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EMERGENCE OF A COMMERCIAL SPACE NUCLEAR ENTERPRISE

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Space nuclear systems have historically been developed and operated solely by the government. Private entities have always played a role in developing and launching nuclear payloads, but the Federal government drove of development and operation of such systems with the private sector playing the role of a contractor. However, recent years have seen growing private sector interest in leading the development, launch, and use of nuclear technologies for space applications. This growth follows similar trends toward commercialization in the broader space sector.

This paper summarizes research that included a survey of the literature and interviews with 12 companies related to the space nuclear industry. The paper presents a definition of commercial space activities, develops a model for space nuclear systems, and then explores the status of commercial space nuclear activities in the United States. Ultimately we assess that the private sector is interested in expanding their role in the space nuclear enterprise, but requires, among other changes, regulatory revision to become fully commercial.

I. Evolution of Private Involvement

The space nuclear industry in the United States has consisted of the Federal government as the principal player using primarily radioisotope power systems (RPS). As of this writing, the U.S. has launched 45 radioisotope thermoelectric generators (RTGs), about 240 radioactive heater units (RHUs), and one fission reactor [1]. Most of these devices have been included on missions that were planned, funded, and launched by the National Aeronautics and Space Administration (NASA). In the majority of these missions, the Department of Energy (DOE) developed and fueled the systems.

Previous and current NASA missions involving nuclear technologies have included private sector entities. Private industry supports both NASA in launch operations and DOE in system development—exclusively in a contracting role. For example, for the upcoming Mars 2020 mission, DOE procured the unfueled multi-mission radioisotope thermoelectric generators (MMRTGs) powering the rover from Aeroject Rocketdyne (AR) and Teledyne Energy Systems (Teledyne) [2]. NASA has contracted with the United Launch Alliance (ULA) to provide launch services. This government-industry model engages private entities, but is not commercial because in each stage the private entity is under contract with and acting on behalf of the government (see Fig. 1).

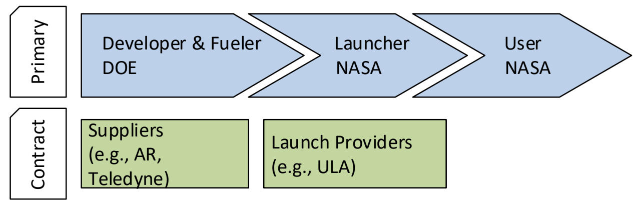

Figure 1: Space Nuclear Enterprise as a Government Led Program

Through our research, we have found that private entities have a growing interest in taking on a larger role in the supply and operation of space nuclear power technologies. This development has occurred in parallel with growing interest in commercial activities in the broader space sector [3]. It is conceivable that a nuclear system could be developed, fueled, launched, and operated in space with only regulatory involvement from the government.

II. Defining Commercial Space Nuclear Power

As discussed above, the private sector has always been part of the space nuclear enterprise. However, it is unlikely that these private activities can be considered "commercial." In order to assess private involvement in the space nuclear enterprise, it is worthwhile to first define what commercial is.

There is no commonly accepted definition of the term "commercial" in the context of space-based activities. Both the Bush Administration in 1991 [4], and current National Space Policy (2010) [5] provide definitions of commercial space activities. In both cases, commercial space refers to activity where companies either use internal funds or other risk-based external equity to develop product and services, and where some of the companies' customers are or will eventually be non-governmental entities. Commercialization therefore has two dimensions, risk and breadth of the customer base. Under this definition, if a private space nuclear company develops a reactor partially or fully with internal funds or funds raised in private markets, and sells the reactor to a variety of users including the government, it is engaging in a commercial activity. Figure 2 illustrates the concept as a quad chart, with examples in each quadrant. The remainder of the paper uses this definition of commercial.

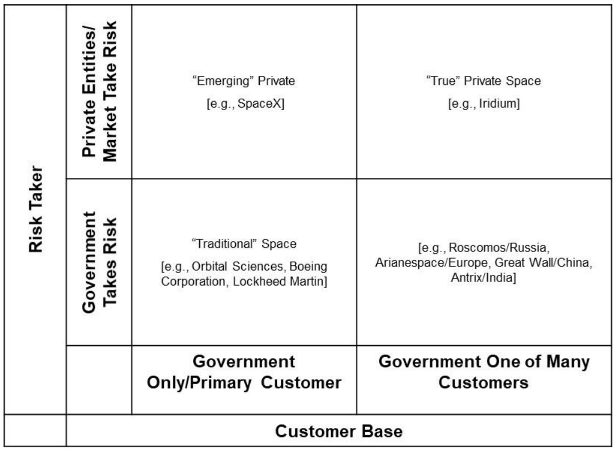

Figure 2: Framework to Define Commercial Space Activities [6]

III. Commercial Roles in the Space Nuclear Ecosystem – Model and Illustrations

The space nuclear enterprise can be seen as having four main elements (Figure 3):

Fig. 3. Space Nuclear Enterprise as a Government Led Program

Development and Supply. Development refers to the technological development of the overall power or propulsion system; supply refers to its actual manufacture.

Fuel and Fueling. Fueling refers to the process of developing and manufacturing the formed fuel for a nuclear system; this could be subsumed under development and supply, but it is considered separately because often entities other than the developer can provide fuel, and there are safety and proliferation concerns for some fuels such as highly enriched uranium.

Launch. A nuclear system, once developed, must be launched and delivered to its destination either in Earth orbit or to a deep space location.

Use. Use refers to the operation of the nuclear system, either independently or as a subsystem in a larger device, in space or on the surface of an extraterrestrial body.

In the sections below, we discuss private involvement and interest in each element of this model, and review the current commercial standing in each specific role.

II.A. Developers/Suppliers

Our interviews indicated no private sector interest in commercially developing RPS, likely due to a combination of insufficient non-governmental demand as well as the legal and regulatory difficulty of acquiring and handling the Pu-238 fuel.

We did find, however, growing interest in providing fission power systems for space applications. We identified three companies with active development projects for space fission reactors (BWXT, Ultra Safe Nuclear Company, and Atomos Nuclear and Space), and three other companies with terrestrial reactor programs that could be applicable to space (NuScale, Westinghouse, and Oklo). The potential suppliers range from recent startups to established suppliers, and most have an existing terrestrial power business. These companies are leveraging developments and trends in terrestrial technology—small or micro reactors, lower power levels, advanced fuels, high outlet temperatures, and off-site fabrication and assembly.

The developing space reactors reflect the technical diversity seen in the burgeoning terrestrial industry. See Table 1 for a review of the common technical characteristics being considered (no company has finalized its designs).

Table 1: Characteristics of the emerging private suppliers

Characteristic	Examples from Private Suppliers
Power levels	10 kWe to 10 MWe
Fuel being considered	TRISO, CERMET, Metal Fuels, PWR Assemblies
Fuel Enrichment	HALEU (19.75% enriched U-235), HEU (>20%)
Coolant	Helium, liquid sodium, light water
Conversion cycles	Brayton, Rankine

The growing private interest in fission systems is mirrored in government trends; NASA has increased its support of fission systems. While government funding is increasing, several of the companies mentioned here have committed significant private funds to developing space systems.

All the entities met our definition of commercial in that they both invest private (or internal) funds, and expect to sell their technology to the government and other private and international customers. The most aggressive private suppliers are looking to test or deploy full power systems in the mid-2020’s.

II.B. Fuelers

U.S. Radioisotope Thermoelectric Generator (RTG) systems have used Pu-238, which is a controlled material. A private entity may be able to handle Pu-238 for RPS, but would likely require close government affiliation and expensive safety processes. This high cost combined with a lack of interest in commercializing RPS, makes a private Pu-238 fuel supply is unlikely.

Highly Enriched Uranium (HEU) has high safety and proliferation risks similar to Pu-238. The only privately-owned facilities licensed to handle and manufacture HEU fuel are owned by BWXT, which supplies and services the Navy's nuclear reactors. Licensing facilities to handle HEU are potentially cost-prohibitive without government support; for example, the annual fee for simply holding a class 1 license is over $7 million (10 CFR 171.16).

Handling Low Enriched Uranium (LEU) fuel, and even at higher enrichments (such as high assay LEU [HALEU] at 19.75%), has lower regulatory and safety requirements. Most private suppliers are planning to use HALEU fuels; however, there is no established supply chain or available source of the HEU feedstock. The fuel required for effective space reactor operation could prove challenging to source commercially and domestically (indeed some companies are considering importing fuel from China).

II.C. Launchers

Launching nuclear payloads serves as the point of approval for space nuclear systems. Only one company, United Launch Alliance (ULA), has launched nuclear payloads: their Atlas V rocket launched New Horizons (2006) and Mars Science Lab (2012) missions, and will launch Mars 2020. Launches such as these cannot be considered commercial under the definition provided above, as most launches have occurred under cost-plus type contracts.

Emerging private companies—namely SpaceX and Blue Origin—are developing larger rockets, and could in principle, launch nuclear payloads as commercial providers with fixed price contracts. However, under the current Federal Aviation Administration-led (FAA) commercial launch regime, privately owned and operated nuclear launches are not easily feasible. None of the existing commercially oriented rockets (Falcon 9, Falcon Heavy) or emerging (New Glenn) rockets have been approved for launching nuclear systems, nor is there a clear path forward for companies to obtain nuclear launch approval. This uncertainty only increases in the case of defining nuclear propulsion systems as an upper stage rather than a payload.

II.D. Users

As defined earlier in this paper, a commercial industry involves a broad customer base where the government is only one of many customers. In this context, a customer is the user of a nuclear system in space or on an extraterrestrial body such as the Moon, Mars, or an asteroid.

No private sector entities have operated a nuclear system in space, and we did not identify any companies actively seeking to procure nuclear devices. There is, however, interest from private entities in using nuclear power. We spoke to at least three companies that expressed interest in using the entire range of nuclear systems, from RHUs for thermal control, to a nuclear electric or thermal propulsion, to a surface reactor to support human and in situ resource utilization (ISRU) operations on the surface of the Moon or Mars.

Companies with interest in space nuclear systems indicated that such systems would provide significant value to their operations. That value, these companies pointed out, would need to be proportional to the cost of procuring a nuclear system, including launch approval. Two companies indicated that they have not seriously considered space nuclear systems because of regulatory uncertainty.

In the longer term, a more mature space economy that encompasses not only Earth orbits but cislunar and deep space, would have more uses for nuclear power, particularly fission reactors. Many of the more compelling use-cases for nuclear power such as sustained human surface operation, ISRU, or long-distance human transportation are not currently commercially viable and thus not providing demand for nuclear systems—but could evolve to support an active commercial market.

Both commercial supply of space nuclear systems and commercial interests in space (as well as commercial interest in launch of government or private nuclear payloads) are rapidly emerging and evolving, so it is difficult to predict the exact demand for nuclear systems from commercial entities. Conservative estimates place a critical mass of demand for nuclear systems to begin in the early 2030s.

III. Challenges

The emergence of a commercial space nuclear market is an exciting development, but faces many challenges including technical, regulatory, and economic. This paper does not address international legal challenges, which will be discussed in a separate paper.

Nuclear power, especially fission, is a relatively mature technology terrestrially, but there are challenges for its application to space with respect to both development on the ground, robustness during launch, and operations in space. The private nuclear industry faces at least two technical challenges: developing increased performance from systems through improvements (e.g., better thermal regulation via advanced materials); and developing sufficient technical understanding and operating experience in space to demonstrate that safe operation in a high radiation, microgravity, vacuum and other environments. The second of these may be a more difficult challenge, as many of the technologies proposed by private entities use advanced materials or fuel types that do not have extensive operational experience, especially in the space environment.

One critical challenge facing the private space nuclear industry is launch approval: there is currently no established approval regime for the private launch of nuclear payloads. Without such a regime, U.S. private entities are left to either work through the government or precipitate a regulatory change, and as a result either constrain their business case or rely on a highly uncertain process.

Even if the government approval regime was expanded to private entities, the cost and time of approval would likely be prohibitive—the average cost and time of tens of millions of dollars and 4–9 years is a nonstarter for all potential users that we spoke to [7]. Of these two factors, time may be more important to private users: a long approval time restricts the ability of a company to get to market and initiate revenue, may contrast with how venture capitalists evaluate and fund investments, and restricts a company's ability to quickly develop missions.

III. Implications

With time and investment, space nuclear systems are technically feasible, but their commercial success is uncertain in part due to legal and regulatory challenges. A commercial industry requires active or emerging supply and demand, and a fully commercial process involves private entities from development to operation.

Private companies will theoretically invest in the capability to commercially supply space nuclear systems when demand is or will be sufficient to amortize costs; a private company will theoretically demand space nuclear systems when the cost to procure, integrate, and transport the nuclear device is offset by value added to ongoing or planned operations, weighted by the degree of certainty in that value. The status of this supply and demand of space nuclear systems can be further developed by investigating potential industry scenarios.

In the course of our research, we identified two principal scenarios which both private and government support makes likely. In the first scenario, the government would supply nuclear power to private users in space—specifically, private entities would lease or license the use of a system such as NASA's surface reactor KiloPower on the lunar surface (see Fig. 4). In such a scenario, especially if structured as a public-private partnership, the government tests their system while involving private companies, and the private user(s) take advantage of the power source with limited risk.

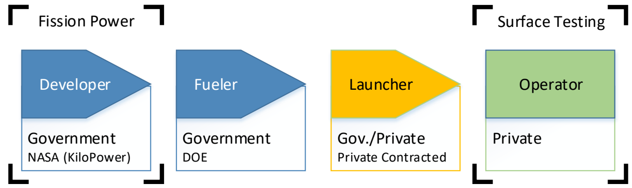

Fig 4: NASA delivers system to private entity in space for testing

In the second scenario, a private entity would supply a nuclear system to a government user—for example, a fission propulsion system to transport cargo between Earth orbit and deep space destinations, whether cislunar space or Mars orbit, or a commercial reactor for use on the surface of the Moon or Mars by NASA (See Fig. 5). This scenario limits the risk a supplier is exposed to, and takes advantage of the government use-cases that are not commercially viable—the government has mature interests that may not be commercially viable for a private company (e.g., human transportation to Mars), and these interests take full advantage of the value of nuclear systems.

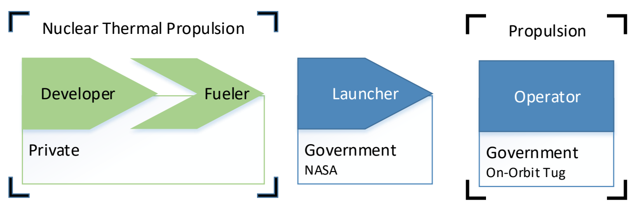

Figure 5: Private entity supplies the government

In both of these scenarios, the private sector takes some risk to either develop capabilities to use a nuclear system or to develop the system itself. The government would still assume some or even most of the risk, and more importantly, it would be serving as the principal if not sole customer. Using the definition of commercial space stated earlier, these scenarios are at best emerging commercial.

The union of the two scenarios, however, results in companies fulfilling each role of the enterprise. The commercial supply capabilities and demand already exists, but might not be strong enough to currently survive independent of government support. Even if private supply matures, and private demand grows (e.g., requiring high thrust propulsion or operations during the lunar night or in shadowed craters), commercial transactions have to be facilitated by private transportation (See Fig 6).

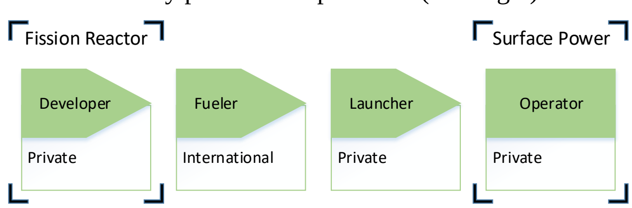

Figure 6: Fully commercial space nuclear chain

The missing piece of a fully commercial space nuclear enterprise is the ability to commercially launch a nuclear system. As has been noted, the private launch of nuclear material is not easily feasible. The process for a private company to procure transportation of a space nuclear system is unproven, but we can think of three launch options: (1) lease the materials to NASA or another government agency for launch; (2) procure presidential approval with no established regime for doing so; or (3) launch from a foreign country. Each of these options are theoretically plausible, but would not allow U.S. companies to easily scale operations; or, in the case of international launch, might be a potential U.S. security risk.

In interviews, potential users indicated that the lack of a clear regulatory regime prevents them from considering using nuclear systems. In other words, the lack of a clear regulatory regime adds sufficient uncertainty that completing a cost-benefit comparison is not even worthwhile. While an updated regulatory regime is not likely to spur the immediate development of a commercial space nuclear enterprise, creating an approval pathway is a logical first step to lower uncertainty to a manageable threshold, and to open the viability of privately owned and operated space nuclear power.

Furthermore, it may not be enough to just have a regulatory regime for the commercial launch of nuclear materials. A regulatory system must be low enough cost and time and high enough certainty to promote and nurture ongoing commercial activities.

IV. Conclusion

To-date, space nuclear systems have been government developed, fueled, launched, approved, and used. In the future, this paradigm might change, and private actors may play a more central role in one or more of these elements. Private entities are emerging in both the development and launch domains, and have potential in the fueling and operational roles. The only role that cannot be commercialized is the approval role, where the government will likely retain its regulatory and oversight role due to the safety and proliferation concerns of both launching and operating a nuclear device as well as to adhere to international treaties.

There is no process in place for the U.S. Government to approve private launches of government-owned or of private nuclear systems. This presents a risk to the continued development of the space industry as a whole, and forces private entities to consider other options—such as launching from countries other than the United States.

Government entities other than the current of agencies (NASA, DOE), may need to be involved in ensuring full private participation in the space nuclear enterprise. Only through a change in policy is the development of a fully commercial space nuclear enterprise possible.

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