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EMERGENCE OF A COMMERCIAL SPACE NUCLEAR ENTERPRISE

Jericho Locke[1,2] and Bhavya Lal[1]

[1]IDA Science and Technology Policy Institute (STPI), 1701 Pennsylvania Ave. NW, Suite 500, Washington, D.C., 20006,
[2]Corresponding author, 202-419-3720, jlocke@ida.org

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 the 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 over a dozen 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 guidance to mature.

I. Evolution of Private Involvement

As of this writing, the U.S. government 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), Sunpower, 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).

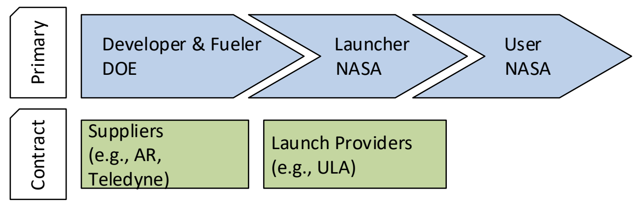

Figure 1: Space Nuclear Enterprise as a Government Led Program

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], interest in other in-space activities such as cryogenic propellant storage, and growing interest in small nuclear systems for terrestrial applications. 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 if there is commercial 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. As can be seen in Figure 2, commercialization therefore has two dimensions, risk and breadth of the customer base.

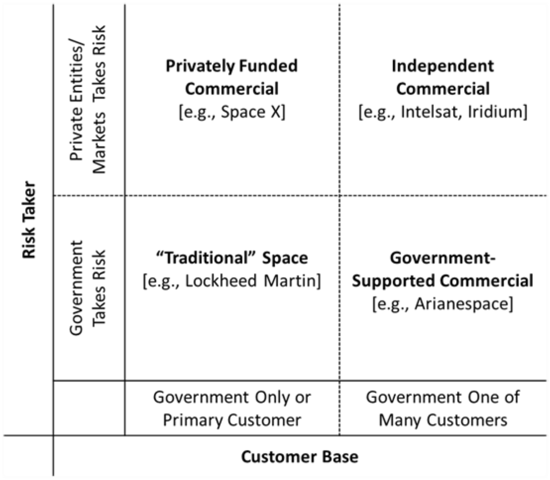

Figure 2: Framework to Define Commercial Space Activities [6]

Three of the quadrants are a form of commercial, differing in their relation to the government and thus their independence. None of the quadrants seem objectively better, nor would all private companies inherently seek to enter the independent commercial quadrant. However, companies operating in the independent quadrant require neither government risk-taking nor government business to survive. Growing independence and moving away from the "Traditional" space paradigm would signal the emergence of a commercial enterprise.

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

The space nuclear enterprise can be seen as having four main elements (see 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 plutonium or 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. Launch can be government-sponsored or commercial.

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.

III.A. Developers/Suppliers

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

We did find, however, growing interest in providing fission power systems for space applications. We identified four companies with active development projects for space fission reactors, and four other companies with terrestrial reactor designs that could be adapted to space. 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, specifically power systems.

Most of the entities actively interested in space nuclear systems met our definition of commercial in that they both invest private (or internal) funds and intend 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.

III.B. Fuel Developers

U.S. Radioisotope Thermoelectric Generator (RTG) systems have used Pu-238, which has high proliferation risks. 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 drives lack of interest in commercializing RPS, making private Pu-238 fuel supply unlikely.

Space fission systems require higher enrichment levels than their terrestrial counterparts to increase energy density, but enriching above 20% has proliferation and business challenges. 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. The fuel required for effective space reactor operation could prove challenging to source commercially and domestically especially given the cost of producing it (indeed some companies have considered importing fuel from China).

III.C. Launchers

Launching nuclear payloads serves as the point of approval for space nuclear systems. In recent years, 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.

Newer 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. There is nothing inherently challenging about launching a nuclear payload except for the extensive environmental and safety reviews required due to the real and perceived public health and environmental risk that these launches pose. This uncertainty only increases in the case of defining nuclear propulsion systems as an upper stage rather than a payload.

III.D. Users

Nuclear systems are useful for space applications because they provide energy, either in the form of electrical power or propulsion. A company that procures and operates a nuclear system uses this energy to enable their own applications, or sells it to other actors. Thus the users actually comprise two separate entities—an operator which sells services and a customer which uses them. The use of nuclear systems is supply-demand market, accountable to our definition of commercial.

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 five 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.

Private companies have commercial interest in nuclear power, both to use its outputs (e.g., propulsion and power), as well as to provide those outputs by operating the systems. This interest, however, has not yet been turned into actual investment, and given that there are no systems to purchase in the first place, in our assessment, is not likely to be realized within the next five years. Interviews with suppliers and experts indicated that an independent commercial demand (top right quadrant in Figure 1) for space nuclear systems is not likely to develop until at least a decade from now

IV. 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 forum.

Nuclear fission is a relatively mature technology in the context of terrestrial applications. Adapting a design to operate in space, however, is not a simple process. Designers must either develop new systems, or adapt terrestrial designs and technology to safely survive the launch environment, to operate in the high-radiation, microgravity, and vacuum environment of space, and to operate for extended periods without maintenance or refueling. Technical challenges that developers must continue to overcome include thermal management in a vacuum, minimizing system mass while maintaining performance, and ensuring high reliability operation for the system lifetime. These requirements have generally driven space nuclear systems to operate at higher temperatures than their terrestrial predecessors, requiring significant redesign and new technology.

One critical challenge facing the private space nuclear industry is launch approval. The Department of Transportation (DOT) has authority over commercial launch, but it is uncertain how effectively they could regulate the launch of nuclear materials. If the launch licensing process includes or mirrors the current government approval regime, launch licensing would likely be prohibitive. The cost and time of approval of a government launch of nuclear materials has historically been large: 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.

V. Implications

The common conception of a commercial enterprise would seem to be one consisting only of private, profit-driven entities—what we have called independent commercial. Such a space nuclear enterprise is possible, but in our assessment unlikely to develop within the next decade. Instead, a commercial enterprise is more likely to be achieved by a growing private role in partnership with the government.

An independent commercial enterprise could look similar to the progression shown in Figure 4, in which a private company procures a fission propulsion system and uses it to provide tug services in Earth and cislunar orbit. Such an enterprise requires technological development, procuring launch approval, and robust private demand.

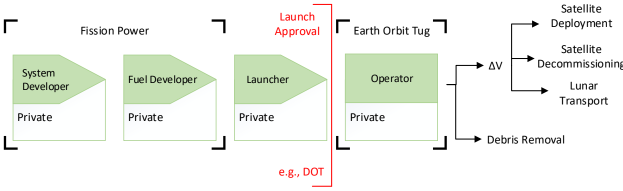

Figure 4: Example of an independent commercial enterprise

The necessary development and investment has not yet been made to precipitate such an independent regime. The growth of commercial interest in space and the developments in small modular reactors have facilitated interest in space nuclear applications, but they have not produced sufficient demand to support the expense of a nuclear system and its regulatory approvals, nor has the supply of space-compatible systems actualized. Connecting terrestrial and space markets will require specific investment and experience.

Partnering with the government may give an opportunity for private entities to acquire that investment and experience. Specifically, this would require working with the government in a commercial capacity rather than the "Traditional" space paradigm. The other two forms of commercial shown in Figure 1, privately funded commercial and government-supported commercial, give a roadmap for how these partnerships might develop.

In a privately funded commercial enterprise, the private entity takes much of the risk but the government serves as the primary customer. By serving as a guaranteed customer, the government would eliminate market risk, possibly giving suppliers the certainty needed to invest heavily in space nuclear systems. While government-funded investment could achieve similar technology gains, serving as a customer instead would allow for more competition and innovation (as opposed to a cost-plus contract). An example of such a market could be NASA purchasing a nuclear thermal propulsion system for Mars in an award style program similar ISS resupply or lunar payload delivery services (See Fig. 5).

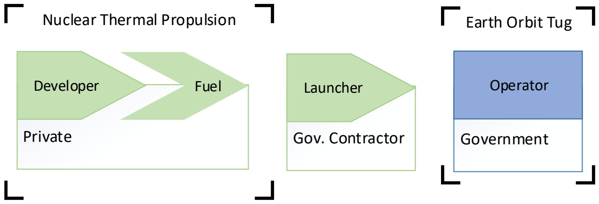

Figure 5: Example of a privately funded commercial enterprise

An alternative and complement to privately funded commercial, is the idea of government-supported commercial activities. By subsuming major risk sources (i.e., development and regulatory), the government could support the growth of a user-base for space nuclear power, including experience in operating nuclear systems in space. An example of this would be NASA and DOE developing a KiloPower based power generating unit, leasing it to a commercial operator, and allowing them to keep a portion of the profits (see Fig. 6).

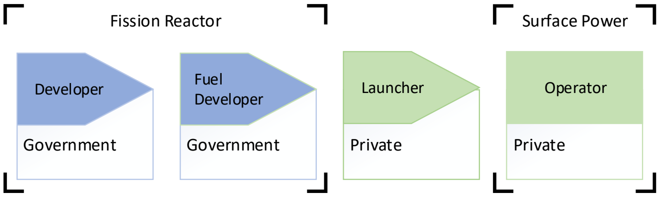

Figure 6: Example of a government supported commercial enterprise

In each of these approaches, the Federal government could receive value—for example, by receiving services or demonstrating new technology. Furthermore, government support for commercial space nuclear involvement could enhance commercial capability to develop and supply technologies. The expansion of these applications and the increase in commercial capabilities may create a positive feedback loop that enables the expansion of the space nuclear economy, stimulates private use of the outputs of nuclear systems, and spurs investment in the space economy. Moving directly from the traditional space paradigm to an independent commercial market will, at the least, take a long time, but the government can support the maturation of commercial supply and demand now.

VI. Conclusion

The emergence of a commercial space nuclear enterprise is an important development for two competing reasons. *The first* is that an independent commercial industry offers commercial investment and sustainment that frees up government funds and assets to allocate to other areas, and potential outcomes of a commercial market such as decreased cost and increased innovation benefit government missions. *The second* is the safety hazard posed by nuclear systems. The development, launch, and use of nuclear systems pose a risk to public health and safety, Earth's environment, and even other celestial bodies.

Based on our research and interviews with companies, it is possible that demonstration missions of privately developed technology could take place within the next five years, but unlikely that an independent commercial market will develop within the next decade. The final maturation of such a market is not certain, and relies on the development of advanced nuclear technology and the space economy along with government action. The government can play an important role in supporting the emergence of this market in several ways. This can be an active role in supporting research and development, partnering with space nuclear suppliers, or stimulating the demand for such systems. The government also plays an important oversight role, which is critical to protecting the public health and safety, but could also be detrimental to the burgeoning industry if not implemented thoughtfully.

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