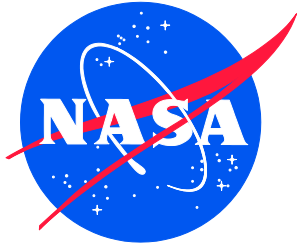


NASA/CR-2019-220397



# Fission Reactor Inadvertent Reentry

## *A Report to the Nuclear Power & Propulsion Technical Discipline Team*

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August 2019

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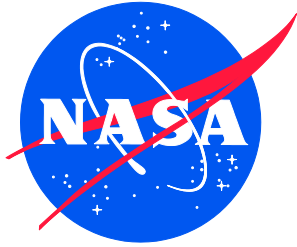
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Space Administration

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Prepared for Langley Research Center  
under Contract 80LARC17C0003

August 2019

## **Acknowledgments**

This study was chartered by NASA's Nuclear Power & Propulsion Technical Discipline Team (TDT) led by Lee Mason and Mike Houts. The Nuclear Power & Propulsion TDT governance resides under the NASA Office of Chief Engineer with oversight by the NASA Engineering Safety Center (NESC) Power Technical Fellow (Chris Iannello) and Propulsion Technical Fellow (Daniel Dorney). The study team would like to thank them along with the other members of the TDT for their guidance and feedback during this effort.

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## Table of Contents

<b>1.0</b>	<b>Introduction and Purpose .....</b>	<b>1</b>
<b>2.0</b>	<b>Types of Inadvertent Reentry Events.....</b>	<b>1</b>
2.1	Accidental Reentry During Ascent to Orbit.....	1
2.2	Accidental Reentry from Low Earth Orbit .....	2
2.3	Accidental Reentry from Mid and High Earth Orbits.....	2
2.4	During an Accidental Flyby Reentry or a Long-Term Reentry due to Failure .....	2
2.5	During a Direct Return-to-Earth Scenario .....	2
<b>3.0</b>	<b>Possible Reentry Outcomes.....</b>	<b>2</b>
3.1	Burnup in the Atmosphere .....	3
3.2	Intact Impact .....	3
3.3	Scattered Impact .....	3
<b>4.0</b>	<b>Potential Radiological Consequences for Reentry Outcomes .....</b>	<b>3</b>
4.1	Burnup in the Atmosphere .....	3
4.2	Intact Reentry.....	4
4.3	Scattered Reentry .....	5
<b>5.0</b>	<b>Security Implications and International Treaties and Resolutions.....</b>	<b>6</b>
<b>6.0</b>	<b>Previous Approaches to Reentry .....</b>	<b>7</b>
<b>7.0</b>	<b>Possible Safety Requirements for Reentry .....</b>	<b>9</b>
7.1	General Design Criteria .....	9
7.2	Risk Criteria.....	10
7.2.1	Likelihood of Inadvertent Reentry .....	10
7.2.2	Consequences of Inadvertent Reentry .....	11
7.2.3	Considerations for Mission Types .....	12
7.2.4	Risk Analysis Issues .....	13
<b>8.0</b>	<b>Mission Implications.....</b>	<b>14</b>
8.1	Requirement for Intact Reentry or Complete Burnup.....	14
8.2	Requirements for Low Probability of Reentry on Land .....	14
8.3	Requirements for Reduced Consequences.....	15
<b>9.0</b>	<b>Conclusions.....</b>	<b>15</b>
<b>10.0</b>	<b>References.....</b>	<b>16</b>

## Acronyms

Ci	Curies
EOL	End-of-Life
GDC	General Design Criteria
GEO	Geostationary Orbit
HEO	High Earth Orbit
HEU	High Enriched Uranium
LEO	Low Earth Orbit
LEU	Low Enriched Uranium
MEO	Medium Earth Orbit
NaK	Sodium-Potassium
NERVA	Nuclear Engine for Rocket Vehicle Application
NRC	Nuclear Regulatory Commission
NTP	Nuclear Thermal Propulsion
OSTP	Office of Science and Technology Policy
RORSAT	Radar Ocean Reconnaissance Satellite
SNAP	Systems for Nuclear Auxiliary Power
SP	Space Reactor Prototype
U.S.	United States
UN	United Nations
UO <sub>2</sub>	Uranium Dioxide Nuclear Fuel

## **1.0 Introduction and Purpose**

The Nuclear Power and Propulsion Technical Discipline Team has directed an effort to consider possible improvements to the launch approval process as it relates to fission reactors. To that end, Reference 1 described possible general design criteria and risk criteria for fission reactors. At the time that Reference 1 was completed, it was felt that additional examination of reentry issues was warranted. This paper presents the next step in that examination, which is to accurately describe and frame the problem and suggest safety criteria that might apply to inadvertent reentry. The report includes a discussion of the issues associated with different types of inadvertent reentry, the possible consequences of those events, a review of previous work in the area, security and nonproliferation issues, and options for safety requirements that might be considered. Note that safety requirements can have significant mission implications, e.g., no operation below a certain orbit.

## **2.0 Types of Inadvertent Reentry Events**

There are a number of types of reentry events that can potentially occur with missions containing fission reactors. Each type of reentry event can produce a variety of possible adverse environments for the fission reactor.

### **2.1 Accidental Reentry During Ascent to Orbit**

During ascent to orbit, a number of complex configurations and events are possible, and it is difficult to completely characterize all of the possibilities. First, the spacecraft configuration is important. The spacecraft containing the fission reactor is attached to all or part of the launch vehicle, depending on which stages have been expended. The spacecraft may or may not still be encapsulated in the launch vehicle fairing depending on when the potential accident occurs. In addition, if the launch vehicle has a destruct mechanism, it may or may not be disabled depending on the system and when the potential accident occurs. These factors all play a role in defining the potential environments the fission reactor may experience.

When an accident occurs, a number of physical phenomena may occur. The fission reactor may experience overpressures from bursting pressurant tanks, destruct mechanisms, and solid and/or liquid propellant explosions in-air. In addition, there may be launch vehicle and spacecraft components or fragments impacting the fission reactor. It may also experience some adverse thermal environment due to the propellant fires. The design and initial configuration of the fission reactor and these potential environments insulating the spacecraft and fission reactor would determine the configuration during reentry.

As reentry progresses, the spacecraft and/or fission reactor would experience aerothermal and aerodynamic loads. The reentry body's shape, mass, aerodynamic properties, tumble rate, altitude, latitude, longitude, azimuth, velocity and flight path angle, as well as the atmospheric properties would determine the amount of aerothermal and aerodynamic loading. The reentry configuration of the spacecraft and the design of the fission reactor will determine the impact of these externally imposed loads. Depending on the severity of these loads and the ability of the reentry structure to withstand them, there is a potential for the reentry body (e.g., spacecraft or fission reactor) to break apart further or ablate/burnup prior to impacting the ground. In addition, the reentry loads can potentially cause energetic material (e.g., fuel and pressurant tanks) to explode, burn, or become projectiles, which may impact the fission reactor.

## **2.2 Accidental Reentry from Low Earth Orbit**

By the time the spacecraft reaches low Earth orbit (LEO), the spacecraft containing the fission reactor would only be attached to the launch vehicle's upper stage(s). The spacecraft would reach LEO at a velocity around 7.8 km/s. Depending on the type of accident, the spacecraft and/or fission reactor may experience blast, fragment and thermal environments described above for the ascent phase. The response of the spacecraft and/or fission reactor to the accident environments would determine its configuration at reentry. Similar to the suborbital case described above, the reentry from LEO would experience aerothermal and aerodynamic loads.

## **2.3 Accidental Reentry from Mid and High Earth Orbits**

The main difference between a reentry from LEO and mid to high Earth orbits is that the initial reentry velocity would be greater for the mid and high Earth orbits. These higher velocities may increase the likelihood of breakup, and possibly burnup, during reentry. Note, that orbits at the Lagrange points or cislunar would fall under this category.

## **2.4 During an Accidental Flyby Reentry or a Long-Term Reentry due to Failure**

For certain missions, such as Cassini, the Earth is used to provide a gravity assist during a flyby maneuver. If a navigation error or other unexpected perturbation causes the spacecraft to deviate from its intended trajectory, it could impact the Earth. Long-term reentries can occur due to events that place the spacecraft in an orbit that may intersect the Earth at a later time. These reentries can occur due to failures that occur far from Earth. For example, a failed burn during a flyby or en route to another planet or a failure to achieve orbit at a distant planet may yield an Earth-intersecting orbit. In these cases, the spacecraft would most likely not be attached to any part of the launch vehicle. For these potential reentry scenarios, the spacecraft velocity would be greater than 11 km/s and the spacecraft and reactor would most likely reenter at a steep flight path angle.

## **2.5 During a Direct Return-to-Earth Scenario**

The direct return-to-Earth scenarios of most interest are ones involving reusable nuclear propulsion systems where the reactor enters Earth orbit at some altitude, drops off and/or takes on cargo, and then returns to the Moon or Mars. For these scenarios, depending on where the spacecraft is inserted into orbit, it would either be similar to an accidental reentry from LEO or an accidental reentry from mid or high Earth orbit defined in Sections 2.2 and 2.3, respectively, with the exception that the spacecraft would most likely not be attached to the launch vehicle (at least the first stage) but may be attached to a cargo module. If the spacecraft fails to achieve orbit and heads directly into Earth at high velocity, then it can be treated as an accidental Flyby Reentry. In all these cases, the nuclear system will have been operated and therefore, will have accumulated fission products that represent a potential radiation hazard.

## **3.0 Possible Reentry Outcomes**

There are three potential outcomes for a fission reactor in a reentry scenario. First, the fission reactor can burnup in the atmosphere due to the aerothermal loads imparted to it during reentry. Second, it can survive the reentry and impact the Earth's surface with or without additional spacecraft components. Finally, it can break apart during reentry, but its various components survive reentry and impact the Earth's surface (a scattered reentry).



### **3.1 Burnup in the Atmosphere**

If the aerothermal loading on the fission reactor during reentry is great enough to ablate and/or vaporize its components, the fission reactor's material would be disbursed throughout the atmosphere. This outcome will minimize the radiation exposure to individuals given the small amounts of material disbursed across a very large surface area. Because fission reactors are designed to utilize materials capable of sustained operation at high temperatures, it would be difficult to verify that the system would sufficiently breakup and vaporize without special design features that would facilitate high-altitude dispersal of the reactor's components, e.g., a destruct mechanism might be deployed for that purpose.

### **3.2 Intact Impact**

If the aerothermal and aerodynamic loads on the fission reactor are not sufficient to completely burn or break it up, then the fission reactor, or at least some of its components, will impact the Earth's surface. In addition, if the aerothermal and aerodynamic loads are not sufficient to break apart the fission reactor from the spacecraft, then the fission reactor would impact the Earth's surface along with the spacecraft and possibly parts of the launch vehicle. The additional structure(s) at impact may alleviate some of the stresses of impact or more likely provide additional dense material that can insult and put more stress on the fission reactor at impact. In addition, if any high-energy material (e.g., pressurant and fuel tanks) survived reentry and impacted the Earth's surface with the fission reactor, the fission reactor may experience additional overpressures, fragment insults and adverse thermal environments.

A completely intact reactor impact is the only scenario that can result in a reactor going critical and generating fission products, either because it was critical during reentry or because criticality occurred as a result of the impact. Without criticality, radiological impacts are limited to those from the fission products present in the reactor from previous operation in space.

### **3.3 Scattered Impact**

A scattered impact of a reactor is similar to a completely intact reactor impact except that the fission reactor breaks up during reentry, and the individual parts would each separately impact the Earth's surface. The separate parts would most likely impact within a wide range of area and not at the same location, thus making criticality impossible. In addition, it is less likely that the spacecraft or launch vehicle components would remain attached to the fission reactor's components.

## **4.0 Potential Radiological Consequences for Reentry Outcomes**

### **4.1 Burnup in the Atmosphere**

The complete burnup of the reactor in the upper atmosphere (above 15 km) will have low individual consequences for any individual person on the Earth. This is why early space reactor missions (such as Systems for Nuclear Auxiliary Power (SNAP)-10A)<sup>2</sup> strived to achieve complete burnup of the reactor in the upper atmosphere. As discussed later, the difficulty in demonstrating full burnup led some later missions to switch to intact reentry strategies. However, complete burnup will yield low consequences if it can be achieved.

The most thorough work on radiological doses in the upper atmosphere was done by B. W. Bartram of NUS corporation in the 1970s and 1980s. Bartram performed a very detailed analysis of worldwide dispersion of aerosols and vapors into the upper atmosphere.<sup>3</sup> The model could

track the deposition of material as a function of atmospheric processes. Dose models included multiple pathways for exposure and included inhalation, immersion, cloud/ground shine and ingestion (including aquatic ingestion). The models could even predict doses to a particular area depending on reentry parameters.

Material dispersed in the upper atmosphere becomes very diluted. This is largely due to upper atmospheric air currents that carry the material around the globe and can keep it suspended for years. Bartram<sup>4</sup> has calculated typical atmospheric dispersion coefficients for the mesosphere and stratosphere (the stratosphere begins at ~15 km up). Upper-atmosphere dispersion will cause 6 to 8 orders of magnitude more dilution (meaning 6 to 8 orders lower dose) than wind dispersion seen at or near ground level. As an example, upper atmospheric dispersion coefficients are on the order of  $1.E-12$  s/m<sup>3</sup> (a very low value indicating large amounts of dilution) as compared to a ground level 1-km dispersion coefficient of  $\sim 1E-4$  s/m<sup>3</sup> (a much higher value indicating less dilution). Atmospheric dispersion coefficients are multiplied by the source term (along with other factors) to arrive at the potential dose to an individual.

Given the level of dispersion in the upper atmosphere, the dose to any specific individual is very low. For a cold reactor the dose to an individual would be many orders of magnitude less than a millirem. This value is sufficiently low that it can be safely ignored for the launch accident analysis as with other accidents involving non-operated (cold) reactors described in Reference 1.

For a previously operated (hot) reactor with a large fission product inventory, the doses will still be very low, but considerably higher than for a cold reactor. Bartram<sup>2</sup> calculates maximum doses to an individual in the millirem range for a 1-MW thermal reactor with a 10-year space mission and 1-year cool-down period after shutdown prior to reentry. This dose is high enough to produce statistical cancers using a linear no-threshold approach that includes the population of the Earth. However, the cancer probability to a single individual would still be far less than  $1.E-6$ ; and as noted in Reference 1, the International Commission on Radiological Protection has stated that collective doses are inappropriate to use in risk calculations and that calculating the number of cancer deaths from trivial individual doses (i.e., applying a very small risk to a very large population) should be avoided.

## **4.2 Intact Reentry**

Intact re-entry is assumed to occur if an engineering solution (such as an aeroshell containing the reactor or other spacecraft design features) is used to keep the reactor core and associated structure in its original configuration. If the impact occurs on land, there is the potential for radiation doses to the public. If the impact occurs in the ocean, doses are effectively zero, as a few meters of water provides sufficient shielding. Recovery in the ocean may be very difficult, but the public risk is effectively eliminated. Therefore, the discussions below apply to land impacts.

Intact reentry has been shown to minimize the radiation threat, compared to a scattered reentry. Quoting from a summary of SP-100 (space reactor prototype) safety issues “One large source cannot seriously affect nearly as many people because it is impossible for as many people to be in the proximity of one radiation source as can be in the proximity of hundreds of sources.”<sup>5</sup> For the SP-100 program, after complete burnup in the upper atmosphere was abandoned as a safety strategy, intact re-entry became the preferred approach. Other benefits of intact reentry included controlling the exposure time for one source over multiple sources and the possibility that a single large source could embed deeper into the ground, thereby providing some shielding.

For a cold reactor, intact reentry will not be an issue unless the reactor goes critical. It does not provide any significant direct radiation dose, nor would dispersal from impact cause any serious dose. A cold reactor that goes critical upon impact will yield low doses similar to those already discussed in Reference 1 for launch phase accidents.

Hot reactor reentry for an intact reactor could have serious radiation impacts to the public. This dose can come from three sources. First, there will be a dose from direct gamma radiation from the fission products in the reactor core. Second, there may be a dose from fission products released due to impact. The impact velocity and system design will affect such releases. Finally, there may be a dose from fission products released due to a criticality excursion that destroys the reactor. Such a criticality may be unlikely due to breakup of the reactor upon impact but should be considered.

Direct gamma radiation dose from the reentry of a reactor was examined extensively for the SP-100 program. Calculations<sup>6</sup> of direct radiation dose from an unshielded SP-100 reactor with zero decay time after space operation that lands without being buried varied from 80 rem/hr at 100 m to ~800,000 rem/hr at 1 m (Note, direct doses are calculated to within a few hundred meters because obstacles in the line of site typically prevent doses to an individual beyond this distance.) The same reactor core with 1 year of decay prior to reentry had a direct radiation dose of 20 mrem/hr at 100 m to 180 rem/hr at 1 m. Without sufficient decay time, the hot reentry of a space reactor to the Earth could be lethal for individuals near the reactor (within tens of meters, depending on the size of the reactor). A reactor that buries itself into the ground upon reentry helps reduce the dose, but doses near the reactor can still be lethal. Limiting doses to the public is directly related to the ability to quickly control public access to the crash site.

Public dose from the impact of an intact reactor with the impact causing dispersion of reactor core fission products or the dose caused by the impact of an intact reactor causing a criticality excursion that destroys the reactor can produce doses to the public in the millirem to hundreds of rem range. Studies of fission product inventory for SP-100 produced a maximum peak inventory of 4.E7 curies after 7 years of operation.<sup>7</sup> Estimates of fission product inventory for the Rover/Nuclear Engine for Rocket Vehicle Application (NERVA) nuclear thermal rocket program predicted a maximum peak inventory at 1.E9 curies.<sup>8</sup> Estimates for burst excursion for a small Kilowatt space reactor predict a maximum peak inventory 1.E7 curies assuming a 5.E18 fissions event.<sup>9</sup> With 1 day of decay, most fission product inventories will drop ~2 to 3 orders of magnitude, within 1 year they drop ~5 orders of magnitude, reaching a final long-term fission product inventory of actinides in several hundred years that is ~6 orders of magnitude lower than the peak. The dose from the dispersion of the fission products will vary depending on three factors: 1) how long the reactor has been shut down prior to reentry, 2) the thermal power of the reactor, and 3) whether the reactor goes critical upon impact. However, it can be anticipated that the dose at 1 m will be in the rem to hundreds of rem range. The dose at 1 km will be in the millirem to 10s of rem range for most dispersal accidents. These doses are high enough that the reentry of a hot reactor should be avoided.

### **4.3 Scattered Reentry**

The radiological consequences for scattered reentry of a hot reactor will not be significantly different from that for intact reentry, except that scattered reentry will have the ability to impact a greater number of people and a much larger area. The reentry of Cosmos 954 scattered debris over a wide area.<sup>10</sup> The total area searched for reentry debris was about 124,000 square

kilometers. Scattered reentry, such as occurred with Cosmos 954, will make it more difficult to control access to the crash site. Even relatively small pieces of a hot reactor can lead to elevated doses in the immediate vicinity. Scattered reentry is considered the least desirable outcome for a reentry event.

## **5.0 Security Implications and International Treaties and Resolutions**

The security implications of an inadvertent reactor reentry are driven primarily by the form of the reactor fuel. The Department of Energy identifies four categories of material based on the nature and quantity of material.<sup>11</sup> The most sensitive material is Category I and includes materials that might be used directly in a nuclear weapon, such as highly enriched U-235 or Pu-239. Category IV material is of little concern from a security and nonproliferation standpoint and includes, for example, U-235 enriched to less than 20%. Category I materials, and to a lesser extent Category II and III materials, need to be secured as quickly as possible should an intact or scattered inadvertent reentry occur. For these materials, contingency plans will be needed for fuel recovery, noting that this may be very difficult for a scattered recovery or if the reentry occurs over the ocean. There are approximately seven nuclear submarines, U.S. and Russian, that were sunk without recovering the reactors due to the difficulty of the recovery or the depth of the site. Note that when the material is highly irradiated due to space operation, it may change to Category IV even with HEU (highly enriched uranium) fuel, but will still likely require recovery as soon as possible. Also, a highly irradiated core may revert to a more stringent safeguards category over time as the fission products decay.

There is very limited guidance regarding reentry in international treaties and agreements. The Outer Space Treaty, Article VII, indicates that a launching nation is liable for damages to other nations:<sup>12</sup>

“Each State Party to the Treaty that launches or procures the launching of an object into outer space, including the Moon and other celestial bodies, and each State Party from whose territory or facility an object is launched, is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons by such object or its component parts on the Earth, in air space or in outer space, including the Moon and other celestial bodies.”

United Nations (UN) Resolution 47/68<sup>29</sup> provides more detail on the use of nuclear power in space; however, this resolution is nonbinding. Keeping in mind the nonbinding nature of the resolution, some of the pertinent parts are:

“...the use of nuclear power sources in outer space should be based on a thorough safety assessment, including probabilistic risk analysis, with particular emphasis on reducing the risk of accidental exposure of the public to harmful radiation or radioactive material...”

To limit exposure in accidents, the design and construction of the nuclear power source systems shall take into account relevant and generally accepted international radiological protection guidelines.

The probability of accidents with potentially serious radiological consequences referred to above shall be kept extremely small by virtue of the design of the system.

Systems important for safety shall be designed, constructed and operated in accordance with the general concept of defence-in-depth.

Nuclear reactors shall not be made critical before they have reached their operating orbit or interplanetary trajectory.

The design and construction of the nuclear reactor shall ensure that it can not become critical before reaching the operating orbit during all possible events, including rocket explosion, re-entry, impact on ground or water, submersion in water or water intruding into the core.

In order to reduce significantly the possibility of failures in satellites with nuclear reactors on board during operations in an orbit with a lifetime less than in the sufficiently high orbit (including operations for transfer into the sufficiently high orbit), there shall be a highly reliable operational system to ensure an effective and controlled disposal of the reactor.

Any State launching a space object with nuclear power sources on board shall in a timely fashion inform States concerned in the event this space object is malfunctioning with a risk of re-entry of radioactive materials to the Earth.

The launching State shall promptly offer and, if requested by the affected State, provide promptly the necessary assistance to eliminate actual and possible harmful effects, including assistance to identify the location of the area of impact of the nuclear power source on the Earth's surface, to detect the re-entered material and to carry out retrieval or clean-up Operations.”

The guidance from UN 47/68 presented above is subjective in nature and does not provide a basis for specific design measures or response procedures. In addition, the recommendations presented in Section 7 of this report will take a different view regarding criticality events that occur in the ocean.

## **6.0 Previous Approaches to Reentry**

A review of each of the previous space reactor reentry strategies is provided in Table 1. The key reentry issues for each program include <sup>13</sup>:

SNAP reactors: Designed for LEO and above. The criterion was established by the Aerospace Safety Program for dispersal upon reentry thereby ensuring no radiological impact on Earth and that the reactor would not go critical.<sup>2</sup> By the late 1960s, testing and analysis showed that the SNAP system would not reliably disperse and burnup upon reentry as initially planned. To maintain intrinsic water sub-criticality for launch accidents and post-operational reentry they investigated the use of spectrum-dependent thermal-resonance neutron absorbers in the fuel and core reflector interface.<sup>14</sup>

NERVA: The range of potential missions included LEO startup and therefore, the project was designing for both cold and hot reentry depending upon the specific mission profile. A definitive mission was never proposed, and the safety program never completed. The safety criteria intended to disperse the reactor upon reentry within the upper atmosphere and allow the fuel to burnup, but the results of testing and analysis showed that the fuel would not adequately burnup prior to reentering. Therefore, the designers devised active means to meet the safety criteria. This included the use of poison wires to prevent criticality<sup>15</sup> and active means of engine destruct as the high temperature refractory materials are inherently resistant to passive destruct upon reentry.<sup>16,17</sup> The flight reactors used 174 kgs of U-235 in the form of uranium-carbide in a graphite matrix, that made it difficult to separate the uranium out of the fuel matrix. The present

Nuclear Thermal Propulsion (NTP) program is proposing to use LEU (low enriched uranium) thereby minimizing nuclear security concerns in a reentry scenario.

Russian Buk: The Russian Buk reactor operated in LEO with end-of-life (EOL) boost to higher orbit (750 to 1000 km)<sup>18</sup>. Cosmos 954 failed to boost, reentered and scattered radioactive debris over northern Canada. The Russians modified the core design to ensure that the fuel would be ejected at EOL. The system operated as planned for Cosmos 1402 reentry. The design was further modified to engage an automatic boost of the reactor unit to higher orbit once atmospheric heating began. This system worked with the Cosmos 1900. For the reactors placed in the higher orbit after operation, the ejection of the Buk core resulted in the release of the sodium-potassium (NaK) coolant resulting in a marked increase in space debris.<sup>19</sup>

Russian Topaz II: The Topaz II was developed in the Soviet Union from around 1969 to 1989<sup>20</sup> and then the system was part of a U.S./Russian joint venture to test and flight test the system from 1991 to around 1994. The Topaz II was a single-cell thermionic reactor with 27 kgs of 96% enriched UO<sub>2</sub> fuel pellets. The system was designed for high orbit operation. Functional safety requirements for the Topaz II mission required that the reactor remain subcritical under launch accident conditions whereas analysis and testing showed that the reactor would go critical for different water and sand immersion scenarios.<sup>21</sup> Therefore, an anti-criticality device was designed to separate some of the fuel outside of the core until a safe operating orbit was achieved.<sup>22</sup> Pre-operational reentry analysis showed that some burnup would be achieved, but there was significant uncertainty as to how much, and whether the fuel pins and UO<sub>2</sub> fuel would be released or not. Analysis from both a safety and a safeguard perspective concluded that cold reentry accidents posed negligible radiological and only minor safeguards risk “regardless of whether the core impacts the earth and remains intact or if all or part of the core disassembles during reentry or upon impact.”<sup>23</sup> Therefore, the safety team opted not to place a functional safety requirement for cold reentry. Given the increased scrutiny in nuclear materials a partial burnup and dispersal of HEU may need to be reconsidered given today’s nuclear security environment.

SP-100: Designed for LEO, high Earth orbit (HEO), deep space, and extraterrestrial surface operations. Based upon lessons-learned from the SNAP reentry program, the SP-100 reactor subsystem was designed to ensure intact reentry of the reactor thereby allowing the retrieval of the HEU, ensuring the safety systems remain in place to maintain the reactor subcritical under all accident conditions, and if post-operational, ensure any radioactive material would remain localized.<sup>24</sup> Nuclear material safeguards were a major focus area of the SP-100 safety program.

Kilopower: Being designed for deep space and extraterrestrial surface missions. Safety and safeguards are currently being defined.

NTP: Being designed for interplanetary missions, especially for human transportation to Mars. The system would be operated for short periods during Earth departure, mid-course corrections and orbit arrival. If the system is designed for reusability, the stage may be returned to Earth with accumulated fission products, which may present a safety risk. The reactor is being designed with LEU and therefore has minimal safeguard concerns.

Based upon a review of the reentry strategies for past reactor programs, it is clear that burnup cannot be achieved without an active system such as the core pusher deployed by the Soviets on the Radar Ocean Reconnaissance Satellite (RORSAT) missions. Implementation of the core pusher resulted in the creation of a significant amount of space debris from the RORSAT

systems that were boosted into HEO and their cores were released resulting in an increase in space debris from the NaK coolant and fuel elements. It is unclear whether a high-temperature refractory nuclear rocket would burnup during reentry even if it were dispersed prior to reentry. The SP-100 program proposed the use of a reentry shield to ensure the reactor remained intact and could be retrieved, but this increased the overall system mass, added mission/operational complexities, and presented challenges relative to verifying the long-term integrity of the structure. The primary lesson learned is that reentry strategies require an integrated plan that includes consideration of the planned mission and operating space, accidental criticality, reentry exposure, and nuclear material security.

Table 1: Overview of power, mission operating space, and proposed reentry strategy.<sup>1</sup>

<b>Program</b>	<b>Power</b>	<b>Proposed Mission Operation</b>	<b>Reentry</b>
SNAP	0.5 to 350 kWe	LEO or geostationary orbit (GEO), planetary, or deep space operation.	Hot reentry considered plausible for some missions: boost to higher orbit, high altitude burnup or intact reentry. <sup>25</sup>
Rover		LEO or Earth-flyby operation. High orbit disposal	Uncontrolled reentry, active destruct considered. Due to limited oxidation of fuel considering intact reentry.
SP-100	100 kWe base design; 5-1000 kWe	LEO-GEO, planetary, or deep space operation. High-orbit disposal.	Cold or hot reenter intact with aeroshell.
Topaz	6 kWe	HEO operation and deep space disposal	Proposed cold reactor reentry dispersal.
Prometheus	100-200 kWe		Cold reactor reentry dispersal.
Kilopower	1-10 kWe	HEO, planetary, or deep space operation.	To Be Determined
NTP		HEO, LEO, medium Earth orbit (MEO) operation	Cold reentry dispersal.

## 7.0 Possible Safety Requirements for Reentry

### 7.1 General Design Criteria

General Design Criteria (GDCs) were used in all space reactor programs after SP-100 including Topaz II and the Prometheus. GDCs are intended to provide fundamental guidance to designers and are at a level in between high-level policy, such as issued by the White House, and specific design and mission details. GDCs should be consistent with policy and reflect good engineering practice. Detailed design and mission information and subsequent risk analyses will determine the degree to which the GDCs are met. After review of each of these programs, the following are the suggested GDCs for space reactor reentry. These criteria are modified from those developed for the Topaz II program by Al Marshall at Sandia National Laboratories.<sup>26</sup> The suggested GDCs are then:

- Planned radiologically hot reentry shall be precluded from mission profiles.
- For any credible radiologically hot reentry accident, the reactor fuel shall reenter essentially intact, or alternatively, shall result in essentially full dispersal as vapor or fine particles of radioactive materials at high altitude.

For the purpose of the second GDC above, credible shall refer to accidents with a likelihood greater than 1E-6. Reactors will be considered hot if the fission product inventory exceeds 1,000 Ci at the time of reentry.

The use of GDCs will provide guidance to designers for achieving adequate nuclear safety. The criteria are purposely written in a non-proscriptive fashion to allow designers the opportunity to pick their own individual path to achieving safety. These GDCs provide a high-level framework for safety, while numerical risk criteria help determine when the implemented safety strategy is adequate.

## **7.2 Risk Criteria**

Reference 1 proposed risk criteria that could, in principle, be applied to inadvertent reentry. Those criteria address the probability of reentry, the conditional probability of criticality, and the doses that would result from an Earth impact. The likelihood and consequence criteria were developed to be consistent with nuclear risk criteria used by selected other Government Agencies. This section takes a deeper look at the application of those criteria to reentry scenarios and the possible alternatives. A guiding philosophy, continued from Reference 1, is that, for credible accidents, both the likelihood of inadvertent reentry and the consequences of a reentry should be addressed in the criteria, thus maintaining an element of defense in depth that is traditional in nuclear safety. Consistent with the guidance in Reference 1, a reentry event will be considered credible if the likelihood exceeds 1E-6 over the life of the mission. It should be noted that 1E-6 is somewhat arbitrary and numbers as high as 1E-5 could be considered reasonable, consistent with the Nuclear Regulatory Commission (NRC) use of 1E-5 as a benchmark for large, early release frequency.<sup>27</sup> The approach below supports any reasonable threshold number.

### **7.2.1 Likelihood of Inadvertent Reentry**

As noted in Reference 1, 1E-4/yr is typically considered a reasonable frequency goal for accidents at nuclear facilities. There are currently more than 400 operating power reactors worldwide. It is unlikely that there will ever be large numbers of nuclear reactors near the Earth at any given time. The hazard associated with a space reactor is expected to be much less than that for a land-based power reactor due to the smaller radioactive inventory. Space reactors do present an added complexity, given the uncertainty in predicting where reentry will occur and the associated political and security problems for a reactor coming down in a foreign country. Therefore, we have conservatively recommended that the likelihood of an inadvertent reentry be 1E-4 over the mission life, instead of per year. Note that if the probability of reentry can be shown to be less than 1E-6, as was done for the Cassini flyby,<sup>28</sup> then the reentry can be considered “incredible,” and thus consequence calculations are not necessary.

Reentry can occur with a reactor in a number of different states:

- Shut down and cold,
- Shut down and hot, or
- Operating and presumed hot

Reference 1 provided evidence that cold reactors represent little risk to the public unless criticality occurs. This will be true regardless of the particular reentry outcome. Therefore, cold reactors can be excluded from further analysis if the probability of inadvertent reentry ( $P_{\text{reentry}}$ ) multiplied by the probability that the reentry is intact ( $P_{\text{intact}}$ ) multiplied by the conditional



probability of criticality upon impact ( $P_{crit}$ ) can be shown to be less than  $1E-6$ . Or, in equation form this would look like:

$$P_{reentry} \times P_{intact} \times P_{crit} < 1.0 \times 10^{-6} \quad (1)$$

The definition of a “hot” reactor is somewhat arbitrary. Reference <sup>29</sup> indicates that reactors should decay down to the level of the actinides prior to reentry. That level can be different for different fuel types. A reactor that has never operated will probably contain less than 100 Ci of radioactivity. A radioactivity limit in Curies could be the basis for the definition of “hot,” e.g., 1,000 Ci as suggested above in the discussion of GDCs. Another possibility would be to show that, for a bounding calculation, the resulting dose from an intact reentry would be less than a given threshold, e.g., 25 rem at 1 km.

### **7.2.2 Consequences of Inadvertent Reentry**

Section 4 indicated that the consequences from complete burnup are small and can be neglected. The problem is that it is very difficult to design for complete burnup, given the utilization of materials capable of high-temperature operation in a nuclear fission reactor. Therefore, other possibilities must be considered.

Reference 1 discussed the need to localize the consequences of a space reactor reentry, for both safety and possible security concerns. As noted in Section 4, scattered reentry is highly undesirable for a number of reasons. Ultimate retrieval will be very complex for a scattered impact as was the case for Cosmos 954.<sup>30</sup> Therefore, it is recommended that a scattered reentry be largely precluded by requiring the combined probability of inadvertent reentry plus scattering to be less than  $1E-6$ . For intact reentry, some scattering of radioactive components may occur due to breakup at the impact site and such scattering should be confined to an impact zone with a radius of less than 1 km. Other mechanisms for fission product transport after intact reentry are discussed below.

For a successful intact reentry of a hot reactor, radiation doses may be very high adjacent to the reactor. Doses at a distance will be small unless there is a driving force sufficient to disperse the fission products, e.g., to cause melting or vaporization. Such a driving force can come from the reactor’s own decay heat if not precluded by design or from criticality upon impact. In any case, per the guidance in Reference 1, it is recommended that the doses be limited to less than 25 rem at a distance of 1 km from the impact site.

For many missions, the most likely impact site will be in an ocean. In that case, doses to the public will be effectively zero unless the site is adjacent to the shore. From purely a public safety standpoint, ocean impacts are not of concern; however, if recovery of the reactor is desirable, then an ocean impact can be problematic. There are approximately seven nuclear submarines, U.S. and Russian, that were sunk without recovering their reactors due to the difficulty of the recovery or the depth of the site. Criticality following impact in water can further complicate recovery but will not significantly change the low consequences. A few meters of water will effectively reduce direct radiation shine to safe levels, and water will also scrub any aerosols that are generated.

For the purposes of this paper, ocean impact will be considered a positive outcome and the probability of ocean impact can be factored into the probabilities discussed above. For example, while the probability of all inadvertent reentries should be less than  $1E-4$  as discussed above, the probability of inadvertent reentry times the probability of scattered reentry times the probability of land impact should be less than  $1E-6$ .

### 7.2.3 Considerations for Mission Types

Overall failure probabilities are developed by combining a number of probabilities for particular events that might occur for a given mission. It is useful to consider those individual probability terms, as they allow designers and mission planners the opportunity to reduce selected probabilities without having to drive every term to a very low number. These thoughts are outlined below for selected mission types.

Earth Departure Missions – Earth Departure Missions are those where the fission reactor leaves the Earth with no intention of returning, e.g., a deep space mission. There is typically a launch and ascent phase, an orbital phase, and a departure phase. It is assumed that reactors will remain cold prior to the departure phase and that fission product buildup will be small during the departure process until the spacecraft is far enough away as to present no further risk. Therefore, the only reentry accidents of interest will be those involving criticality upon impact on land.

For consistency with Reference 1, the sum of all accidents that lead to Earth impact, from the launch pad onward, should be less than 1E-4. The reentry contribution to that number will be approximately:

$$P_{\text{reentry}} = (P_{\text{ascent}} + P_{\text{orbit}} + P_{\text{depart}}) \times P_{\text{land}} \times P_{\text{crit}} \quad (2)^a$$

$P_{\text{reentry}}$  = Probability of reentry on land with an accompanying criticality

$P_{\text{ascent}}$  = Probability of reentry during ascent and orbital insertion

$P_{\text{orbit}}$  = Probability of reentry during orbital phase (function of time in orbit and altitude)

$P_{\text{depart}}$  = Probability of reentry during or after the departure burn

$P_{\text{land}}$  = Probability of land impact (this could be considered separately for ascent, orbit, and departure)

$P_{\text{crit}}$  = Probability of criticality upon impact

If the combined probability of reentry from Equation 2 is less than 1E-6, then no further analysis is necessary. If the combined probability of reentry from Equation 2 is greater than 1E-6, then the doses should be limited to less than 25 rem at 1 km. Note that  $P_{\text{depart}}$  should include the possibility that the departure burn or subsequent trajectory correction burns place the reactor in an orbit that crosses the plane of the Earth orbit resulting in a long-term reentry.

Orbital Missions – Orbital missions, like departure missions, have ascent and orbital phases, but with a disposal phase in place of a departure phase. The more important difference is that an orbital reactor will be operating for long periods of time and will therefore be hot during most of its orbital phase. Thus, a criticality upon impact is not necessary for a significant release, depending upon the design. The probabilistic contribution to the overall accident probability becomes:

$$P_{\text{reentry}} = ((P_{\text{ascent}} + P_{\text{disp}}) \times P_{\text{crit}} + P_{\text{orbit}}) \times P_{\text{land}} \quad (3)$$

$P_{\text{reentry}}$  = Probability of reentry with land impact and hot and/or critical reactor

$P_{\text{ascent}}$  = Probability of reentry during ascent and orbital insertion

$P_{\text{orbit}}$  = Probability of reentry during orbital phase (function of time in orbit and altitude)

$P_{\text{disp}}$  = Probability of reentry during the disposal phase (e.g., boosted to safe orbit)

$P_{\text{land}}$  = Probability of land impact

$P_{\text{crit}}$  = Probability of criticality upon impact

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<sup>a</sup> Note: Equations 2, 3, and 4 are approximations that are valid for small probabilities.

As with departure missions, if the combined reentry probability from Equation 3 is greater than 1E-6, then the doses at 1 km should be less than 25 rem.

Flyby Missions – Flyby missions include all of the aspects of a departure mission plus one or more Earth flybys on the way to a distant destination. Thus, there is one additional term added inside the parentheses of Equation 2—the probability of Earth impact during a flyby. The Cassini mission indicated that the probability of Earth impact could be kept below 1E-6 by implementing a trajectory biasing strategy where the spacecraft is kept on a trajectory away from Earth and uses a series of burns to come closer to Earth incrementally.<sup>28</sup> A flyby can occur at a very high velocity, e.g., >45,000 kph. At such velocities it may be difficult to manage the reentry behavior, and thus the consequences that could result. Therefore, it is recommended that the approach adopted by Cassini be continued and that the probability of a reentry during flyby should be less than 1E-6, negating the need for consequence calculations. This strategy, of course, requires additional propellant mass to carry out the maneuvers. Other aspects of a flyby mission would be calculated according to Equation 2.

Return-to-Earth Missions – Return-to-Earth missions are typically those to the Moon or Mars where the reactor returns to Earth orbit on the spacecraft, likely as part of a propulsion system. Multiple trips may be involved. There are similarities to a departure mission until the point of return when the spacecraft must enter orbit with a possibly hot reactor and then depart again. The equation now becomes:

$$P_{\text{reentry}} = ((P_{\text{ascent}} + P_{\text{coldorbit}} + P_{\text{colddepart}} + P_{\text{coldinsert}}) \times P_{\text{crit}} + P_{\text{hotorbit}} + P_{\text{hotdepart}} + P_{\text{hotinsert}}) \times P_{\text{land}} \quad (4)$$

$P_{\text{reentry}}$  = Probability of reentry with land impact and hot and/or critical reactor

$P_{\text{ascent}}$  = Probability of reentry during ascent and initial orbital insertion

$P_{\text{coldorbit}}$  = Probability of reentry during cold orbital phases (function of time in orbit and altitude)

$P_{\text{hotorbit}}$  = Probability of reentry during hot orbital phases (function of time in orbit and altitude)

$P_{\text{colddepart}}$  = Probability of reentry during the departure burn with a cold reactor

$P_{\text{hotdepart}}$  = Probability of reentry during the departure burn with a hot reactor

$P_{\text{coldinsert}}$  = Probability of reentry during orbital insertion with a cold reactor

$P_{\text{hotinsert}}$  = Probability of reentry during orbital insertion with a hot reactor

$P_{\text{land}}$  = Probability of land impact

$P_{\text{crit}}$  = Probability of criticality upon impact

In this case,  $P_{\text{reentry}}$  should be based on the sum of the probabilities from the individual missions. Disposal has not been addressed in Equation 4 but should be included if the disposal occurs in Earth orbit. As with the other types of missions, if the combined probability is greater than 1E-6, then the doses at 1 km from impact should be less than 25 rem.

#### **7.2.4 Risk Analysis Issues**

Reference 1 suggested the desirability of national standards for performing risk assessments for space reactors. There are varying methodological questions and assumptions ranging from selection and interpretation of data to uncertainty analysis techniques. Without standards, there can be contentious debate regarding the particular approaches to use. While standards development is a slow process, it is recommended that interim guidance be developed for use by designers and others. Coordination of methods with potential reviewers should happen early in the process.

As an example of an area where guidance is needed, consider the issue of parsing of probabilities. In Reference 1 and the discussions above, events with probabilities less than  $1E-6$  are considered incredible. While this seems like a straightforward concept, it turns out that there are many ways to describe scenarios based on level of detail. For example, during orbit a satellite may come down due to impact from space debris, a failure on board the spacecraft, or natural orbital decay. These can be further subdivided, for example, to consider different types of spacecraft failures. A problem arises if the types of scenarios are sufficiently subdivided that the individual parts are determined to each be below  $1E-6$  and discarded. One can imagine a situation where there are 1000 scenarios, each with a probability of  $1E-7$ , that are ignored. This problem can be addressed in a number of ways. In fault tree analyses, low truncation limits are generally set to retain combinations of low-probability scenarios. Tests can be constructed to estimate the fraction of the probability that is retained or excluded in the analysis, e.g., a process that captures 90% or more of the total probability.

The discussions earlier in Section 7 have not been precise in defining how scenarios or scenario classes should be defined. Those definitions will undoubtedly be somewhat arbitrary. This is an example of the sort of issue that could be defined and resolved in a technical standard. Pending that, it is suggested that the  $1E-6$  threshold be applied to significant mission phases where each would be compared to the threshold. These phases would include launch, ascent and orbital insertion, departure, flyby, etc. In contrast, the  $1E-4$  threshold applies to a complete mission.

## **8.0 Mission Implications**

As noted in Section 6, it is important to consider safety criteria early in the mission design process. Missions may be impacted in a variety of ways, including payload mass and configuration, orbital altitudes, and the ability to perform near-Earth operations. While no particular missions are intended to be precluded by the criteria of Section 7, certain missions are likely to require more restrictive safety measures.

### **8.1 Requirement for Intact Reentry or Complete Burnup**

In the event of an inadvertent reentry, Section 7 indicates the need to avoid scattered reentry. If reentry is to involve complete burnup, then several factors will impact spacecraft and mission design. For example, a combination of fuel and reactor design, possibly including active means to eject and disperse the core, may be required. The velocity and angle of reentry will also be important. If reentry is to be intact, then an aeroshell may be required, impacting both reactor and spacecraft design and also the overall system mass.

### **8.2 Requirements for Low Probability of Reentry on Land**

There are a number of mission parameters that will be affected by the need to maintain a low probability of reentry on land. For orbital missions, including Earth departure and return missions, the likelihood of inadvertent reentry decreases with altitude. In addition to altitude, the probability of inadvertent reentry can be reduced through increased reliability and redundancy of control systems, as well as greater resistance to micrometeoroid impact. Such design changes may increase the mass of the reactor system and/or spacecraft.

For Earth-flyby missions, the approach used in Cassini involving trajectory biasing reduced the probability of Earth impact to acceptable levels. That approach does require greater propellant on-board to carry out the multiple trajectory changes. This approach may also apply to return-to-

Earth scenarios, although the spacecraft in this case may ultimately return to Earth orbit. It is also possible that mission times will be increased for flyby or return-to-Earth scenarios.

### **8.3 Requirements for Reduced Consequences**

Consequences can be managed through reactor and spacecraft design, reentry behavior or reducing the fission product inventory. The reactor design determines the number of fission products that might be released during a criticality event upon impact and also influences the reentry behavior. The reentry behavior (intact, burnup, or scattered) can be managed by including an aeroshell or a high-altitude ejection or destruct system. These additions will add to the mass of the reactor system and/or spacecraft. Operationally, a spacecraft in a higher orbit will have greater time for decay of radionuclides in some scenarios. Intentionally moving a spacecraft to a higher orbit at the EOL requires that propellant be preserved to carry out that maneuver. For Earth-flyby scenarios, the reactor could remain off prior to the flyby. For return-to-Earth scenarios, operational profiles that minimize the radionuclide inventory prior to Earth approach could be considered. These measures will affect mission times and capabilities and require carrying additional propellant to perform needed maneuvers.

In summary, mission profiles may be significantly affected by the proposed safety criteria. Safety should be considered early in the design process to avoid major design changes and/or adverse mission impacts.

### **9.0 Conclusions**

This report has proposed treatment of fission reactor reentry consistent with the guidance provided in Reference 1 for launch approval. Suggested general design criteria and risk criteria have been presented. The general theme is that the likelihood of inadvertent reentry should be kept as low as possible. Further, if reentry is to occur, either burnup or intact reentry is preferred over scattered reentry. A significant departure from past guidance is the notion that reentry into the ocean may be considered a success state, whether or not criticality occurs. It is anticipated that the guidance in this report may be modified following the issuance of further policy guidance from the Office of Science and Technology Policy (OSTP). In particular, issues that may warrant future discussion include:

- Definition of a “hot” reactor
- Whether or not to consider criticality for ocean impacts
- Suggested general design criteria
- Suggested risk criteria
- Application of criteria, i.e., parsing of numbers
- Mission Implications

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<b>1. REPORT DATE (DD-MM-YYYY)</b> 08/29/2019		<b>2. REPORT TYPE</b> Contractor Report		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b> Fission Reactor Inadvertent Reentry  A Report to the Nuclear Power & Propulsion Technical Discipline Team				<b>5a. CONTRACT NUMBER</b> 80LARC17C0003	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b> Camp, Allen; Borenstein, Elan; McClure, Patrick; VanDamme, Paul; Voss, Susan; Klein, Andy				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b> 869021.03.07.01.21	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> NASA Langley Research Center Hampton, VA 23681-2199				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> National Aeronautics and Space Administration Washington, DC 20546-0001				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> NASA	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> NASA/CR-2019-220397	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Unclassified - Unlimited Subject Category 15 Launch Vehicles and Launch Operations Availability: NASA STI Program (757) 864-9658					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> The Nuclear Power and Propulsion Technical Discipline Team has directed an effort to consider possible improvements to the launch approval process as it relates to fission reactors. This paper presents the next step in that examination, which is to accurately describe and frame the problem and suggest safety criteria that might apply to inadvertent reentry. The report includes a discussion of the issues associated with different types of inadvertent reentry, the possible consequences of those events, a review of previous work in the area, security and nonproliferation issues, and options for safety requirements that might be considered.					
<b>15. SUBJECT TERMS</b> Fission Reactor; Inadvertent Reentry; Nuclear Power; Nuclear Thermal Propulsion					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b>	<b>b. ABSTRACT</b>	<b>c. THIS PAGE</b>			STI Help Desk (email: help@sti.nasa.gov)
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