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SAFETY QUESTIONS RELEVANT TO NUCLEAR THERMAL PROPULSION EGG-M--91517

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## SAFETY QUESTIONS RELEVANT TO NUCLEAR THERMAL PROPULSION

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### Abstract

Nuclear propulsion is necessary for successful Mars exploration to enhance crew safety and reduce mission costs. Safety concerns are considered by some to be an impediment to the use of nuclear thermal rockets for these missions. Therefore, an assessment was made of the various types of possible accident conditions that might occur and whether design or operational solutions exist. With the previous work on the NERVA nuclear rocket, most of the issues have been addressed in some detail. Thus, a large data base exist to use in an assessment. The assessment includes evaluating both ground, launch, space operations and disposal conditions. The conclusion is that design and operational solutions do exist for the safe use of nuclear thermal rockets and that both the environment and crews can be protected against harmful radiation. Further, it is concluded that the use of nuclear thermal propulsion will reduce the radiation and mission risks to the Mars crews.

### INTRODUCTION

Nuclear thermal propulsion (NTP) is critical for successful human Mars exploration (Synthesis Group Report, 1991). The safety of the crew is greatly enhanced by shorter trip times. This has the affect 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. The nuclear thermal propulsion rocket engine has many fewer moving parts than chemical rockets which it replaces and should, therefore, be more reliable. There is no need for a chemical rocket 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 two to three times better performance than chemical rockets, less or no assembly is needed in Earth orbit. This makes the spacecraft more reliable, less costly and easier to meet schedule. In fact, the mass in low Earth orbit will be one-third to one-half of a chemical rocket mission configuration.

### SAFETY QUESTIONS

A series of questions relevant to the use of nuclear thermal rockets is postulated in order to evaluate accident conditions. These cover ground, launch and space operations (See Table 1) and were designed to encompass the full range of accident conditions that a NTP will need to address to demonstrate safe operations. No particular rocket engine configuration is used as a model. Thus, the assessment is to determine whether generic design solutions exist. 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.

The questions related to safe ground operations in Table 1 will now be addressed.

TABLE 1.

Safety Questions Relevant to Nuclear Propulsion

<u>Ground Operations</u>
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?
<ul style="list-style-type: none"> <li>- Fires</li> <li>- Explosions</li> </ul>
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?
<u>Launch and Space Operations</u>
How safe is the crew from reactor radiation?
How will inadvertent criticality be prevented for launch/ascent accidents?
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 reentry of a radioactive core be averted?
How is a "Nuclear Safe Orbit" determined?
Will nuclear engines release radioactive materials which contaminates 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?

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

To meet environmental safety standards, radioactive material removal scrubbers will probably be needed to remove fission gases from the engine hydrogen exhaust and to catch any radioactive material releases. The basic technology has been demonstrated during Nuclear Furnace-1 testing in 1972 (see Figure 1). In addition, a scenario worst 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 that the reactor chemically exploded without significant nuclear contamination.

#### Special Precautions Needed At The Launch Pad

The requirement is to maintain the radiation dose levels below established health standards. Design options include not operating the reactor prior to launch (a zero power reactor test can be performed to verify the reactor physical assembly is correct). Acceptance testing at the launch facility will be needed

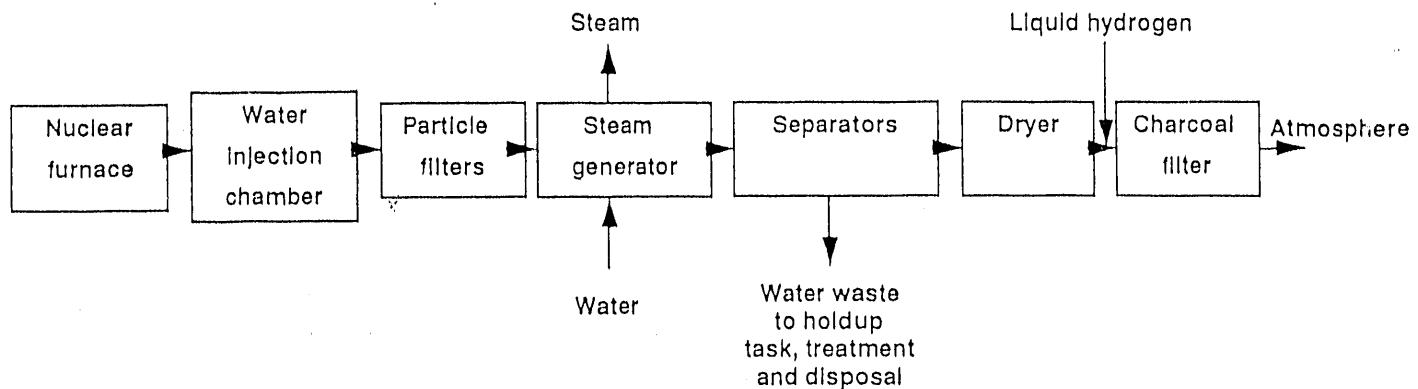


FIGURE 1. Nuclear Furnace Scrubber Concept

to ensure that all components are functional prior to mating with the launch vehicle. This could include cold flow testing; that is, testing where hydrogen is run through the engine for short periods of time to demonstrate that all valves and the turbopump are operational while maintaining the reactor shutdown.

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 exist to avoid transportation criticality accidents.

#### Launch Site Contamination Accidents--Fires

The primary requirement is to maintain the reactor subcritical without releases of hazardous radiation or radioactive materials during a fire. 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 along side of them.

A series of propellant fire tests were performed as part of a project called Pyro to investigate the temperatures and duration of liquid propellant fires (Project Pyro, 1968). 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 also indicate that melting is insufficient to cause a critical mass.

Solid propellant test show that they burn at approximately 3000 K, with some chunks burning for up to 10 minutes. Again, the fuel melting temperatures are above the fire temperature. Using evaluations of the Lincoln Laboratory Experimental satellites LES 8/9 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 affects 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

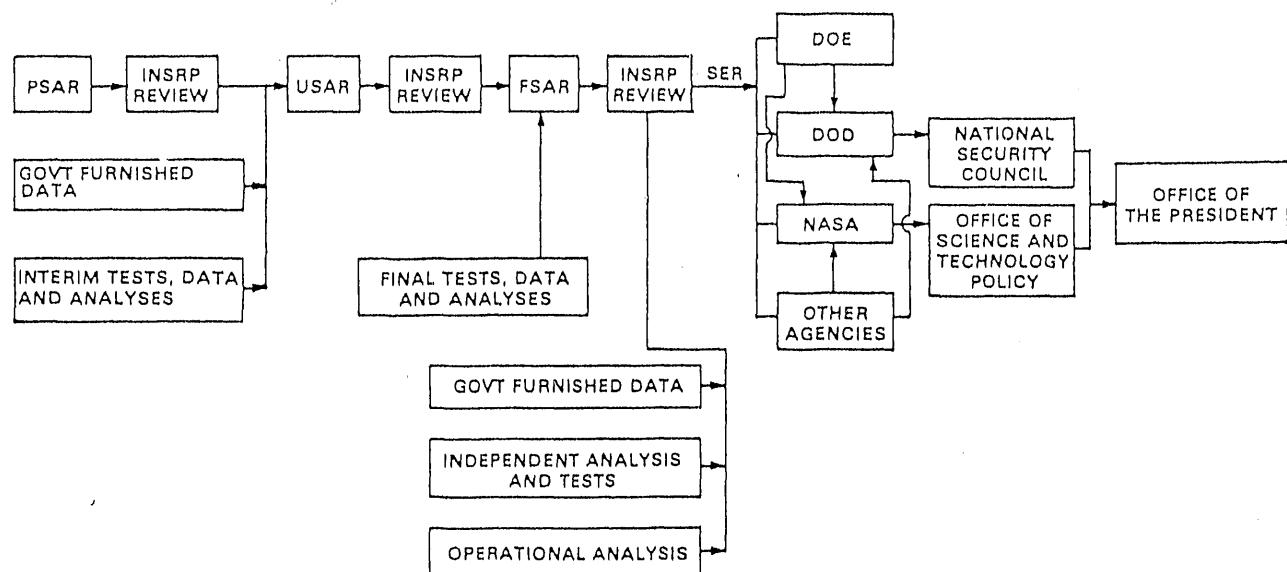
radiological risk from an explosion is projected. A major safety analytical and experimental program has shown that radioisotope generators are safe to launch (Bennett, 1990); NTPs, with their geometry and non-radioactive materials at launch, should be even less risk at launch.

#### Ground Nuclear Waste

The requirement is 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, measured in hours. Reprocessing of the fuel and burning the actinides can minimize/eliminate nuclear waste. This was demonstrated when NERVA fuel was reprocessed and reused.

#### 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 (Sholtis and Nelson, 1990). The Panel provides the necessary independent risk evaluation that will be used by decision makers who must weigh the benefits of the mission against the potential risks. The agency



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

wanting to fly a nuclear powered payload than requests permission for flight to the Office of Science and Technology (OSTP). OSTP reviews the request and makes the launch decision; however, the Executive Office of the President makes the final decision if OSTP feels that is appropriate.

Turning now to launch and space operations, the questions in Table 1 will be addressed.

#### Crew Safety From Reactor Radiation

NASA crew dose guidelines for astronauts is 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 continuous 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's 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 2, the radiation exposure levels for the crew is about 45 rem, of which the reactor contributes less than 3%.

#### Criticality Prevention During Launch/Ascent Accidents

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 subsystems with sufficient design 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. Command destruction of the reactor can be provided to ensure that debris from an accident terminates in an ocean.

#### 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 have 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 Search Team).

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

Nuclear Safe Orbit (NSO) or Sufficiently High Orbit (SHO) refers to the acceptable reactor space storage location after use. The latter term, SHO, is now preferred. It means an orbital lifetime long enough to allow for sufficient

TABLE 2. Typical Mars Mission

Typical Mars Mission	
	(rem)
Galactic	34
Solar flares	7.7
(with storm shelter)	
Earth radiation	
belts	1.5
Nuclear rocket	<1.1
Mars (30 days)	<1
Total	45.3

decay of the fission products to approximately the activity of the actinides before reentry occurs. 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. 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. The stage can be slowly rotated to average the thrust direction to safeguard against thrust nozzle misalignment failures. If fission gas retention is a problem at the higher temperatures, and correspondent higher rocket performance, the temperature can be reduced until the altitude is such that the fission gases are no longer a problem.

On-board devices have generally been used to boost low altitude satellites 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 (Lee, 1990).

#### Determination of "Nuclear Safe Orbit"

A NSO is a function of the 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 a orbital altitude above 400-500 nmi.

#### Near-Earth Space Contamination

The requirements include no significant additions of radioactive materials to the near Earth environment and protection of crews 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 will need to 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.

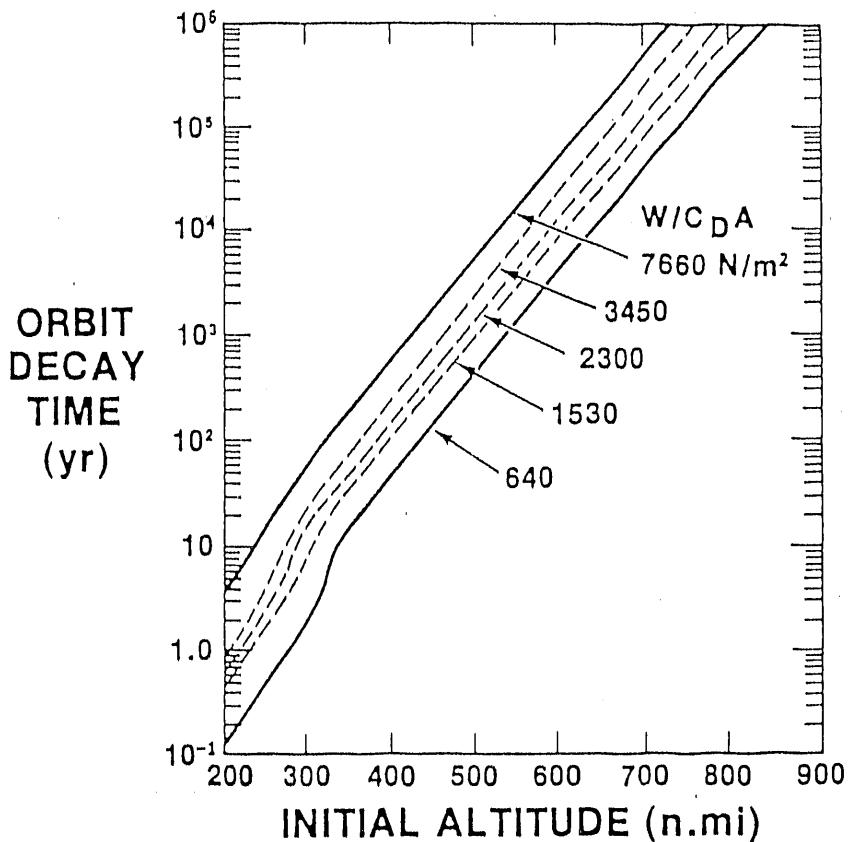


FIGURE 3. Orbital Decay Times

### Affects On Other Satellites and Experiments

It will be necessary to avoid/minimize affects 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 is a function of distance, power level and duration. Just from the desire to avoid collisions these should be negligible; 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 or passing within the close proximity of Earth. From Mars, since NTR reuse 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; the NTR is not planned to be used in spacecraft Earth capture or achieving Earth orbit. From the Moon, if reuse is not planned, the NTR can easily 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.

### CONCLUSIONS

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. 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, there were no questions that did not appear to have practical design/operational solutions.

### Acknowledgments

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