Anti-Criticality Methods for Nuclear Thermal Rocket Launches and Their Associated Assembly / Disassembly in Space

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When launching a nuclear reactor into space for use in a nuclear thermal rocket (NTR), safety to the public is of the outmost importance. Ensuring that the reactor will not go critical in an accident scenario is the biggest risk that must be overcome to protect the public. Use of anti-criticality devices and methods, such as the use of poison materials in the core or loading a select portion of the fuel on orbit, can prevent the reactor from going critical in any accident scenario. However, both methods (unpoisoning / loading fuel into the reactor core on orbit) will likely require the use of In Space Assembly and Manufacturing (ISAM) technology to remove the safeguards and ensure the reactor is fully operational before use. This paper discusses the use of ISAMs to help with the unpackaging of anti-criticality devices on orbit along with ISAMs ability to help verify and preform maintenance and inspection checks of the reactor system before operation and in between engine burns.

I. INTRODUCTION

In the pursuit of more efficient and effective space travel, for both long distance and cislunar missions, NASA intends to utilize Nuclear Thermal Propulsion (NTP) due to its increased specific impulse compared to conventional rockets. The nuclear thermal rocket design works on the principle of accelerating propellant (hydrogen) by flowing hydrogen through a super-heated nuclear reactor (>2300C) and firing it out the nozzle to produce thrust. The rocket is simple in the fact that no combustion occurs, it's simply heating a propellant and flowing it out of the nozzle. However, launching these nuclear rockets into space pose several concerns, such as regulations and interlocks to maintain the "off" status on the reactor during launch and in the event of an accident scenario. Ensuring that the public is not harmed by the reactor in the event of an accident scenario is crucial in certifying and launching a nuclear thermal rocket into space. The White House recently put out guidance for launching nuclear reactors into space, with the directive of keeping exposure to the public to under 25 REM in any accident scenario involved with the space reactor [1]. Similar stipulations have been implemented in the past for US space reactor programs [2]. Unfortunately, many of the programs were canceled due to the safety issues of launching the reactors. In this paper, a review of previous space reactor programs and their safeguards and safety solutions are presented. Additionally, a discussion about the removal of these safeguards once on orbit is given using In Space Assembly and Manufacturing (ISAM), a technique never discussed before in previous space reactor programs.

II. SAFELY LAUNCHING OF NTP REACTOR

There are two main concerns when launching an NTP reactor system into space: 1) an accidental criticality of the reactor from a launch failure and 2) the 'hot' reentry of the reactor (reactor has been in operation and is now re-entering the Earth's atmosphere). The first scenario would occur if the launching rocket fails and crashes into a body of water (river, beach, swamp, etc.) The combination of water incursion in the core and a potentially condensed fuel region (from the reactor 'pancaking' on impact) could cause excess reactivity in the core causing a criticality event that would create a large radiation spike and a contamination situation. The second event, a 'hot reentry' involves a reactor being operational in space and accidently re-entering the atmosphere spreading highly radioactive fission product contamination over a large area. There are other accident scenarios such as the dispersion of the 'cold' fuel from a launch explosion or the 'cold' reentry of the reactor into the atmosphere. These events would spread uranium but would not be deemed a health risk to the public due to the low activity of un-irradiated nuclear fuel (it might cause a PR nightmare though). A 'hot' reentry can be mostly mitigated by choosing a high orbit for the reactor to be placed in. Operating the reactor at a high orbit would ensure that a reentry would take hundreds to millions of years to occur. For an NTP system designed for Mars or cislunar operations, a high orbit is the likely launching destination (hot reentry is only a major concern for typically low-earth orbiting satellite reactors). This leaves an accidental criticality as the most important safety concern for launching the reactor. Previous space reactor programs (NERVA, SNAP, SP-100, RORSAT, TOPAZ, PROMETHUS, etc.) have spent large chunks of resources and time looking at solving this criticality problem (causing some of the programs to be canceled as a result); this section briefly covers the safeguards and ideas that previous reactor programs have thought of and a proposed way forward to prevent costly testing programs which have doomed previous space reactors.

II.A. Previous Space Reactor Programs Safeguards

Throughout the past 6 decades, several space reactor systems have been designed by both the US and the former Soviet Union. These include the SNAP-10A, NERVA, RORSAT, TOPAZ-II, and other projects [2]. As mentioned previously, accidental criticality and hot reentry were the main safety concerns for these reactor programs. The following paragraphs briefly cover each reactor program and their solution to safeguard and prevent criticality of the reactor in the event of an accident scenario.

SNAP-10A

The SNAP-10A reactor system, launched on April 3, 1965 from Vandenberg Airforce base, represents the only fission reactor launched into space by the United States. The reactor was a 40 kWth, 500W electric, liquid metal (NaK) cooled reactor with fully enriched UZrH fuel [2-4]. Four semicylindrical control drums were used to control the criticality of the reactor by either reflecting the neutrons back into the core or letting them escape out into space, see Figure 1 below.

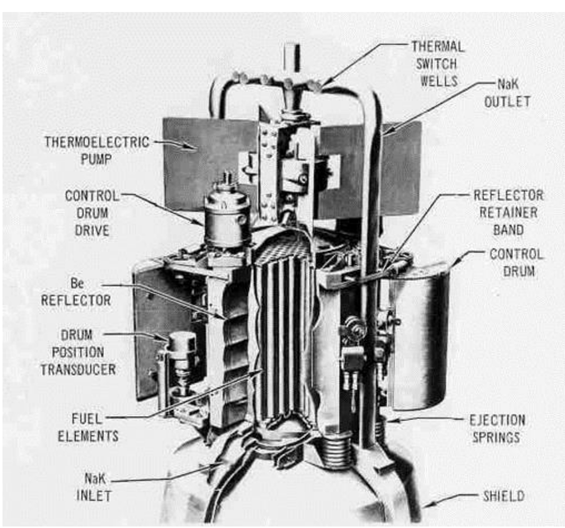

Figure 1: Diagram of the cross section of the SNAP-10A reactor; diagram courteous of US Department of Energy.

The SNAP program had a rigorous safety program that included: reactor disintegration upon reentry studies, reactor transient analysis, destructive reactor reactivity insertion experiments, critical configurations experiments, fission product release experiments, and other safety studies [2]. The safeguards to prevent the SNAP-10A reactor from going critical included removal of the reflector, control drum locking arms, void filler blocks, and a special neutron poison sleeve that surrounded the reactor during transport. However, once the reactor was mated to the rocket, most of the safety features were removed with only the control drum arms and locking pins preventing the reactor from going critical. Analysis showed that water immersion into the core would cause a criticality event and a subsequent rapid disassembly of the core [4]. To reduce risk, a trajectory was chosen for the launch of the reactor "that restricted the impact point to a small segment of private property between the launch site and the Pacific coastline" [3]. Essentially, the safety plan was to fly the rocket over a very sparse population area. To prevent a 'hot reentry' scenario, the space craft would boost into a higher orbit (nuclear safe orbit) once its mission was complete, to decay for thousands of years before reentry into the atmosphere.

NERVA

The Rover/NERVA program began in 1955 and was canceled in 1972 with the overall goal of producing a nuclear thermal rocket for transit to the moon and Mars [5]. Over the span of the program, numerous designs were created: KIWI-A, KIWI-B, PHOEBUS, PEWEE, NRX, NERVA, and XE with the general reactor design (before program cancellation) having a ~1100 MW power. The reactor used high enriched uranium fuel elements embedded in a ZrH moderator surrounded by a beryllium reflector with boron coated control drums placed in it. The reactor was susceptible to going supercritical in the event of water incursion into the core [2][5]. To prevent this, the NERVA team came up with two concepts: 1) Add poison wires into the coolant channels to ensure the reactor would not go critical in any accident scenario and 2) explosively destroy the reactor in the event of a launch accident [5]. The poison system was favored since it would keep the reactor safe both during the transit and handling of the reactor on the ground and during launch. The program was canceled though before any reactor got launched and the designs for both systems were never finalized.

BES -5 "Buk"

The Soviet Union launched 33 nuclear reactor powered satellites between 1967 and 1988 under the RORSAT program. The reactor onboard these satellites were called BES-5 or "Buk" reactors and comprised of 30 kg of high enriched U-235 capable of producing 100 kW thermal power and 3 kW electric [6]. Control of the reactor was done by sliding reflective beryllium drums into the surrounding reflector region. Liquid metal coolant (NaK) transferred the heat from the reactor to the thermoelectric generators. Literature on the safeguards to prevent criticality on launch of these reactors was sparse but their safety mechanisms for hot reentry are well documented.

The RORSAT satellites had two safety features for preventing a hot reentry of an intact core: 1) boost the satellite to a higher orbit to enable longer decay and 2) eject the core from the satellite and have it burn up in the atmosphere. The later feature was added to the satellite after an accidental hot reentry of Cosmos 954 from a failed higher orbit boost. The intact core of the reactor reentered the atmosphere and spread highly radioactive material across a large swath of land in upper Canada [7]. Cosmos 1402 also malfunctioned when trying to reach a higher orbit and reentered the atmosphere, but the core was ejected from the satellite and believed to have burned up into safe levels of radioactive debris somewhere over the south Atlantic Ocean [7].

TOPAZ-II

A joint US-Russian program, Topaz-II was a space reactor designed by the Soviets and purchased by the US for testing and potential integration into a US satellite. The Topaz-II was a 115 kWth liquid metal (NaK) reactor incorporating a thermionic conversion efficiency of 5.2% into electrical output [8]. The fuel was highly enriched UO_2 set in ZrH moderator blocks, surrounded by a beryllium reflector with 12 control drums in it [9]. The initial calculations of the reactor by the US showed that if immersed in water, the reactor would go critical. As a result, modifications by the US-Russian team were needed to create an anti-criticality device to ensure the reactor was safe in an accident scenario. The design team came up with two ideas: 1) "poison-in" and 2) "fuel out" [10]. The "poison-in" refers to the use of poison wires in the coolant channels to reduce the reactivity of the reactor until it was in orbit. The "fuel-out" refers to keeping a select amount of nuclear fuel rods out of the core until the reactor was in a safe orbit, at which time they would be inserted. This option was favored among the programs scientists as it created a fail-safe scenario where the reactor could not go critical in any accident scenario. Like other space reactor programs, the program was cancelled before anything was built or flown.

II.B. Anti-Criticality Methods for Launch

Past space reactor programs have developed four safety mechanisms to prevent a criticality accident and subsequent dose to the public from a failed launch: 1) poison wires, 2) removal of fuel rods before launch 3) explosively destroy the reactor and 4) fly the reactor over a sparse population (this doesn't prevent a reactivity, rather just ensures nobody is around if it does go critical). In Table 1, a list of different space reactor programs is shown along with their safety mechanisms for keeping the public safe in the event of an accident scenario.

TABLE 1: Space Reactor Safeguards

Reactor Program	***Criticality prevention***	***Hot reentry prevention***
SNAP-10A	None (Fly over sparse population)	Boost to high altitude / aeroshell to contain reactor/radioactivity upon reentry
NERVA	Poison wires / explosive disassembly	Placed in high orbit / explosive disassemble / aeroshell
RORSAT	None (Fly over sparse population)	Boost to higher orbit / core ejection
TOPAZ-II	Poison wires / fuel loading on orbit	Placed in high orbit

Poison Wires

The NERVA project investigated the use of poison wires to ensure that the reactor could not go critical under any accident scenario. While the NERVA reactor never flew, the design of the poison wire system was developed. The poison wires would consist of enriched B_4C encased in Teflon to ensure the wires were flexible, had a low coefficient of friction and could withstand the temperatures and vibration of the rocket (i.e. ensure that the poison wires would not break, stick, or flake off in the reactor and potentially permanently poison it) [11]. Tests of the poison wires during the NERVA project found that indeed the core could be substantially poisoned such that a criticality event would not occur even in full water incursion into the core. While insertion and removal of the poison wires on the ground was well documented [12], information on the removal of the poison wires while on orbit was not found by the authors. 'Removal of the wires once in orbit' from the reactor is referenced in many documents but the exact process was not found in detail.

Removal of Fuel Rods

The Topaz-II reactor was found to go critical when submerged in water and one of the solutions to preventing that is to launch the reactor with only a subset of the fuel in the core and load the rest once the reactor was in orbit. This subset could be simply a fuel rod or two or two separated fuel regions comprised of an inner section and outer doughnut section that are combined once in space. By removing select fuel assemblies, the reactor would remain subcritical even in the event of total water submersion and other accident scenarios. The mechanism for inserting the remaining fuel on orbit was never fully flushed out in the Topaz-II program (canceled) but using remote space assembly or even just sliding the elements in using simple devices could be accomplished.

Explosively Disassemble Reactor

The second option discussed during the ROVER/NERVA project was to explosively break up the reactor to both prevent a criticality event during a failed launch or in the event of a hot reentry. Questions on the efficacy of the explosive disassemble of the reactor led the program to favor an intact reentry of the reactor core instead using an aeroshell. The explosive disassembly, while crude, would prevent a criticality event but at the cost of spreading enriched uranium fuel over a large swath of area.

Fly it Over a Sparse Population

The SNAP program opted to go with a safety solution of simply flying over a sparse population area, hoping that in the event of a criticality accident, no one would be close enough to receive a significant dose. This solution would be the most cost-efficient solution but could potentially create environmental contamination that would be a PR nightmare. A potential launch of the reactor from Eniwetok Atoll out in the Pacific where the sparse population density surrounding the island chain would dramatically reduce the risk of exposure of a failed launch to the public is a potential solution.

However, it is also important to consider the resources required to support the launch operation. To launch the SNAP reactor, the Air Force had to construct the entire launch complex at Vandenburg base to support operations. [3]. It is important to consider the resources available on site which include sufficient fabrication facilities, security, and infrastructure to support a Category One nuclear facility for handling and receiving the nuclear reactor. For this reason, Vandenberg is the most practical option.

Besides trying to explosively disassemble the reactor (which may not be effective) or launching it from a remote place, poison wires and fuel rod removal / loading will require in space assembly to get the reactor operational. In addition to using a higher orbit to avoid any reentry issues, it is also important to select an orbit that is devoid of space debris and to avoid making any additional debris. In the view of the public this is a problematic issue, as the Soviet BUK nuclear reactors have added significant pollution to LEO. The NaK droplets released by the Soviet RORSAT reactors caused a significant increase in the rate of debris cratering in the 850 – 1000km altitude range [13]. The risk of launching into LEO from the standpoint of both existing debris and the accidental creation of more debris into LEO would be disastrous to both the mission and PR standing of the NTP program. Simulation of space debris collisions shows that the place with the fewest collisions would be between 1200km and geostationary orbit [14]. This orbit though would place it in the inner Van Allen radiation belt which would likely require the removal of the anti-criticality safeguards and the assembly of the NTP vehicle to be completed remotely via remote space assembly. The next section of this paper covers the current state of the art in remote space assembly and how it could be used to safely assemble / disassemble the reactor safeguards and the aggregation of a nuclear thermal rocket in space.

III. ASSEMBLY / DISSASSEMBLY IN SPACE

One of the biggest challenges for NTP is its assembly. Assembly of a nuclear thermal rocket requires the integration of multiple components launched over an 18-to-24-month period. The number of components integrated will depend on how many are pre-integrated for launch. A recently released Mars Transportation Assessment Study (MTAS) [15] cited there would be 47 launch elements for a NTP mission to Mars. Additionally, NASA has made it clear that an assembly involving nuclear space propulsion should be made without the use of humans [15] and focus on robotic assembly. Aggregating the NTP vehicle in a nuclear safe orbit of 1200 km x 7000 km altitude prevents a reentry scenario involving the reactor but also puts the space craft in the inner Van Allen radiation belt which would be harmful long-term if astronauts were required to assemble the vehicle. Thus, for NTP aggregation and to disassemble any anti-criticality devices used to safely package the reactor (poison wires / fuel loading on orbit), ISAM techniques could be implemented to solve these problems.

III.A. ISAM Background

NASA Langley Research Center (LaRC) has been researching the in-space assembly of large space structures (a NTR is considered a large structure) for decades using astronauts and robotic agents [16]. ISAM takes a modular approach to large space structures, breaking down the structure into smaller components that can be launched in a packaged configuration and robotically assembled on orbit to achieve the desired structure. Modules can be deployables (e.g., TriTruss modules for an in-space assembled telescope [17]) but rather than having to design complex deployment mechanisms, robotic agents can be used to aid deployment. The same robotic agents used for assembly of the structure can be kept on board for future servicing activities to enable a reusable spacecraft. One example is the Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN) [18] long-reach manipulator. Current development activities in this area focus on not only the structures needing to be assembled, but also the robotic agents required, and autonomy capabilities to perform these activities in latent communication arenas. A summary of NASA and commercial activities being performed under the ISAM umbrella relevant to space nuclear propulsion are presented in [16].

Co-designed infrastructure, like the Precision Assembled Space Structures project at LaRC, considers the technical challenges of both the structural assembly as well as the autonomy required for the robotic assembly agents from the onset of the design. High-fidelity simulations of the assembly environment can rapidly investigate assembly concepts of operations. For nuclear propulsion applications, autonomous fluid coupling and leak checking is a gap needing development activities for ISAM applications involving fluid transfer.

III.B. ISAM for NTP Missions

Autonomy is a key component of ISAM. Aggregation of the vehicle will take place in a nuclear safe orbit without humans present in contrast to assembly of the ISS, which was performed using tele-operated robotic agents and extravehicular activity. ISAM technology can be used for multiple aspects of the NTP mission, from vehicle aggregation to removal of poison wires, loading of fuel elements, inspection, maintenance of the reactor before operation, etc.

The presence of robotic manipulators enables servicing of the spacecraft during set-up and operation. The nuclear reactor for the NTP system will require anti-criticality devices to prevent the reactor from going critical if there is a launch failure. As mentioned in the previous section, these anti-criticality methods could include poison materials or the loading of a select amount of fuel once the reactor is in orbit. Depending on the technology chosen (poison material, fuel loading, or some other shielding device), robotic manipulators with customized tooling are an ideal choice to deshield, de-poison, or load fuel assemblies into the reactor on orbit. In addition, ISAM could be used for verifications and testing to ensure that everything was assembled correctly and is properly working before the first firing of the nuclear rocket. This includes but is not limited to leak checking, visual inspection of the reactor core, and verification of assembly.

Furthermore, a long reach manipulator can perform inspection of the spacecraft and reactor after burns for any damage caused to ensure that the spacecraft will be operational for the next burn. Servicing may be required at points during transit or at Mars that are vital to bringing the crew back safely to Earth. For instance, if a micrometeoroid strikes a critical nuclear component, robotic agents, rather than astronauts can be used to repair the vehicle. Upon return to Earth, robotic agents can be used to refurbish and repair the vehicle to ready it for future mission. Designing the spacecraft to be serviced from the onset reduces complexity than designing a system after the fact, which ensures reusability.

Proposed NTP architectures exclusively incorporate large components that are in-line and require docking and undocking at various stages of the mission to add or eliminate modules. By incorporating a long-reach robotic manipulator, such as the TALISMAN, into the architecture, the primary means of assembly for these large modules can become berthing (grapple assisted) instead of docking (unassisted). If the module can be berthed, the mass, cost, and complexity of systems such as: propulsion; guidance, navigation, and control; attitude control; etc. can be eliminated. Additionally, berthing eliminates potential issues associated with assembly-bots firing maneuvering thrusters near components being assembled. Thus, berthing may lead to less expensive and less complicated modules. Many spacecraft architectures can benefit from adopting the ISAM/persistent platform layout that incorporates a backbone truss as the main vehicle structure. This backbone truss can be deployed, constructed, or manufactured on site. Mature technologies for large deployable and erectable space structures and robotic in-space assembly have been developed. The backbone truss would incorporate standard modular connectors for mechanical, electrical, data and fluid attachments. Utilities are routed through the truss interior, as was done for the shuttle radar topography mission (STRM) truss that was flown twice on the space shuttle. All vehicle subsystems, such as tanks, solar arrays, etc. are connected to a face of the backbone truss, with modules being berthed using a long reach manipulator. This approach also eliminates all in-line connections needed in the current architectures to separate linear components (which then become free flyers) at various stages of the mission to allow for removing or adding components.

The NTP vehicle architecture has the potential to take advantage of new and innovative ideas that would be supported by ISAM technologies, approaches, and operational concepts. Given the long lead time before the first potential NTP mission to Mars (late 2030s), it would be appropriate to propose new spacecraft and mission architectures, ideas and solutions that incorporate projected capabilities that are likely to exist 15 years from now. Currently, ISAM technology needs to elevate to a higher

TRL level to ensure the capabilities needed for use in assembling a nuclear thermal rocket [15]. By adding ISAM into the conops, investment in cross-cutting technologies like ISAM could further the TRL level to what is needed for NTP use.

IV. CONCLUSIONS

The launch of a nuclear thermal rocket will require anti-criticality devices to ensure that the reactor does not go critical in an accident scenario. Using poison materials in the core or loading a select portion of the fuel on orbit are two of the main anti-criticality methods for ensuring the reactor is safe even in an accident scenario. Unpoisoning / loading fuel into the reactor core on orbit will likely require the use of ISAM technology to ensure the reactor is fully operational before use. Additionally, ISAM can be used to help verify and preform maintenance and inspection checks of the reactor system before operation and in between engine burns. In conclusion, the reactor will need to employ anti-criticality measures for safe launch and the use of ISAM technology could help with removing the anti-criticality devices and get the reactor operational once it reaches its designated orbit.

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