Expanding the Price-Anderson Act (PAA) to Cover Private Sector Space Nuclear Power and Propulsion (SNPP)

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Space nuclear power and propulsion (SNPP) systems may prove vital to advancing U.S. interests tied to exploration, resource extraction, and the use of the Moon, Mars, and other celestial bodies. However, the liability risk for commercial launches of nuclear material is unclear – absent clearly defined liability and liability protection, the development and commercialization of a U.S. private sector nuclear space program could be chilled. The aim of this study is to examine the global space economy, SNPP technology development, accidents, and safety, and technical government and industry reports to provide insights surrounding Price-Anderson Act (PAA) coverage for private sector SNPP.

I. INTRODUCTION

In the context of the 21st century space race, tech titans in the U.S. private sector are vital to continued U.S. competitiveness. Given continued space nuclear power and propulsion (SNPP) developments and their potential to catalyze public and private sector participation in the expanding global space economy, SNPP systems may prove vital to establishing U.S. leadership in the areas of technology RD&D, deep space exploration, resource extraction, permanent settlement of the Moon and Mars, and other emerging priorities. However, the liability risk for commercial launches of nuclear material is unclear – absent clearly defined liability and liability shields, the U.S. private sector may be hindered from leveraging the SNPP technologies needed to solidify an edge in an increasingly competitive, global space industries. The aim of this study is therefore to provide historical, policy, regulatory, empirical, and technical insights on potentially expanding the nuclear accident financial protections of the Price-Anderson Nuclear Industry Indemnity Act of 1957 (PAA) to cover private sector SNPP applications.

II. BACKGROUND

The global space economy of the 2020s is marked by precipitous revenue and investment growth. This section outlines the private and public sector developments that have occurred primarily between 2014 and 2023.

II.A. Developments in the Global Space Economy

The trend of annual space industry revenues, which rose sharply from $175 billion in 2005 to $424 billion by 2019,[1] support projections over $1.2 trillion in annual industry revenues by 2040.[2] And since 2014, the industry has attracted $283.9 billion in cumulative private market equity investment across 1,796 unique companies. This investment includes $65 billion in the infrastructure technology layer that spans the (1) Launch, (2) Satellite (e.g., global positioning satellite (GPS), satellite communications (SatCom), and geospatial intelligence (GEOINT) sectors), (3) Stations (e.g., habitats and services sectors), (4) Lunar (e.g., transport, construction, and deep space satellites sectors), (5) logistics (e.g., space situational awareness (SSA), on-orbit servicing, and debris mitigation sectors), and (6) Industrials (e.g., manufacturing and assembly, mining and minerals, and energy generation and storage sectors) industries. It also includes $8.8 billion in the Distribution technology layer across the GPS, SatCom, and GEOINT sectors in the satellite industry; and $210.1 billion in the Applications technology layer within the same sectors.

In the private sector, $3 billion in investment was distributed across 103 companies in the third quarter (Q3) of 2023. At the country level, the U.S. led investment in all three technology categories, respectively accounting for 69%, 50%, and 41% of investments in infrastructure, distribution, and applications during Q3 2023. Though the UK was the second largest investor in the infrastructure category (accounting for 12%), China was the next largest cumulative investor in all three categories, respectively accounting for 7%, 22%, and 35%.

Geopolitical competition between the U.S. and China is driving much of the technological innovation, international collaboration, and large-scale investments behind this economic expansion. With respect to the U.S., the National Aeronautics and Space Administration (NASA) Artemis Program is funneling billions of dollars into the lunar industry with the aim of establishing a permanently crewed outpost on the Moon.[3] Beyond its successful technology demonstrations of the December 2022 Artemis I Mission in which the Orion spacecraft travelled 1.4 million miles beyond the Moon and back,[4] NASA established its Moon to Mars Program Office to catalyze growth in emerging space industries.[5] Complementary to these developments, out of the Biden Administration's $773 billion Department of Defense (DOD) budget request in 2023, the Consolidated Appropriations Act of 2023 made about $25 billion available for NASA and $26 billion available for the U.S. Space Force through September 2024.

With respect to China, since 2014, Chinese companies have raised nearly $2 billion (over 13 billion Chinese renminbi (RMB)), including $1 billion (~ 6.7 billion RMB) from both private and government investors.[6] Within that period, private, central government, and provincial and city funding for Chinese commercial space companies ballooned from just over $150 million in 2015 to around $600 million in 2019,[7] resulting in the formation of over 100 commercial space companies throughout the country. At the same time, China plans to lead the Earth-Moon space industrial market by establishing a presence on the lunar south pole and securing priority access to its resource-intense landscape. NASA Administrator Bill Nelson has noted that China's Chang'e 7 moon mission to explore ice at the lunar south pole[8] could potentially land in areas where the NASA Artemis 3 mission is scheduled to visit in 2025.[9]

II.B. Space Nuclear Power and Propulsion (SNPP)

Space nuclear power can be further classified into radioisotope thermoelectric generators (RTGs), radioisotope heater units (RHUs), and nuclear fission reactor groups. Space nuclear propulsion can be subclassified into nuclear thermal rockets (NTRs), nuclear electric propulsion (NEP) systems,[10] and nuclear fusion-based concepts. A brief overview of each follows.

II.B.1. Space Nuclear Power

Among space nuclear power technologies, RTGs, convert the heat generated by radioisotopic decay into electricity.[11] Previous DOE-built RTGs leverage plutonium-238 oxide fuel and static electrical converter systems that employ thermocouples to generate current. Multi-mission radioisotope thermoelectric generators (MMRTGs) contain 4.8 kilograms or more of plutonium dioxide (PuO2) fuel and initially provide 2,000 watts (W) of thermal power in deep space environments.[12] MMRTGs powered the NASA Mars 2020 Perseverance rover and will serve as the baseline power system for the NASA Dragonfly mission to Saturn's moon, Titan.

Next, RHUs, are small devices that use plutonium-238 (Pu-238) to heat a spacecraft's electronic instruments and mechanical systems operating in cold temperatures of space.[13] Three distinct advantages of RHUs are that they: (1) allocate scarce spacecraft electrical power to operate systems and instruments; (2) reduce potential electromagnetic interference with instruments or electronics; and (3) only require a nearly pencil eraser-sized fuel pellet which outputs about 1 W of power.[14]

Finally, space nuclear reactors operate according to the same process employed by terrestrial nuclear reactors. Through this process, (1) neutrons strike unanium-235 (U-235) atoms, (2) said atoms are split into lighter atoms and emit additional neutrons, and (3) such neutron emissions cause a subsequent chain of fission reactions that yield high levels of energy.[15] Nuclear reactors generate reliable electrical power ideal for power-intensive, long-duration space missions.[16]

II.B.2. Space Nuclear Propulsion

Nuclear thermal rockets (NTRs) were first tested in the 1970s and employed highly enriched uranium in the nuclear fission process.[16] Through this process, uranium atoms are split, and the resulting high levels of heat are utilized to vaporize rocket propellants such as liquid hydrogen. Thereafter, the gaseous propellant is accelerated through a nozzle in a manner akin to that which takes place in a conventional chemical rocket engine.[17] NTR propulsion offers a high thrust-to-weight ratio that is roughly 10,000 times greater than electric propulsion. It also currently offers as little as two and as much as five times greater specific impulse than in-space chemical propulsion. NTR engines are thus anticipated to enable future long-duration spaceflight missions, the efficient and quick transport of materials and people to the Moon and Mars, and robotic missions in space.

Nuclear electric propulsion (NEP) systems, another variety of propulsion technology, consist of power subsystems and propulsion subsystems.[18] Its power subsystem comprises a nuclear reactor which generates heat, - thermal-to-electric power converters, and a primary power distributor connected to the interface between the two subsystems. The propulsion subsystem consists of a secondary power distributor and a power processing module which delivers power in the form required by the thruster engines. Overall, NEP systems benefit from high exhaust velocity and specific impulse and can generate electric power at the hundred-kilowatt (kW) to megawatt (MW) scale. Multimegawatt electric propulsion systems show potential to substantially reduce propellant mass and therefore initial mass in low Earth orbit (IMLEO) as well a shorten trip times for both robotic interplanetary exploration and cargo missions.[19]

NASA, the DOE, and the DOE have been independently or jointly developing at least 11 NEP concepts. These include: (1) liquid metal cooled, solid fuel, dynamic power conversion concepts; (2) gas cooled, solid fuel, static conversion concepts; (3) gas cooled, solid fuel, dynamic power conversion concepts; and (4) vapor core reactor concepts. 10 NEP thruster concepts have also been researched, including: (1) steady state, electromagnetic concepts; (2) pulsed electromagnetic concepts; (3) pulsed electrothermal thruster concepts; and (4) steady state electrostatic ion engines.[20]

Finally, recent tests and demonstrations involving nuclear fusion technologies add to the list of potential space nuclear propulsion applications. The high temperatures allow the attractive nuclear force to outweigh mutual electrical repulsion and fuse the respective atomic nuclei, releasing massive amounts of energy. On December 5, 2022, a team at the National Ignition Facility (NIF) of the DOE Lawrence Livermore National Laboratory (LLNL) successfully conduced an experiment in which laser energy was utilized to spark the first controlled fusion burn that yielded more energy than the energy required to commence the process.[21] Data from this NIF experiment provided fundamental insights for researchers at the DOE Princeton Plasma Physics Laboratory (PPPL) who are studying how to develop a fusion-based rocket thruster to propel humans at greater speeds to Mars and beyond.[22]

One fusion application under development at PPPL involves using electromagnets to replicate the magnetic reconnection process that occurs on the surface of the sun and elsewhere throughout the universe. The process occurs when magnetic field lines converge, separate, and reconverge, suddenly and cyclically, in a manner that produces considerable loads of energy. Though the large energy loads have considerable implications for space propulsion, feasibly scaling down fusion reactors to fit spacecraft size and weight constraints will challenge scientists and engineers moving forward. A number of private companies are also seeking to develop fusion technologies for space applications, pursuing various technical approaches.

II.C. Space Treaties, Laws, and Policies

Various international treaties, multilateral accords, intergovernmental frameworks, and domestic laws and policies affect the development and proliferation of SNPP applications. Many of these are outlined in part below.

II.C.1. International Treaties and Multilateral Accords

Five major U.N. Treaties on outer space lay the foundations of international space law. These include: (1) Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (i.e., the Outer Space Treaty or OST), (2) Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space (i.e., the Rescue Agreement), (3) the Convention on International Liability for Damage Caused by Space Objects (i.e., the Liability Convention), (4) the Convention on Registration of Objects Launched into Outer Space (i.e., the Registration Convention), and (5) the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (i.e., the Moon Agreement). The UN's AR 47/68 Principles Relevant to the Use of Nuclear Power Sources in Outer Space was approved at the 35th session of U.N. Committee on the Peaceful Uses of Outer Space (COPUOS). It recognizes, inter alia, that the compactness, long life, and other attributes of nuclear power sources render them ideal for some outer space missions.

Turning to U.S.-led multilateral efforts, The Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes were initially adopted by Australia, Canada, Italy, Japan, Luxembourg, the United Arab Emirates (U.A.E.), the U.K., and the U.S. on October 13, 2020. The Accords provide a novel set of principles which build upon the legacy of the Apollo 11 program, welcome coordination via such multilateral forums as the U.N. COPUOS, and reinforce and implement the major U.N. Treaties and Conventions on outer space. Specifically, the Artemis Accords aim to establish a common vision via "...Adherence to a practical set of principles, guidelines, and best practices in carrying out activities in outer space..." which is intended to "...increase the safety of operations, reduce uncertainty, and promote the sustainable and beneficial use of space for all humankind." They further state that: (1) cooperative activities shall be implemented through Memoranda of Understanding, Government-to Government and Agency-to-Agency Agreements, and other appropriate bilateral instruments; and (2) all cooperative activities should be exclusively for peaceful purposes, in accordance with relevant international law, and compel broad dissemination of information and scientific information sharing among Signatories and with the public and the international scientific community where appropriate.

Next, jointly published by the U.N. COPUOS Scientific and Technical Subcommittee and the International Atomic Energy Agency (IAEA), the 2009 *Safety Framework for Nuclear Power Source Applications in Outer Space* provides voluntary guidance on launch, operation, and end-of-service mission phases of space nuclear power sources (NPSs). It complements the IAEA Safety Standards Series and existing national and international safety guidance and standards related to the design, manufacture, testing, and transportation of space NPS. Echoing the OST, its safety objective is "... the protection of people and the environment in Earth's biosphere from potential hazards associated with relevant launch, operation and end-of-service mission phases of space NPS applications..." Accordingly, it states that governments should (1) establish safety policies, requirements, and processes for space NPS missions; (2) "verify that the rationale for using the space [NPS] application has been appropriately justified," (3) establish and sustain a mission launch authorization process for space NPS applications, and (4) prepare in advance to respond to potential emergencies involving space NPSs.

II.C.2. U.S. Space Laws

U.S. law related to space date at least as far back as The Communications Act of 1934 which was enacted implement "…rapid, efficient, Nation-wide, and world-wide wire and radio communication service…" for national security, safety, and other public welfare purposes. In 1958, U.S. President Dwight Eisenhower signed the National Aeronautics & Space Act of 1958 intended to "provide for research into problems of flight within and outside the earth's atmosphere, and for other purposes." Thereafter, the Commercial Space Launch Act of 1984 aimed to "promote economic growth and entrepreneurial activity through use of the space environment for peaceful purposes... to encourage the United States private sector to provide launch vehicles, reentry vehicles, and associated services," among other pursuits. Then, the Land Remote Sensing Commercialization Act of 1984 transferred the government-owned Landsat satellite program to private industry, while the Land Remote Sensing Policy Act of 1992 established the National Satellite Land Remote Sensing Data Archive at the United States Geological Survey (USGS).

Of recent note is the U.S. Commercial Space Launch Competitiveness Act of 2015 which was "...designed to encourage commercial spaceflight and innovation" through at least three major measures. The first involved postponing significant regulatory oversight of private spaceflight companies. The second was to provide government indemnification of third-party commercial launch damages beyond those covered by launch companies' compulsory insurance. The third allowed U.S. companies to retain rights to resources they extract from asteroids, the Moon, and other celestial bodies.

Next were the Weather Research and Forecasting Innovation Act of 2017, the National Aeronautics and Space Administration Transition Authorization Act of 2017, and the National Defense Authorization Act for Fiscal Year (FY) 2020. The first aims to improve the National Oceanic and Atmospheric Administration's (NOAA's) forecast and warning capabilities to protect lives and property and to enhance the economy. The second authorized a $19.5 billion FY 2017 funding level to support (1) the James Webb Space Telescope, (1) the Space Launch System, (3) the Orion crew vehicle, (4) the International Space Station (ISS), (5) commercial crew and cargo programs, (6) demonstration of technological and scientific goals of the Asteroid Robotic Redirect and human missions to Mars, (7) NASA's Mars 2020 rover, (8) the Wide-Field Infrared Survey Telescope, and (9) a mission to Europa. And the third established the U.S. Space Force within the U.S. Air Force and articulated its mission, makeup, duties, and chain of command.

II.C.3. U.S. Space Policies

The National Security Presidential Memorandum on the Launch of Spacecraft Containing Space Nuclear Systems ("NSPM-20") was issued by . President Donald Trump on August 20, 2019. Its purpose was to update the launch processes for Federal Government and Department of Transportation (DOT)-licensed commercial space launches of spacecraft containing space nuclear systems (e.g., RTGs, RHUs, and nuclear fission-based power, propulsion, and heat systems). It further established, as a matter of policy, that, inter alia, that: (1) the U.S. "...shall develop and use space nuclear systems when such systems safely enable or enhance space exploration or operational capabilities...;" and (2) Executive Branch Departments and agencies "... shall seek to ensure that safe application of space nuclear systems is a viable option for Federal Government and space activities."

Section 3(a) of NSPM-20 requires all mission planners and launch authorization authorities in missions involving U.S. Government or U.S. Government-licensed launches containing space nuclear systems (SNS) to ensure that their normal operations comply with applicable Federal, State, and local requirements. It further stipulates three probability-based guidelines, including ensuring that there is: (1) a less than 1 in 100 probability of an accident resulting in the exposure of between 25 millirem and 5 rem total effective dose (TED) to any member of the public; (2) a less than 1 in 10,000 probability of an accident resulting in the exposure of between 5 rem and 25 rem TED to any member of the public; and (3) a less than 1 in 100,000 probability of an accident resulting in the exposure of greater than 25 rem TED to any member of the public.

Section 4 stipulates, inter alia, that launch both "federal Government missions" (e.g. ,non-commercial launches conducted or sponsored by an agency) and commercial launches (e.g., those licensed by the Secretary of Transportation's authority under 51 U.S.C. chapter 509) of spacecraft containing SNS "...shall follow a three-tiered process based upon the characteristics of the system, the level of potential hazard, and national security considerations." Section 4(a) specifies that Tier I applies to spacecraft launches containing up to (and including) 100,000 times the quantities of radioactive sources listed in the relevant table of the International Atomic Energy Agency's Specific Safety Requirements No. SSR-6 (SSR-6). Section 4(b) dictates, inter alia, that Tier II applies to three specific launch types, including: (1) launches of spacecraft containing more than 100,000 times the quantities of radioactive sources listed in SSR-6;[23] (2) Tier I launches with associated safety analyses which determine a 1 in 1,000,000 or greater probability of an accident during launch or subsequent operations resulting in the exposure of between 5 and 25 rem TED to any member of the public; and (3) launches of spacecraft containing nuclear fission systems or other devices with a potential for criticality through the utilization of low-enriched uranium. (i.e., less than 20% uranium-235 enrichment). Section 4(c) then stipulates that Tier III applies to launches of spacecraft: (1) with associated safety analyses which determine a 1 in 1,000,000 or greater probability of an accident during launch or subsequent operations resulting in the exposure of greater than 25 rem TED to any member of the public; and (2) containing nuclear fission systems and other low-enriched uranium-using devices with a potential for criticality.

Furthermore, a collection of seven Space Policy Directives (SPDs) issued by the President guide U.S. policies and procedures related to space activities. In 2017, SPD-1, "Reinvigorating America's Human Space Exploration Program," amended the 2010 Presidential Policy Directive-4 and called for space missions to the Moon, Mars, and other celestial bodies beyond low Earth orbit (LEO). In 2018, SPD-2, "Streamlining Regulations on Commercial Use of Space," compelled Executive Branch agencies to review existing rules and regulations to ensure that they are not duplicative and to promote economic growth, advance national security and foreign policy goals, and encourage U.S. leadership in space commerce. And SPD-3, "National Space Traffic Management Policy," was issued in 2018 and called for a new space traffic management (STM) method, established space situational awareness and STM innovation priorities, aligns with national security priorities, and encourages U.S. growth in commercial space.

SPD-4, "Establishment of the United States Space Force" was issued in 2019 and directed the Department of Defense to submit a legislative proposal for the establishment of a U.S. Space Command and the U.S. Space Force as the sixth branch of the U.S. Armed Forces. SPD-5, "Cybersecurity Principles for Space Systems," of 2020 directed Executive Branch Departments and Agencies to establish government and commercial space industry practices which protect space assets and supporting infrastructure from cyber threats. Skipping to SPD-7, "U.S. Space-Based Positioning, Navigation, and Timing Policy," which was issued in 2021, this policy established implementation actions and guidance for U.S. space-based positioning, navigation and timing (PNT) programs for civil, commercial, scientific, national security, and homeland security purposes.

Of particular import to this study, SPD-6, "National Strategy for Space Nuclear Power and Propulsion," issued in 2020 established a national strategy, policy goals, and roadmaps for safely and sustainably utilizing SNPP systems for scientific, exploration, national security and commercial objectives. Issued as a means to direct interagency coordination for the implementation of NSPM-20, SPD-6 established, as a matter of policy, that safely, securely, and sustainably utilizing SNPP systems is critical to "...maintaining and advancing United States dominance and strategic leadership in space." SPD-6 specifically designates SNPP systems as critical given their unique abilities to (1) enable operations in "...environments where solar and chemical power are inadequate..."; (2) produce more power at lower mass and volume compared with other energy sources; and (3) reduce transit times and therefore radiation exposure for crewed and robotic spacecraft.

III. ANALYSIS AND DISCUSSION

As the global space economy undergoes precipitous growth, the treaties, laws, and policies stand to guide the research, development, demonstration, and deployment (RDD&D) of SNPP applications. Despite recent development of SNPP-related policy, there remain a number of nuclear risk-related shortcomings persist, including: (1) a lack of exclusive liability for launching states or entities and (2) a lack of a statutory cap on maximum damages in the event of a nuclear release. This section considers multiple government agency, national laboratory, and industry sources to assess the historical, empirical, technical, policy, regulatory, and technical factors affecting PAA coverage of SNPP launches.

III.A. DOE PAA Recommendations

The Department of Energy's January 2023 Report to Congress on the Price-Anderson Act recommends (1) the expansion of the PAA; (2) the continued and expanded broad and mandatory coverage of DOE indemnification; and (3) PAA continuation in compliance with the IAEA Convention on Supplementary Compensation for Nuclear Damage. Considered together, the first two of these recommendations would be conducive to expanding the PAA to cover nuclear accidents resulting from private sector SNPP applications. [24]

Regarding the first recommendation, the DOE Report notes that the mandatory and exclusive nature of DOE indemnification coverage under the PAA adds stability and reassurance to private for-profit and non-profit prime contractors, prime contractor partner entities, subcontractors, support service contractors, supplier companies, non-profit organizations (NPOs), and educational institutions. The Report further notes that continued and mandatory PAA coverage is needed now more than ever due to the DOE's role in supporting new and advanced small modular reactors (SMRs), microreactors, HALEU and other fuels, and other cutting-edge nuclear technologies, many of which have potential space applications. Moreover, this dovetails with the DOE's Energy for Space strategy[25] which aims to develop space nuclear technologies and fuels to ensure America's leadership and competitive advantage in space.

In its second recommendation, the DOE suggests that PAA coverage for DOE contractual activities performed even by non-DOE entities should include those activities which advance such next generation nuclear capabilities as small modular reactors, microreactors, and space and defense applications. Furthermore, given the increasing and diverse work that the DOE conducts outside the U.S., it also supports expanding Price-Anderson Act coverage to provide up to $2 billion in compensation for nuclear incidents which occur outside of the Unites States as a result of contractual activities performed for or on behalf of the DOE. Additionally, given the broad array of contractual activities related to nuclear non-proliferation, nuclear risk reduction, terrestrial and space microreactors, and other pursuits performed outside of the U.S., the DOE suggests expanding PAA coverage to include nuclear incidents arising from activities which involve nuclear materials that are not necessarily owned by the U.S. Notably, this could result in substantial changes in practice, DOE currently maintains ownership of radionuclides launched into space in order to comply with PAA provisions and maintain coverage under the system.

The DOE Report's third recommendation states that PAA provisions should continue to provide protections required by the 2015 *IAEA Convention on Supplementary Compensation for Nuclear Damage (CSC)*. The CSC aimed to establish a minimum national compensation amount for Contracting Parties which could be increased through Contracting Party contributions it is insufficient to cover by nuclear incidents damages. To comply with the protections required by CSC Annex Article 2, the PAA must continue to provide: (1) strict liability for nuclear incidents causing substantial offsite damage; (2) indemnification, to the extent legally liable, to non-operator entities; and (3) roughly $1.4 billion in indemnification for damage at civilian nuclear plants and roughly $425 million in indemnification for similar damage at other nuclear installations.

III.B. Soviet and American Accidents and Failures

Historically, only a few SNPP-related accidents have occurred, and those that have were not very severe. In both U.S. and former Soviet government space programs, SNPP-related accidents generally led to small or negligible releases of radioactive material without requiring large scale cleanup efforts or costs. This suggests the potential for the amounts available under the PAA nuclear accident compensation would be sufficient to address SNPP-related incidents.

III.B.1. American Accidents and Failures

In the U.S., the Transit 5-BN-3 satellite mission[26] was launched on April 21,1964 and aborted due to an RTG design-based launch failure. The failure resulted in burnup during re-entry of the satellite's SNAP-9A RTG over the upper atmosphere of the southern hemisphere.[27] The 2.2 pounds of Pu-238 fuel in the RTG also completely burned up during re-entry.[28] Following the incident, NASA reported that roughly 25% of the released plutonium was deposited in northern latitudes and 75% settled in the southern hemisphere.[29] Though some scientists expected the dispersal of Pu-238 to have health effects for decades thereafter,[30] scientists from NASA, the DOE, and the Federation of American Scientists contend that such a release would have minimal if any human health impacts. As a result of this accident , future American RTGs were designed to enable plutonium fuel modules to survive orbital re-entry.

Next, the Nimbus B-1 meteorological satellite was launched on May 18, 1968 from Vandenberg Air Force Base in California. The mission was aborted and the launch vehicle destroyed shortly after launch via a range safety destruct command. Thereafter, radioactive heat source material was recovered off the California coast and fuel capsules were reused in a later mission. Importantly, there was no evidence of plutonium release in the environment, and the incident confirmed that radioisotope fuel capsules can remain in a marine environment following a mission failure without releasing radioisotopic material into the water.

Finally, the Apollo 13 mission to the moon was aborted in April 1970 due to an oxygen tank explosion in the spacecraft service module. During re-entry, the mission's lunar excursion module equipped with a SNAP-27 RTG broke up above the south Pacific Ocean and dropped its intact RTG heat source into the Tonga Trench where it remains to this day. The DOE commented that that extensive testing of the RTGs in sea waters suggests that it would not release any plutonium over time.[31]

III.B.2. Soviet Accidents and Failures

Additionally, between 1969 and 1982, at least six Soviet space nuclear power sources experienced launch failures or other malfunctions which resulted in the reentry of reactor-powered radar ocean reconnaissance satellites (RORSATs) into the Earth's atmosphere.[32] The first involved a January 25, 1969 RORSAT launch failure which reentered the atmosphere the same day. Subsequently, the Cosmos 300 and Cosmos 305 missions of September 23, 1969 and October 22, 1969 may have been carrying Pu RHUs and reentered the atmosphere after upper stage malfunctions prevented their respective payloads from leaving Earth orbit. Next, an April 25, 1973 launch failure of a reactor-based RORSAT led to reentry on the same day. Notably, the spacecraft fell into the Pacific Ocean where radioactivity was detected.

Later, the September 18, 1977, Cosmos 954 mission experienced a payload malfunction which led to reentry above Canada. The Atomic Energy Control Board of Canada reported that the reactor completely disintegrated during reentry and that roughly 4 kg of fuel reached Earth and spread over roughly 100,000 square kilometers.[33] The report further noted that: (1) the environmental impact of unrecovered particles is likely insignificant compared with (then-) existing fallout deposition; (2) since the reactor had disintegrated, the residual hazards to people from direct radiation were negligible; and (3) the effect of debris on the natural environment were considered insignificant. In fact, the lake in which most of the radioactive contamination was concentrated "...was found to be considerably less radioactive than the natural radioactive background from rocks in the surrounding area."[34] Furthermore, a follow up study on health impacts conducted by the Canadian Radiation Protection Bureau concluded, inter alia, that field investigations showed no detectable contamination of air, drinking water, soil, or food supplies and that radioactive debris would not be encountered in doses that impact public health.[35]

Next, after its payload failed to boost into orbit, the spacecraft structure and reactor fuel core of Cosmos 1402 which were launched on September 18, 1977 respectively reentered the atmosphere on January 23 and February 7, 1983. Notably, the reactor core was ejected to facilitate burnup following the boost failure. The Soviets commented that the Cosmos 1402 reactor was designed to completely burn up during reentry to prevent activated components from reaching the ground[36] and that radiation releases would be within the limits recommended by the International Commission on Radiological Protection.

Furthermore, as an example of an accident that did not involve reentry, following the launch of Cosmos 1900 on December 12, 1987, the Soviets lost command of the reactor's two autonomous safety systems while it remained operational. The first system was designed to separate and boost the spacecraft's reactor upon detection of anomalies. The second system was designed to eject the core should the first system fail to boost the reactor. Failures of the stabilization and thermoelectric conversion systems, reactor temperature increases, voltage fluctuations, and loss of main instrumentation integrity were among reported events which may have triggered the system's boost. A DOE-sponsored study estimated that because Cosmos 1900 reached its storage orbit, the long-term risk associated with reentry within 500 years was less than 0.005 excess cancer fatalities.[40]

III.C. NRC PAA Recommendations and the INES

The Price-Anderson Act: 2021 Report to Congress was published by the NRC[37] in fulfillment of Subsection 170(p) of the Atomic Energy Act of 1954. The Report covers (1) history, major provisions, and scope of the Price-Anderson system, as well as legal issues with PAA litigation, the condition of the nuclear industry, and the state of knowledge of nuclear safety. The report continues to cover the availability of private nuclear liability insurance, the estimated liability costs for radiological accident, the adequacy and appropriateness of government indemnification, issues raised by the IAEA Convention on Supplementary Compensation for Nuclear Damage, and the potential burdens of rising retrospective premiums. Of import to this study, the report covers the 2005 PAA Amendment which provides financial protection for modular and other reactors, which may have implications for SNPP systems. The report additionally compares the placement of both the Three Mile Island and Fukushima Daiichi incidents on the IAEA/OECD NEA International Nuclear Event Scale (INES)[38] to compare PAA applicability. It also provides probability risk assessments related to the most extreme projected nuclear accidents in terms of offsite economic costs. Each of the above may inform the treatment and liability cost estimations for radiological accidents resulting from SNPP system launches.

II.D. SNL Space Nuclear Launch Safety Assessment

The *Nuclear Risk Assessment 2019 Update for the Mars 2020 Mission Environmental Impact Statement* (NRA) published by Sandia National Laboratories (SNL) researchers "...addresses the responses of the MMRTG option to potential accident and abort conditions during the launch opportunity for the Mars 2020 mission and the associated consequences." [39] The report incorporates the Mars 2020 Mission technology profile to simulate probabilities of nuclear accidents and associated radiological consequences at various spacecraft launch stages. The 2019 NRA was provided to support the Mars 2020 Mission Supplemental Environmental Impact Statement (SEIS) and comports with SNS-enabling safety assessments required by NSPM-20.

SNL's space nuclear launch safety analyses assess, inter alia, the: (1) mean probability of an accident; (2) mean probability of release of radioactive material; (3) mass of material released ("source term"); (4) health effects as measured by radiation doses and latent cancer fatalities; and (5) land and cropland contamination. Its assessment methodology employs simulations and Monte Carlo sequence codes in probabilistic risk analyses of: (1) potential accidents associated with launches (e.g., probability, environment); (2) system responses to insults (e.g., explosion overpressure, fragments, ground impact, thermal environment, reentry, criticality); and (3) atmospheric transport and consequences (e.g. thermal buoyancy effects from fires, meteorological conditions, population and land usage distribution).[40]

The Mars 2020 Mission included the launch of a robotic rover designed to perform comprehensive scientific investigations on the surface of Mars. The rover was launched via an Atlas V 541 launch vehicle comprised of (1) a First Stage with strap-on solid rocket boosters (SRBs), (2) a Second Stage Centaur III, and (3) the Payload Fairing (PLF) which housed the rover. The objectives of the mission were expected to be completed within 1.25 Mars years while the rover flight system was developed to enable up to 1.5 Mars years of surface mission capability. To traverse the Martian surface, the rover employed an MMRTG comprised of eight general purpose heat source (GPHS) modules fueled by 4.8 kg (10.6 lbs.) of PuO2 in ceramic form (roughly 59,000 ci). It also employed lead-telluride (Pb-TE) thermoelectric converters that operate at comparatively lower temperatures than those of GPHS-RTG configurations.

The NRA assessed risks throughout the following mission phases: (1) Phase 0: the Pre-Launch stage from MMRTG installation to immediately prior to the ignition of First Stage liquid rocket engines (LREs); (2) Phase 1: the early launch phase, from the LRE starts to just prior to a point in time where there would be no potential for debris or intact vehicle configurations resulting from an accident to impact land in the launching area; (3) Phase 2: the late launch phase in which the vehicle reaches the 30,480 m. (100,000 ft.) altitude above which reentry heating could occur; (4) Phase 3: the suborbital reentry phase beyond the 30,480 m. altitude to the end of the Stage 2 burn 1; (5) Phase 4: the orbital reentry phase from the end of the Stage 2 burn 1 to the Stage 2 or spacecraft separation; and (6) Phase 5: the long-term reentry phase after spacecraft separation until no chance of Earth Reentry. The results demonstrate three key insights.

First, the overall mean exceedance probabilities for maximum individual dose levels during all mission phases are far below the exceedance probabilities outlined in the NSPM-20 guidelines. Specifically, the NSPM-20 stipulates that the probabilities that any member of the public will be exposed to 25 mrem, 5 rem, and 25 rem should not exceed 1 in 100, 1 in 10,000, or 1 in 1000,000, respectively. The results reveal that the early launch stage has the highest, 1 in 1,000 probability of an accident and that accident probabilities at the remaining stages do not exceed 1 in tens of thousands.

Next, regarding maximum individual doses, accidents during the late launch stage would lead to the lowest, 0.0492 mrem of exposure, while the prelaunch, early launch, and orbital reentry phases could lead to 81.5 mrem, 107 mrem, and 86.4 mrem of exposure in the low probability that they occur. These results, in addition to the overall mission's 1 in 96,000 probability of an accident with 25.8 mrem of exposure, are far below the 1 in 100 probability of a 25 mrem to 5 rem exposure guidelines outlined in NSPM-20.

Finally, the maximum individual dose exposures and land contamination given both accidents and releases would be far lower than what resulted from both the Three Mile Island and Fukushima incidents. Specifically, the 10,000,000 Ci and 25,405,405 Ci respective source terms of the two aforementioned incidents is far greater than the highest probable source term of the overall Mars 2020 Mission simulation (2,340 Ci). This is significant because, given the significantly lower magnitude of an SNPP-related accident compared with nuclear power plant accidents the PAA was designed to cover, the PAA regime could feasibly cover launch accidents involving technology profiles similar to the Mars 2020 Mission

The Mars 2020 Mission would have a 1 in 96,000 probability of a 2,340 source term that is roughly 0.02% and less than 0.01% of the Three Mile Island and Fukushima source terms. It would thus likely lead to far smaller cleanup costs and time periods. Moreover, PAA insurance pools covered (1) approximately $71 million in liability claims costs and litigation expenses and (2) $160 million accident damages following the Level 5 Three Mile Island accident. This suggests that the PAA regime could cover the financial risks that would arise from an INES Level 2 or smaller accident that would likely result from a launch accident involving an MMRTG similar to that of the Mars 2020 Mission technology profile.

III.E. DOT and FAA Launch Liability Analysis

The 2002 *Liability Risk-Sharing Regime for U.S. Commercial Space Transportation: Study and Analysis* report by the DOT and Federal Aviation Administration (FAA) assessed, inter alia: (1) current U.S. liability risk-sharing regime for commercial space transportation; (2) regimes of other countries with space capabilities; (3) appropriateness of labelling all space transportation activities as "ultrahazardous activities" for which a strict liability mat attach; (4) the effect of relevant international treaties on Federal Government liability for commercial space launches; (5) evolving the commercial space transportation liability regime towards an airline liability regime approach; (6) changes to the Federal Government's indemnification of commercial spaceport operations; and (7) possible modifications to the commercial space transportation liability regime. The Report notes that the current regime is adequate, appropriate, effective, and needed. However, it differs from others in comprising a three-tier system with a defined limit on government indemnification. It also is unique in including a sunset provision, limited government indemnification subject to appropriations, and a risk-based method to determine primary insurance coverage requirements. The Study also suggests, among other things, that the U.S. maintain adequate third-party space launch liability insurance, establish trust funds and require the industry to self-insure, require maximum-probable loss (MPL)-based insurance familiar to launch customers and contractors, and establish full cost internalization by launch participants.

IV. CONCLUSIONS

Considering all of the above, this study provides the following insights into expanding the PAA to cover private sector SNPP:

1) **Historical**: Dating back to U.S. and Soviet pursuits throughout the middle of the 20th century, SNPP applications are the products of targeted, decades-long R&D and show tremendous promise for fulfilling the objectives of expanding private and public sector operations in the burgeoning space economy.

2) **Policy**: SNPP applications, as demonstrated by the SNL assessment of the Mars 2020 Mission technology profile, and a review of historical incidents involving SNPP launches, can be developed to comport with launch safety guidelines articulated by NSPM-20 and reinforced by SPD-6. PAA coverage could help developers manage risk, thus catalyzing SNPP development and furthering U.S. policy objectives.

3) **Regulatory**: The DOE recommends expanding PAA to cover private SNPP systems that are integral to its domestic and international contractual activities. The NRC has signaled support for PAA coverage of non-LWR, novel nuclear technologies with space applications. And the DOT and FAA suggest PAA coverage may complement existing space launch regulatory frameworks.

4) **Empirical**: The SNL Mars 2020 Mission assessment revealed that potential radiological and human health consequences of SNPP accidents are likely less probable, severe, and costly than major terrestrial nuclear power accidents. PAA schemes may provide sufficient compensation for private sector SNPP accidents.

5) **Technical**: SNPPs leverage the technical expertise of nuclear power, space, and heavy industries and can be designed to avoid or mitigate the most adverse consequences of nuclear accident precedents. HALEU and other nuclear fuel development and the gradual proliferation of fusion and fission reactors stand to revolutionize space economy activities yet require risk liability shields such as those in the PAA system.

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