Analysis. Failure Mode Analysis (FMA) is a systematic method used to ensure that components have high, inherent reliability. The FMA developed for NERVA clearly defined the conditions for success. A probability equation was written to express each condition. These equations were then used to define the principal distributions and to provide an indication of the kind of analysis performed.

A thorough, unbiased narrative - listing all credible ways that failures can occur - was written so that changes could be identified and used to eliminate those failures or minimize their effects. This listing gave insight into fundamental causes and interactions and served as the basis of the subsequent reliability assessment.

IV. Life Cycle Risk Assessment[8]

Life cycle risk can be thought of in terms of fabrication, transportation to launch pad, pre-launch, launch, operations, stand-by, and disposal. Emphasis here is placed on launch pad, launch and operations, since fabrication and transport are routinely performed on terrestrial reactors. Accident environments result from launch pad explosions or fires, loss of control, land or water impact, random reentry, etc. A series of questions have been formulated to cover different situations, requirements developed, and design options evaluated to see if these can be safely handled. The questions are given in Table 5. For the postulated accident conditions, the primary safety requirements were determined, design options examined, and the experience base reviewed. The results are given in terms of top level summary discussions. Once a particular design is selected for either unmanned scientific or exploration missions or for crew missions to Mars, detailed design and operational solutions will be needed. The important element here is to have examined the key questions in significant depth to show that solutions exist.

Safe Ground Testing of Nuclear Rockets

Safety is the prime requirement in all testing and operational procedures. The established standards for radiation levels and radioactive releases levels must be met.

Safety Questions Relevant To Nuclear Propulsion

Ground Operations

What must be done to safely ground test nuclear rockets?

What special precautions will be needed at the launch pad?

How will radioactive material contamination at the launch site be avoided in rocket launch pad accidents?
- Nuclear criticality
- Fires
- Explosions

How will ground testing be handled so that there are not significant additions to the nuclear waste problem?

Who approves the launch of vehicles with nuclear rockets on-board?

Launch and Space Operations

How safe is the crew from reactor radiation?

How will inadvertent criticality be prevented and the population/environment protected for launch/ascent accidents?

How safe are flight operations:

If radioactive materials impact on land, what plans exist to clean up contaminated land areas?

If a reactor is started below a "Nuclear Safe Orbit" (NSO) or "Sufficient High Orbit" (SHO), how can re-entry of a radioactive core be averted?

Will nuclear engines release radioactive materials which contaminate near-Earth space?

Will an operating nuclear rocket affect other satellites and experiments?

What are the plans for final disposal of nuclear engines in space?

Returning from Mars, how will a nuclear rocket be prevented from impacting the Earth?

Table 5

Environmental Impact Statements will be needed before testing facilities can be constructed.

To meet environmental safety standards, radioactive material removal scrubbers will be needed to remove fission gases from the engine hydrogen exhaust and to catch any radioactive material releases. The basic technology was demonstrated during Nuclear Furnace-1 testing in 1972 (see Figure 1). In addition, a scenario worse than what is considered the worst case credible scenario was intentionally tested in 1965 in Kiwi-TNT by building special rapid neutron control devices into the reactor. The result of the test showed that even in this extreme scenario, the reactor chemically exploded without significant nuclear contamination.

Special Precautions Needed At The Launch Pad

Special handling issues relative to ground operations are: (1) worker constraints in performing duties around a payload that includes a nuclear power plant must meet radiation dose levels established by health standards, and (2) minimizing the use of special handling equipment. The radiological levels in the vicinity of the reactor can be maintained well below established radiological standards by minimizing testing to zero power levels. Acceptance testing at the launch facility will be needed to ensure that all components are functional prior to mating with the launch vehicle. This could include cold flow testing; that is, testing

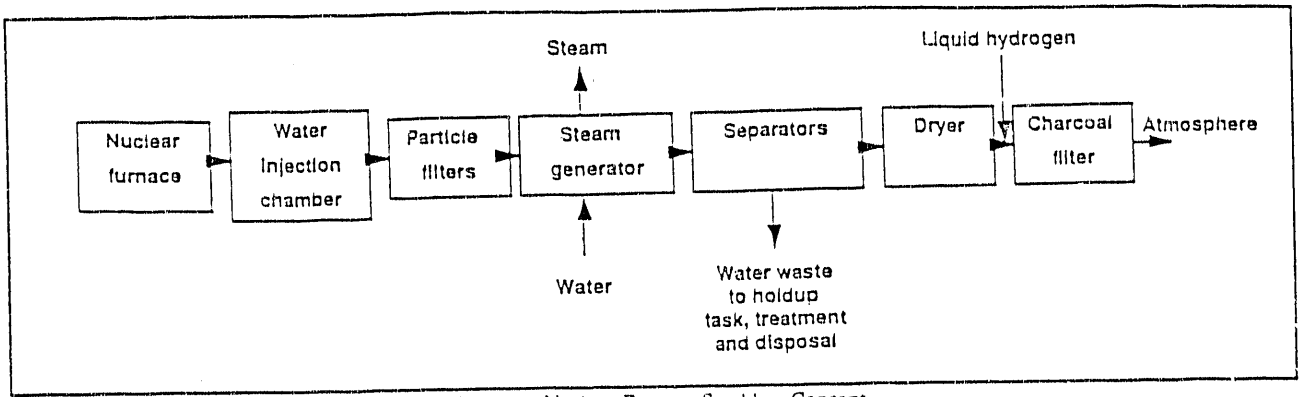


Figure 1. Nuclear Furnace Scrubber Concept

where hydrogen is run through the engine for short periods of time to demonstrate that all valves and the turbopump are operational with the reactor shutdown. A system of safety interlocks and mechanical key locks is also usually provided in the designs so that individual components can be tested prior to launch without permitting the reactor to go critical. The designs can also readily incorporate redundant and independent safety devices for worker protection. In NERVA, neutron poisons were inserted through the nozzle on the launch pad.

The U.S. has launched one space reactor. This reactor, SNAP-10A, demonstrated the capability to launch a reactor without special radiation handling at the launch site. Further, nuclear fuels and reactors are transported around the country using well established containers and procedures. Sufficient design and operational experience exists to avoid transportation criticality accidents.

<u>Launch Site Contamination--Nuclear Criticality</u>

The requirement is to avoid nuclear criticality in case of impact, crush, and/or immersion in water or fluids in case of an accident. The concern here relates to damage during handling, assembly on the stage, or a stage mishap prior to launch. Design features in the nuclear thermal rocket are important here. The rocket needs to be designed so that considering the full range of potential impact forces, that the neutron poisons in the core will remain in the core and the reactor remains subcritical. This includes the case where fluid enters the core. In addition, the core design can take advantage of weak and strong points so that the core disassembles for certain impact forces rather than suffer significant compaction.

<u>Launch Site Contamination Accidents--Fires</u>

The primary requirements are to maintain the reactor subcritical without releases of hazardous radiation or radioactive materials and to preclude or minimize the release of toxic non-nuclear materials in fires. Design options relate to choice of materials and physical layout on the launch vehicle. For example, in case of an accident, it is more desirable to have the nuclear rocket in-line with chemical boosters rather than alongside of them.

A series of propellant fire testings was performed as part of a project called PYRO to investigate the temperatures and duration of liquid propellant fires.[9] Theoretical data showed a peak temperature of 2900 K for hydrogen-oxygen fires. The experimental data measured 2500K. This is below the melting temperatures of the nuclear rocket fuel, so that melting is not a problem. An analysis of the structural materials, such as stainless steel, also indicated that melting is insufficient to cause a critical mass.

Solid propellant tests show that they burn at approximately 3000 K, with some chucks burning for up to 10 minutes. Again, the fuel melting temperatures are above the fire temperature. Using evaluations of the Lincoln Laboratory Experimental satellites LES8/9 that used a Titan III launch vehicle, the probability of an accident is 2-3 in a hundred. In a given accident, the probability of propellant chunks being in close proximity to the reactor is between one in a thousand and one in a million.

The conclusion is that the reactor can be designed not to melt or go critical in a launch pad fire. Detailed evaluations will be needed of particular nuclear thermal rocket and launch vehicle configurations.

Launch Site Contamination Accidents--Explosions

Here, the requirements are to prevent core compaction criticality and dispersal of radioactive materials. Design options are based on analysis from SP-100, where it was shown that the reactor would not go critical from the blast effects of launch vehicles. Similar design features can be built into nuclear rocket engines. Fragments may shear through the engine, but no fission fragment inventory exists within the core at this time. Therefore, no significant radiological risk from an explosion is projected. A major safety analytical and experimental program has shown that radioisotope generators are safe to launch[10]; NTPs, with their geometry and non-radioactive materials at launch, should be even less risky at launch.

Ground Nuclear Waste

It is highly desirable to minimize the amount of radioactive waste generated during the NTP program, especially long life waste. Detailed issues will be addressed as part of a programmatic Environmental Impact Statement. NTP characteristics tend to minimize nuclear waste because of the very short operating times. Reprocessing of the fuel and burning the actinides can minimize/ eliminate nuclear waste. This was demonstrated when NERVA fuel was re-processed and re-used.

Launch Approval

It is required that a formal flight safety review be completed with the approval of the Office of the President, before nuclear power systems can be launched in the United States. This process, shown in Figure 2, requires an independent review by the Interagency Nuclear Safety Review Panel that performs safety and risk evaluations.[11] The Panel provides the necessary independent risk evaluation which will be used by decision makers who must weigh the benefits of the mission against the potential risks. The agency wanting to fly a nuclear powered payload then requests permission for flight, the Office of Science and Technology (OSTP) reviews the request and makes the launch decision; however, the Executive Office of the President makes the final decision if OSTP feels that it is appropriate.

The formal safety review conducted by the Office of Science and Technology Policy for the Office of the President is for nuclear safety approval for launch only. A launch range formal safety review of ground operations on range property and a formal safety review of flight operations are also conducted by range personnel.

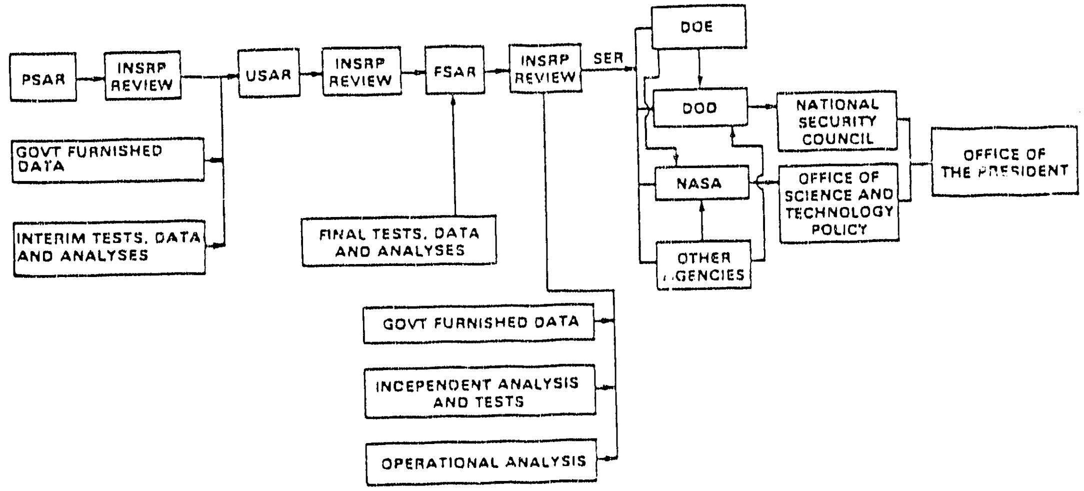
Turning now to launch and space operations, the questions in Table 5 will be addressed.

Crew Safety From Reactor Radiation

NASA crew dose guidelines for astronauts are 50 rem/year. Mars trips involve crew exposures to galactic cosmic radiation, Earth's radiation belts, solar radiation, and reactor radiation. Galactic cosmic radiation is between 24 and 60 rem/year. Solar flares are stochastic short duration events with potentially high doses (>120 rem); the crew can be protected by a storm shelter for the limited duration of the events. Earth belt radiation is minimized by limiting the amount of time spent there. The radiation to the crew from a NTP reactor is reduced by spacecraft geometry, local reactor shielding, hydrogen tanks and spacecraft shielding to levels of about one rem. For a typical NTP Mars trip (see Table 6), the radiation exposure levels for the crew are about 45 rem, of which the reactor contributes less than 3%.

Criticality Prevention During Launch/Ascent Accidents And Population/Environment Protection

Requirements are for the system to remain subcritical for all credible launch/ascent accidents and to have no power operations until the system achieves its intended orbit or flight path trajectory. Design options include a built-in redundant shutdown subsystem with sufficient design



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

Figure 2. Flight Safety Review and Launch Approval Process for Space Nuclear Power Systems

margins in each system to ensure shutdown in case of a failure within either subsystem. NERVA was designed, in addition to its control drums, with neutron absorption wires in the core through the nozzle to further protect against launch criticality. Configurations can include in-core safety/shutdown rods or wires with locking devices and weak links.

TYPICAL MARS MISSION
(rem)

Galactic	34
Solar Flares (with storm shelter)	7.7
Earth Radiation Belts	1.5
Nuclear Rocket	< 1.1
Mars (30 Days)	≤ 1
Total	45.3

Table 6

Flight Operations Safety

A number of methods can be used to leave Earth orbit for Mars. For instance, perigee kicks upon leaving an Earth assembly orbit of about 500 km have safety advantages in that the spacecraft is placed in elliptical orbits with the perigee at the 500 km altitude. If a major accident occurred, the crew could be rescued at the perigee point without any engine burns. The initial orbit lifetimes will be on the order of 400 to 4000 days. After 400 days, the reactor radiation level is about 300 Curies and tissue dose about 15 mrem/s at 10 m. Once the Earth escape burns and other burns occur to put the spacecraft on a Mars encounter and return to Earth, propulsion will be needed to return the crew to Earth. At what point in the mission a postulated accident occurs will determine the type of safety actions to be taken. Very high (>0.995) reliable and redundant engines can provide the necessary insurance of safe crew return. On the return trip from Mars to Earth, the final Earth capture should use chemical propulsion or aerobraking, with the nuclear stage left in a much higher altitude. This avoids concerns about the high radiation levels that exist in the reactor on return to Earth of about 1,000,000 Curies. After 400 days for orbital decay, the radiation levels will still be about 70,000 Curies.

Plans To Clean Up Contaminated Land Areas

If radioactive debris is deposited on land areas, it will be necessary to remove the material to designated storage sites. The approach here is mainly a preventative one. If an abort occurs near the beginning of the mission, the vehicle will likely land in the Atlantic Ocean. Based on Titan and Shuttle data, one failure in 57 flights of the solid rockets has occurred; however, no land impacts have occurred on other continents. The footprint from aborts later in the flight profile can be controlled by command destruct mechanisms to cause debris to fall into an ocean. Also, the reactor contains no radioactive fission products at launch. In the unlikely event of land debris impact, standard clean up organizations and mechanisms are in place, such as the NEST Team (Nuclear Emergency Support Team).

Operation Below "Nuclear Safe Orbit" or Sufficiently High Orbit"

Nuclear Safe Orbit (NSO) or Sufficiently High Orbit (SHO) refers to the acceptable reactor storage location after use. The latter term, SHO, is now preferred. It means an orbital lifetime long enough to allow for sufficient decay of the fission products to approximate the activity of the actinides before reentry occurs. A SHO is a function of the vehicle and operating geometry of the vehicle and operating history. Figure 3 shows the orbital decay time as a function of altitude in terms of mass, drag coefficient, and cross sectional area. Typically, an orbital lifetime of 300 years has been used as the time for the radioactive materials from nuclear power plants to decay to safe radioactive levels. This corresponds to an orbital altitude above 750-900 km.

One design option is to initiate operations above the SHO for a given mission. However, for Mars missions and many others, it will be highly desirable to start below SHO (See Figure 4, based on scaling from Titan IV characteristics). For these missions, provision can be made for on-board or external boost systems. Nuclear thermal propulsion stages can be throttled to ensure that the thrust vector is in an increasingly safe direction before accelerating to full propulsion power. Thrust alignment is critical to the success of planetary missions, and success is well demonstrated in planetary flyby missions.

On-board boost devices have generally been used to boost low altitude satellites

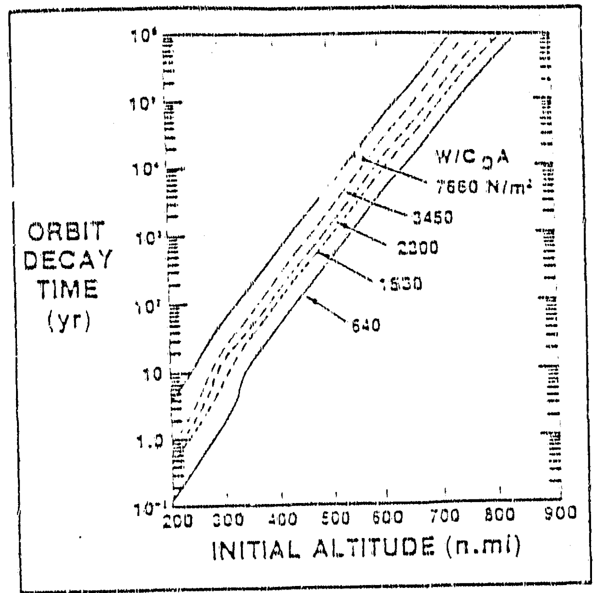


Figure 3. Orbital Decay Times

to higher orbits. This approach has been demonstrated on the USSR RORSAT satellites. However, these sometimes fail. An external capability is being evaluated under a project called SIREN (Search, Intercept, Recover, Expulsion Nuclear) for boosting radioactive materials to higher orbits.[12]

Near-Earth Space Contamination

The requirements include no significant additions of radioactive or non-nuclear toxic materials to the near Earth environment and protection of the crew from exposures that exceed safety limits. During flight operations, insignificant amounts of fission products are expected to be released. These should mostly be in the form of the fission gases. As part of the flight environmental impact statement, an assessment must establish acceptable fission gas release levels. If a sensitive environmental area is being traversed, power and temperature can be reduced to maintain releases to background levels.

Effects On Other Satellites and Experiments

It will be necessary to avoid/minimize effects on other satellites. This can be accomplished as part of particular mission planning. Operations should generally be well away from other satellites; the radiation level exposures at other Earth satellites are a function of

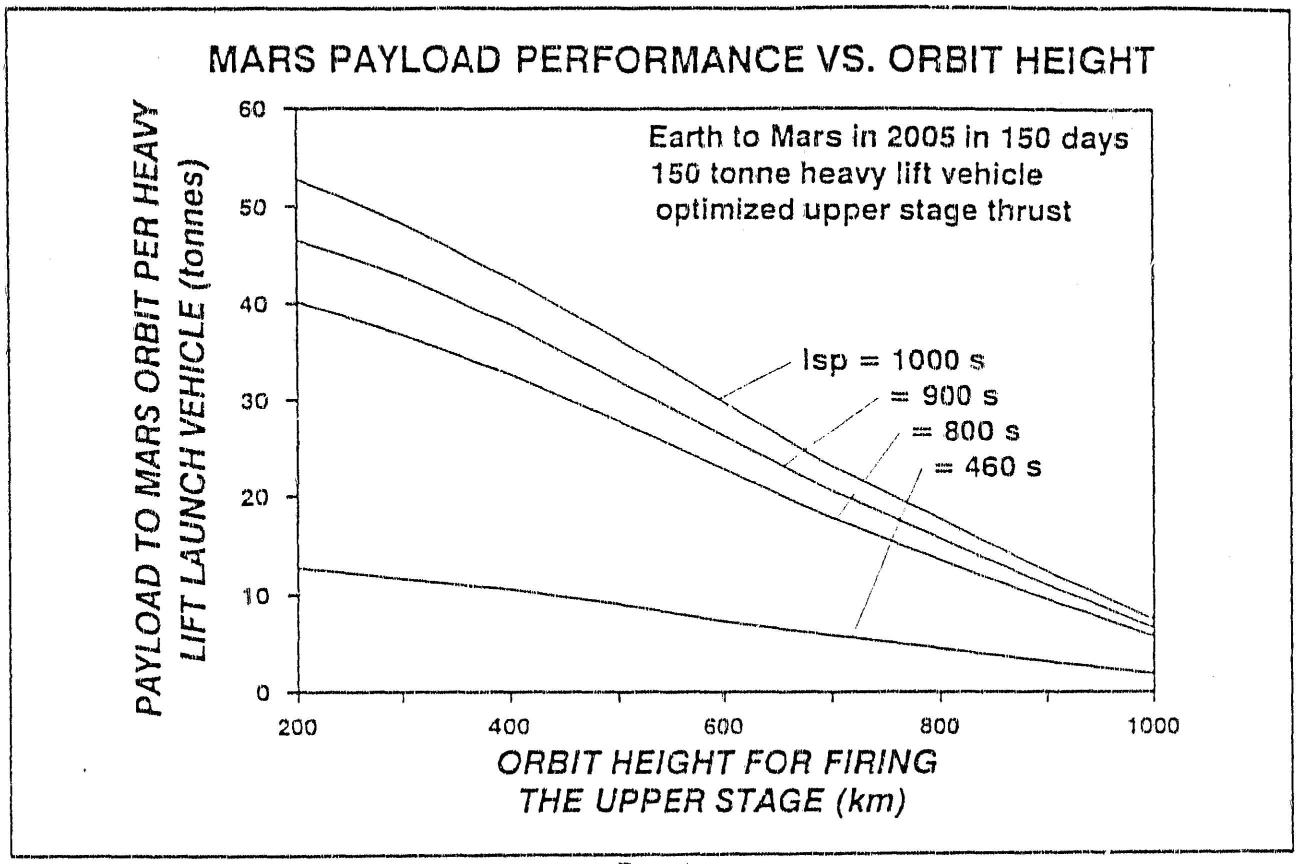


Figure 4.

distance, power level and duration. These should be negligible just from the desire to avoid collisions; however, power can temporarily be reduced if necessary in the vicinity of other satellites. During the limited operating time while leaving the vicinity of Earth (about 90 minutes), radiation sensitive sensors on other satellites will probably record the nuclear radiation from the reactor.

Final Disposal of Nuclear Engines/ Prevention Of Nuclear Rocket Earth Impact

Final disposal of nuclear engines must be such that there is negligible probability of intersecting the Earth or passing within the vicinity of the Earth. From Mars, since NTR re-use is not planned by the Synthesis Group, it will be placed in a deep space orbit that will not intersect the Earth. The NTR stage can be ejected after the Mars burn or mid course correction used to return the manned spacecraft to Earth; not used in spacecraft Earth capture or achieving Earth orbit. From the Moon, if re-use is not planned, it will also be placed in a deep space disposal orbit. For a nuclear tug, it will eventually be disposed of either above a Sufficiently High Orbit or in deep space, not back to Earth.

The principal safety issues in final disposal are long-term orbit contamination and random reentry into the biosphere. If the rocket is returned to below a sufficiently high orbit, a suggested approach is to use the space infrastructure and attach booster rockets to move the spent reactors to a permanent disposal site.[13] Multiple boost attempts can be made, if necessary, until success is achieved. Operated space reactors should probably never be returned to Earth, in order to minimize risk to the Earth's population.

V. Summary

In summary, nuclear thermal propulsion can be designed to operate safely if safety standards are defined at the initiation of any nuclear thermal propulsion program and continuously monitored for compliance. Techniques, such as failure modes and effects analysis and fault tree analysis exist to systematically assess safety issues. Design and operational solutions to meet these standards have been addressed in previous programs, such as NERVA. The solutions depend on particular concepts and their intended missions. However, after reviewing a wide range of questions related to safety, all questions could be answered by practical design/operational solutions.

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