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NUCLEAR SECURITY CONSIDERATIONS FOR SPACE NUCLEAR POWER: A REVIEW OF PAST PROGRAMS WITH RECOMMENDATIONS FOR FUTURE CRITERIA

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Nuclear security plays an integral role in the design and mission planning for the proposed use of high enriched uranium (HEU) in small, compact power systems for space. Nuclear security issues have taken on great importance within the United States (US) and internationally since the early 1990's with the end of the Soviet Union resulting in excess weapons usable nuclear materials (NM) and the rise of international terrorism. As a result, US leadership has made nuclear security and the reduction in the use of weapons-usable materials a high national priority. For some missions, the use of HEU in space nuclear reactors and rockets may be enabling for future space missions. I examine whether or not the use of HEU can be justified based upon US Presidential policy. I also examine the unique challenge that space nuclear reactors present in establishing safety and security requirements. A review of past US and Russian nuclear security and safety guidelines for space nuclear power provides insights into what has worked in the past and how it may be applied in the future.

I. NUCLEAR SECURITY AND NONPROLIFERATION

For nations that have nuclear weapons-usable material within their program, goals of the international nuclear security and nonproliferation programs are to ensure that nuclear material is protected and controlled by the nation that maintains ownership of the material, to ensure the material is not diverted outside of national control, and to limit or reduce the amount of available weapons-usable nuclear material. The nuclear security and nonproliferation community provide the expertise for this work both domestically and internationally.

Nuclear security entails prevention and detection of – and responses to – the theft, sabotage, unauthorized access, illegal transfer, or other malicious acts involving nuclear or radioactive materials. This makes nuclear security a sibling discipline of nuclear safeguards – which aims to prevent deliberate diversion of material or technology from permissible to prohibited purposes by those already possessing it, whereas nuclear security focuses upon preventing access by those who shouldn't have it in the first place.[1]

US policy and funding for nuclear security and nonproliferation significantly expanded in the early 1990's with the breakup of the Soviet Union, the rise of international terrorism, and the expansion of potential nuclear weapon states including North Korea and Iran. At the fall of the USSR, there was estimated to be more than 1300 metric tons (MT) of HEU and over 130 MT of weapons-grade plutonium in nuclear weapons, weapons production plants, and research institutes. These international factors significantly changed and expanded the US nonproliferation programs. Efforts were significantly ramped up again following the September 2011 attacks on the US to ensure vulnerable material was adequately secured and to further reduce the international use of HEU. While the probability of obtaining weapons-usable nuclear materials is small, the overall goal is to further reduce the probability of diversion by eliminating, to the maximum extent possible, the use of HEU and weapons plutonium.

IAEA defines a significant quantity as "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded." [2] According to the IAEA a significant quantity of HEU is defined as 25 kgs[2] and per US safeguard categories for special nuclear materials (SNM) greater than 5 kgs of U235 enriched to above 20% falls under the Category 1 for strategic SNM.[3] Many of the space power reactors and nuclear propulsion systems under consideration have more than a significant quantity of HEU in their core.

I.A. History of Nonproliferation Policy

In the early 1990's, the US governmental policy on nuclear material security shifted under President George H. W. Bush after the breakup of the Soviet Union. The need to reduce the threat of nuclear materials and weapons diversion resulted in the 1991 implementation of the Cooperate Threat Reduction (CTR) program. The program was aimed at ensuring stockpile safety and reducing the possibility of the theft or illicit transfer of nuclear weapons or material. Each US president from this point forward has identified nuclear security as a top priority to be addressed both domestically and internationally. Broadly speaking the goal of nuclear security includes increasing material security, reducing the use of weapons-usable nuclear materials, and when possible eliminating the material itself, e.g. the blend down of HEU to low enriched uranium for nuclear reactor fuel in both the US and Russia.

In September 1995, President Clinton issued PDD-41 with a statement that "the security of nuclear materials

[is] a matter of the highest priority".[4,5] In 2001, a bi-partisan Senate group wrote: "The most urgent unmet national security threat to the United States today is the danger that weapons of mass destruction or weapons-usable material in Russia could be stolen, sold to terrorists or hostile nation states, and used against American troops abroad or citizens at home" with "HEU being of particular concern as it is the material of choice for terrorists."[6]

In 2002, President Bush issued NSPD-17/HSPD 4 that states "The gravest danger our Nation faces lies at the crossroads of radicalism and technology. Our enemies have openly declared that they are seeking weapons of mass destruction, and evidence indicates that they are doing so with determination."[7] Where as part of the Nonproliferation and Threat Reduction Cooperation, the US will continue to "discourage the worldwide accumulation of separated plutonium and to minimize the use of highly-enriched uranium."[7] In 2006, President George Bush and Russian President Vladimir Putin issue a *Global Initiative to Combat Nuclear Terrorism* that noted "The United States of America and Russia are committed to combating the threat of nuclear terrorism, which is one of the most dangerous international security challenges we face."[8] The best ways to reduce the threat of nuclear terrorism is to reduce the stockpiles of weapons-nuclear materials internationally and ensure that the material has adequate security.

In the April 2009 speech in Prague, President Obama said that nuclear terrorism is the "most immediate and extreme threat to global security," and announced "a new international effort to secure all vulnerable nuclear material around the world within four years." [9] International efforts are being made to eliminate or minimize the HEU, yet the Obama Administration "stopped short of calling for a ban on HEU for civilian use."[10] This is significant, as there were nongovernmental organizations pushing for a ban on the use of HEU yet the recognition that there are times when the risk is worth the benefit won out. President Trump continues to support the domestic and international efforts in nuclear security.

I. B. Security Risks of Highly Enriched Uranium

It has been suggested that using HEU in a space reactor program would result in security risks and specifically by supporting the HEU infrastructure, would encourage other nations to use HEU as well.[11] The two key points expressed by non-advocates are:

1. HEU infrastructure – "fabricating, transporting, and test irradiation fuel" thereby creating vulnerabilities.

This statement neglects the nuclear security requirements and infrastructure already in place and funded at US nuclear facilities for manufacturing, testing, and transportation. Nuclear security for launch operations is currently being evaluated. Once the possible provisions for prelaunch preparation and storage are established the costs can be estimated. The overall security risks at the launch site should be low since requirements and procedures for handling the material are already in practice for US Defense Programs.

2. The use of HEU in space reactors by the US will establish a precedence thereby establishing a justification for other countries to justify the use of HEU.

The decision to transition from HEU to LEU has been made by each nation based upon their specific civilian and military needs. When possible, and often with funding by the US, European Union and International Atomic Energy Agency (IAEA), they have eliminated excess weapons-usable nuclear materials or converted their reactors to low enriched uranium (LEU). But the US decision to use LEU for specific applications has not been a primary deterrent for reducing or eliminating HEU as in the case of Russia which has a large number of research reactors that use HEU fuel.

What is important to note is that while the US has committed to nuclear security and the reduced use of HEU where feasible, there is not a ban on its use. Therefore, there needs to be a clear understanding by the agency developing and designing space nuclear reactor systems of the:

1. Risk versus benefits

2. Design trade-off studies with HEU and LEU identifying how changes impact the system and the proposed missions.

3. Established criteria and guidelines on the use of HEU that ensures that under all phases of the program including manufacturing, transportation, testing, launch preparations, launch, operation, and post-operation that ensure nuclear security is given the highest priority and attention.

II. SECURITY and SAFETY INTEGRAL IN THE DESIGN OF SPACE POWER REACTORS AND NUCLEAR PROPULSION

Safety and security criteria are integral to the design of space nuclear reactors. It is important to establish consistent safety and security criteria and design requirements early in the program. A review of the past programs helps to identify technical problems encountered in the past and to incorporate lessons-learned.

The primary safety concern during the launch and post-operational phases of a nuclear reactor is ensuring the reactor remains subcritical and meets appropriate standards for radiological impact. Whereas the primary security concern for space reactor systems is ensuring that the nuclear material is tracked without the loss and diversion of special nuclear material (SNM). Both LEU and HEU material would require monitoring, but HEU presents a special challenge due to the extreme consequences that could result should that material be lost to a foreign threat. There are two primary requirements that have been implemented to meet the security and safety criteria for the accidental reentry of a space reactor: intact with tracking and retrieval or dispersal and burnup in the upper atmosphere. Table I provides an overview of the safety and safeguard objectives for each launch phase.

TABLE I: Launch phases and safety and safeguard objectives for LEO and above.

Launch Phase		**Op's**	**Safety and Safeguard Objectives**
Ground handling, transportation & storage	Pre-op'l		Maintain HEU control. Reactor remains subcritical.
Prelaunch, launch and orbital ascent	Pre-op'l		Track and retrieval is needed; no accidental criticality.
Orbital injection	Pre-op'l		Track and retrieval is needed; no accidental criticality.
In-space operation	Post-op'l	LEO	Plan for space debris impact.
		Non-LEO	Ensure long-term operational orbit. Extraterrestrial surface operations.
Mission completion	Post-op'l	LEO	Plan reentry. Recover HEU or confirm dispersal. Remain subcritical & limit radiological impact.
		Non-LEO	Ensure long-term operational orbit. Extraterrestrial surface operations.
Long-term disposal	Post-op'l	LEO	Plan reentry. Recover HEU or confirm dispersal. Remain subcritical & limit radiological impact.
		Non-LEO	Ensure long life orbit. If extraterrestrial surface, plan for long-term disposal.

One of the primary drivers in the system design is whether or not the system is planned to startup and/or operate in low earth orbit (LEO). Nuclear reactor systems that are not to be operated prior to reaching a sufficiently high orbit as defined by UN Resolution 47/68[12] have significantly simplified safety, safeguard and system design criteria. Space reactors designed for missions which include operation in LEO significantly impact the design to ensure the system can safely reenter for all possible accident conditions. The systems designed for LEO operations include: US SNAP, NERVA, and SP-100, and the Soviet Buk used on the RORSAT missions. The nuclear systems designed without LEO operations or startup include JIMO/Prometheus and Kilopower, and the Russian systems Topaz I and Enisy (Topaz II). The mission space for Nuclear Thermal Propulsion (NTP) is being defined. Both LEO and non-LEO operations are considered but based upon a review of the projects it is clear that non-LEO operation is the preferred mode from both a safety and safeguards perspective.

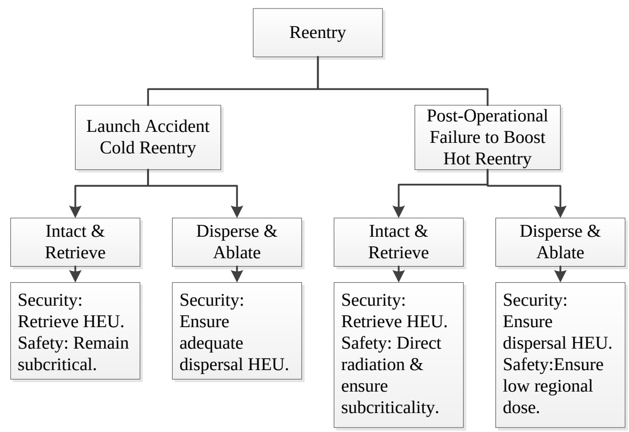

Fig. 1. Key safety and security concerns for both cold and hot accidental reentry.

A review of each of the previous space reactor reentry strategies is provided in Table II. The key issues for each program include:

1. 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.[13] By the late 1960's, 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.[14]

2. 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 ingenious and active means to meet the safety criteria. This included the use of poison wires to prevent criticality[15] and active means of engine destruct as the high temperature refractory materials are inherently resistant to passive destruct upon reentry.[16,17] The flight reactors used 174 kgs of U235 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 NTP program is proposing to use LEU thereby minimizing nuclear security concerns.

3. Russian Buk: The Russian Buk reactor operated in LEO with end-of-life (EOL) boost to higher orbit (750 to 1000 km)[18]. Cosmos 954 failed to boost, reentered and scattered radioactive debris over northern Canada. Russians modified core design to ensure 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.[19]

4. Russian Topaz I: Designed for high earth orbit operation. Two test units were launched and operated as expected.

5. Russian Topaz II: The Topaz II was developed in the Soviet Union from around 1969 to 1989[20] and then the system was part of a US/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 UO2 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.[21] Therefore, an anti-criticality device was designed to separate some of the fuel outside of the core until a safe operating orbit was achieved.[22] 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_2 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." [23] 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, deep space and extraterrestrial surface operations. Based upon lessons-learned from the SNAP reentry program, the SP-100 reactor subsystem was designed to ensure the reactor would reenter intact 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.[24] Nuclear material safeguards were an important part of the SP-100 safety program.

6. Kilopower: The Kilopower system is being designed for deep space and extraterrestrial surface missions. Safety and safeguards are currently being defined.

7. NTP: The NTP stage is 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 low enriched uranium and therefore has minimal safeguard concerns.

Based upon a review of the safeguards and safety criteria for past and present programs, both within the US and Russia, safeguards/nuclear security are an integral part of the safety and design criteria. Integrating nuclear security early in the design process can help insure that it is an important aspect of the mission profile including emergency operations.

Either ensuring the reactor subsystem reenters intact and can retrieved or is dispersed in the upper atmosphere where it may burnup prior to entering the earth's biosphere will be important to verify the proposed system. For planned dispersal, it is difficult to ensure the nuclear fuel will separate from the reactor vessel and burnup without active measures therefore a more conservative approach may be ensuring intact reentry and retrieval as a means of meeting both the safeguard/nuclear security and safety requirements.

II. CONCLUSIONS

Nuclear material safeguards have taken on greater importance in the past few years due to concerns over non-state actors acquiring SNM and the ability to construct nuclear weapons. Yet even with the heightened concern, US presidential policy has refrained from banning HEU use in nuclear systems. The use of HEU in highly specialized systems such as space power reactors and propulsion systems must be balanced with the potential risks associated with the proposed mission.

Integrating nuclear security with safety in the design of the space nuclear systems will ensure that it is given the high degree of attention required. Based upon a review of past space reactor programs, the primary concern for materials security is during the launch and orbital ascent phase when the unirradiated nuclear material could reenter and land in an uncontrolled way due to a launch accident. Both intact reentry with recovery and high altitude dispersal with burnup have been considered as design options for accidental reentry by past programs. There were considerable problems ensuring the core would passively disperse and the fuel burnup in the SNAP, NERVA and Russian RORSAT programs. Based upon this experience, the SP-100 program chose intact reentry for both pre- and post-operational accident reentry. Future systems will have to establish guidelines that integrate safeguards and security into their design and mission planning. Integrating lessons learned from past programs should be helpful.

TABLE I. Space Reactor and Nuclear Propulsion Systems

System	Year	Mission Profile	Pe kWe	Pth (kWth)	Life-time (yrs)	Fuel	Enr	Fuel & U-235 kgs
SNAP RX	1955-1973	SNAP RX LEO, HEO, deep space & planetary						
SNAP 10A[25]	1958-1973		0.5	30		U-ZrHx	93.15%	4.74 kg U235
SNAP 2	1955-1973		5	55		U-ZrHx	93.15%	
SNAP 8DR25[25]	1960-1973		35-50	600		U-ZrHx	93.15%	8.2 kg 93.15% U
NERVA Nuclear Rocket	1955-1973	NERVA RX LEO, HEO, deep space & planetary						
NRX[26] A5	1963-1968						93.15%	174.9 U235
NERVA26 XE2	1967-1970						93.15%	174.4 U235
Russian[27] Buk/Cosmos	~1960-	LEO	3	100	0.3-0.4	U 3%Mo	90%	30 kg of U-235
Russian Topaz[28] 1/Cosmos	~1960-1990	HEO	5	150	0.5-1	UO_2		12 kg U-235
Russian Topaz II[29]	~1960-1990	HEO	6	115 BOL & 135/EOL	1	UO_2	94%	27 kgs UO2
SP-100[30]	1983-1994	SP-100 RX LEO, HEO, deep space & planetary	100	2500	7	UN	89%/97 %	170 kgs U235
JIMO 1	2000-2006	Deep space	135	500	15-20	UN		
JIMO 2 Prometheus	2000-2006	Deep space	200	1000	10 to 12	UO2		
Kilopower	2013-present	Deep space, planetary power						
Kilopower 1	2013 to present		1	4.3	15-20	U 7% Mo	93%	28.4 kgs
Kilopower-10	2013 to present		10	43.3	15-20	U 7% Mo	93%	43.7 kgs
NTP	2013-present	HEO, deep space					<20%	

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