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The affirmation of the U.S. space nuclear technology strategy

Amaury Dufay

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Analyse technico-capacitaire

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Abstract

Since 2017, U.S. interest in space-based nuclear power applications appears renewed. In a context of growing international competition, these applications are even receiving increasingly structured political support. The objective of this note is to examine these developments in order to put into perspective the issues that accompany them.
Although primarily intended for interplanetary exploration (surface energy supply and high performance propulsion), space nuclear technologies remain dual. By their very nature, they pose proliferation problems that are of interest to the field of law as well as to strategic studies and international political science. These technologies also constitute a challenge in terms of perceptions, insofar as they have a definite impact on the way in which public opinion perceives the security orientation of space policies imposed by governments and international organizations.

Résumé

Depuis 2017, l'intérêt des États-Unis pour les applications de l'énergie nucléaire dans le domaine spatial apparaît renouvelé. Dans un contexte de compétition internationale grandissante, ces applications bénéficient même d'un soutien politique de plus en plus structuré. L'objectif de cette note est d'examiner ces développements afin de mettre en perspective les enjeux qui les accompagnent.
Bien que destinées en priorité à l'exploration interplanétaire (alimentation énergétique de surface et propulsion hautes performances) les technologies nucléaires spatialisées demeurent en effet duales. Par leur nature même, elles posent des problèmes de prolifération qui intéressent le champ du droit comme celui des études stratégiques et la science politique de l'international. Ces technologies constituent aussi un défi en termes de perceptions, dans la mesure où elles possèdent un impact certain sur la manière dont l'opinion publique perçoit l'orientation sécuritaire imprimée aux politiques spatiales par les gouvernements et les organisations internationales.

About the author

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The affirmation of the United States strategy for space nuclear technologies

On Wednesday, October 20, 2021, during a hearing of the subcommittee on Space and Aeronautics entitled « Accelerating Deep Space Travel with Space Nuclear Propulsion », NASA[1] Associate Administrator for the Office of Technology Bhavya Lal took a relatively frank stance on this issue. According to her, « *Strategic competitors including China are aggressively investing in a wide range of space technologies, including nuclear power and propulsion.* »[2]. Corollary of this observation for B. Lal : « *The United States needs to move at a fast pace to stay competitive and to remain a leader in the global space community.* »[3]. This statement should be placed in a double context[4]. First, domestically, the political discussions about the calibration of NASA's budget for fiscal year 2022 are in full swing. The bill released by the Senate proposes $24.83 billion for NASA, slightly more than the $24.8 billion requested by the Biden administration, but less than the $25.04 billion in a House bill. The *Human Landing System* (HLS) project, which should result in the design of a manned lunar module for the Artemis program, is emblematic of these debates, with the NASA administrator Bill Nelson considering it underfunded[5]. In these circumstances, the argument of Chinese progress in the space domain may remobilize some of the skeptical parliamentarians. Externally, this hearing was held a few days after the Financial Times reported on China's test of a hypersonic nuclear delivery system in August 2021[6]. The exact nature of the vehicle launched is still debated and has no direct relationship with nuclear space propulsion technologies. However, this test illustrates the difficulty of evaluating the progress of Chinese research and the extent of the financial efforts made. Beijing's ambitions are, in any case, real.

On November 16, 2017, the China Aerospace Science and Technology Corporation (CASC), one of the two major corporations in China's space program, published precisely one roadmap stretching to 2045, and calling for nuclear-powered shuttles to enter service around 2040[7]. This horizon is often the one envisaged for the first crewed mission to Mars.

In the shorter term, and in a similar vein, the Russian design bureau *KB Arsenal* of Saint Petersburg unveiled on September 17, 2020 images of a model of a tug with electric nuclear propulsion[8]. Called TEM for Transport and Energy

[1] National Aeronautics and Space Administration

[2] United States House Committee on Science, Space, and Technology, *Accelerating deep space travel with space nuclear propulsion*, videoconference, October 20, 2021, 56min 38s, science.house.gov, https://science.house.gov/hearings/accelerating-deep-space-travel-with-space-nuclear-propulsion, consulted on November 2, 2021.

[3] Aud. Cit., 57min 25s.

[4] FOUST Jeff, « Senate appropriators direct NASA to select second Artemis lunar lander », article, published on October 19 2021, *spacenews.com*, https://spacenews.com/senate-appropriators-direct-nasa-to-select-second-artemis-lunar-lander/, consulted on November 2, 2021.

[5] Op. Cit. e.

[6] WALL Mike, « China successfully tested hypersonic weapon in August: report », article, published on October 19, 2021, *www.space.com*, https://www.space.com/china-hypersonic-weapon-test-august, consulted on November 2, 2021.

[7] JONES Andrew, « China sets out long-term space transportation roadmap including a nuclear space shuttle », article, published on November 16, 2017, findchina.info, https://findchina.info/china-sets-out-long-term-space-transportation-roadmap-including-a-nuclear-space-shuttle, consulted on November 2, 2021.

[8] ZAK Anatoly, « Russia reveals a formidable nuclear-powered space tug », article, September 17, 2020, last update on august 25, 2021, *www.russianspaceweb.com*,

Module, it will be the central piece of the Zeus exploration complex, whose objective is to take probes simultaneously to the Moon, then Venus and finally Jupiter in a single journey of 4 to 5 years[9]. KB Arsenal's experience with Russian nuclear-powered military satellites US-A, US-P and Plazma-A since the 1960s[10], makes the project seem credible.

In this context, it is relevant to examine American developments in a synthetic manner, to identify their stakes, as well as their capability implications. A comparative study of Russian and American programs, backed up by a complete historical context, will be the subject of a future IESD publication.

The *Space Policy Directive - 6*, the Trump administration's still effective policy framework for space nuclear power and propulsion

The White House is historically the initiator of all American space policies. The reason for this is very simple: rocket technology and nuclear energy have been associated since the early 1950s, either through ballistic missiles, which are essential for deterrence, or as a means of propulsion. It is striking to note that almost all the space powers are nuclear powers, and that those considering nuclear energy as a means of propulsion are all at the top of the hierarchy of inter-state relations.

If nuclear energy has never really disappeared from the minds of planetary mission planners, it has only been the object of real political support in the United States on two occasions. The first concerned the Rover project, launched in 1955 (a contract between the US Atomic Energy Commission and Westinghouse). The second was the NERVA program (Nuclear Engine for Rocket Vehicle Application), starting in 1961, in association with NASA. The results of this program exceeded all expectations, since in 1969 NASA already had a tested and operational nuclear engine with a performance superior to anything that is still in use today.

However, the project was abandoned at the same time as the *Program Plan*[11] in 1972, following the relative political disinterest that followed the triumph of the Apollo program. Subsequent programs never reached such a degree of progress.

Since 2017 U.S. nuclear space programs have been renewed, taking advantage of the Trump administration's revival of lunar ambitions with the Artemis program. On December 16, 2020, President Trump signed the Space Policy Directive - 6, or SPD-6[12], defining the U.S. space strategy for nuclear power in space. Substantially, it is first a roadmap for replenishing nuclear fuel processing capabilities needed for space systems

https://www.russianspaceweb.com/tem.html, consulted on November 2, 2021.

[9] TASS Russian news agency, « First mission of Russia's nuclear-powered space tug to take 50 months – The first flight has been scheduled for 2030 », article, published on may 22, 2021, tass.com, https://tass.com/science/1292721, consulted le 2 November 2021.

[10] ZAK Anatoly, « US-A and US-P military satellites », article, January 2020, last update on June 25, 2021, *www.russianspaceweb.com*, https://www.russianspaceweb.com/us.html, consulted on November 2, 2021. It was one of these satellites, Cosmos 954 that disintegrated over the Arctic regions of Canada in 1978, causing the first space nuclear incident. An agreement was reached on April 2, 1981 between Canada and the Soviet Union, providing for the payment of 3,000,000 Canadian dollars in reparations.

[11] DRYE Paul, « Mars Expedition 1969 : NASA's Waterloo », article, published on august 8, 2012, *falsesteps.wordpress.com*, https://falsesteps.wordpress.com/2012/08/08/mars-expedition-1969-nasas-waterloo/, consulted on November 2, 2021.

[12] White House, *Memorandum on the National Strategy for Space Nuclear Power and Propulsion (Space Policy Directive-6)*, December 16, 2020, www.whitehouse.gov, https://trumpwhitehouse.archives.gov/presidential-actions/memorandum-national-strategy-space-nuclear-power-propulsion-space-policy-directive-6/, consulted on November 2, 2021.

by the middle of the decade, and testing a nuclear surface power system for lunar missions by 2030. The objective of the directive is twofold. On the one hand, it provides support and a policy framework for NASA's nuclear research by prioritizing Fission Surface Power (FSP), and committing it to Nuclear Thermal Propulsion (NTP). It also attempts to rationalize and centralize the initiatives of the Department of Defense, the Department of Energy and NASA.

On January 12, 2021, SPD-6 was supplemented by an order[13] defining a common area of cooperation between the Department of Defense and NASA, focused on military applications of space nuclear technologies (sections 3 and 4). It includes the demonstration of micro-reactors (less than 10 MW electrical generation capacity), i.e., a class of Small Modular Reactors (SMRs), for self-sustaining power at defense sites. Cooperation also extends to the Department of Energy and the Department of Commerce.

For the moment, the Biden administration has not gone back on this policy framework. On the contrary, the new president seems to maintain the direction of his predecessor, a continuity unseen since the Apollo program. It will therefore be interesting to observe possible inflections of American space policy in the coming years, although China's rapid progress makes a major change in current developments unlikely.

Fission Surface Power, priority development of a technology applicable to electric nuclear propulsion systems

The need for a system capable of providing power under conditions where solar power is unavailable was identified by NASA long before SPD-6 made it a priority. Fission Surface Power (FSP) can sustain a small lunar base for at least ten years, including fourteen-day nights. It would also allow extraction of oxygen and minerals from the regolith[14], as much for the survival of astronauts as for the production of fuel and parts *in situ*.

That's why NASA launched the Kilopower program in 2017, with an initial allocation of $15 million[15]. Its objective is to develop a design capable of delivering between 1 and 10 kW for the first prototypes, and up to 150 kW for future Mars versions. The horizon set is the second half of the 2020 decade, coinciding with the goals of the Artemis program. On May 2, 2018, NASA's Glenn Research Center in Cleveland announced that the first phase of the program was successful, as the KRUSTY (Kilowatt Reactor Using Stirling Technology) prototype was able to deliver 1 kW for twenty-eight hours[16]. The next step is the design of a model using low-enriched uranium,

[13] White House, *Executive Order on Promoting Small Modular Reactors for National Defense and Space Exploration,* January 12, 2021, www.whitehouse.gov, https://trumpwhitehouse.archives.gov/presidential-actions/executive-order-promoting-small-modular-reactors-national-defense-space-exploration/, consulted on November 2, 2021.

[14] According to the definition of George P. Merrill dating from 1897, the regolith is the mantle of debris coming from the fragmentation, by physical or chemical actions, of the underlying rock or mother rock. It thus designates the layer of geological debris that covers the surface of a celestial body.

[15] LISOIR Hugo and LISOIR Maxime, « US Space Corps/ Projet Kilopower / Télescope XRAM », *Dernières Nouvelles des Etoiles*, July 11, 2017, www.youtube.com, https://www.youtube.com/watch?v=JtpEvoPGMrA consulted on November 2, 2021.

[16] FOUST Jeff, « NASA considering flight test of space nuclear reactor technology », article, published on May 3, 2018, *spacenews.com*, https://spacenews.com/nasa-considering-flight-test-of-space-nuclear-reactor-technology/, consulted on November 2, 2021.

with a power of 10 kW, for a first deployment test in the middle of the decade.

The applications are primarily oriented towards ground infrastructures, such as a lunar base, but also include the possible supply of advanced electric propulsion systems. To evaluate the performance of a propulsion system, two pieces of data are particularly important: the specific impulse - noted *I*sp and expressed in seconds (s) - and the thrust - expressed in Newtons (N). The *I*sp indicates the time during which the engine can produce a thrust equivalent to 1 kg using 1 kg of fuel. The higher the *I*sp, the greater the acceleration the engine can provide with the same amount of fuel. Thrust, in turn, determines how long it takes the motor to achieve the desired acceleration. Electric motors use solar or nuclear power to ionize gases and eject them at very high speed, producing considerable specific impulses of the order of 2000 to 10000 seconds. However, this is achieved at the expense of the thrust, which rarely exceeds a few tens of Newtons, implying very long acceleration times. Coupled with the very high energy density of a nuclear reactor, this solution makes it possible to propel light vessels for very distant explorations, hence a certain interest for interplanetary probes. The table below compares the performances of the Russian TEM system with those of the two best chemical combustion engines of the world: the Russian Rd-0120[17] and the American Space Shuttle Main Engine (SSME)[18].

System/engine	**TEM**	**Rd-0120**	**SSME**
Country	Russie	Russie	États-Unis
Type	Nucléaire électrique	Chimique	Chimique
Spécific impulse in vacuum (*I*sp)	7000 s	455 s	453 s
Thrust (in kilonewtons)	0,018 kN	1961 kN	2278 kN

However, there is a family of nuclear engine concepts capable of combining very high *I*sp and high thrust: nuclear thermal propulsion.

Research for the development of a nuclear thermal propulsion system: a technological key for space operations with high energy requirements?

Nuclear thermal propulsion consists in using a nuclear reactor core to heat a propellant mass, typically liquid hydrogen. There are three basic types of core configurations: solid, liquid and gaseous, each with higher theoretical performance than the others at the cost of increasing complexity. The configuration that is currently attracting the attention of engineers is the solid core, traditionally offering an Isp of 800 to 1200s, and scalable thrust of up to 300,000N or more. This is a design that has been widely tested experimentally by the NERVA program between 1961 and 1972, but which, after almost 50 years of research and development stoppage, must be completely rethought with the progress of materials and contemporary computing. Current security and non-proliferation requirements must also be taken into account.

With this goal in mind, on August 3, 2017, NASA signed a three-year, $18.8 million contract with BWX Technologies[19]. It was for the development of a space nuclear thermal reactor concept. This budget was allocated within the framework of NASA's Game Changing Development program, whose objective is to identify and test technological breakthroughs that could change the way NASA designs its space

[17] WADE Mark, Rd-0120, article, www.astronautix.com, http://www.astronautix.com/r/rd-0120m.html, consulted on November 2, 2021.

[18] WADE Mark, SSME, article, www.astronautix.com, http://www.astronautix.com/s/ssme.html, consulted on November 2, 2021.

[19] ANON., « BWXT Awarded $18.8 Million Nuclear Thermal Propulsion Reactor Design Contract by NASA », article, published on August 3, 2017, www.businesswire.com, https://www.businesswire.com/news/home/20170803005233/en/BWXT-Awarded-18.8-Million-Nuclear-Thermal-Propulsion-Reactor-Design-Contract-by-NASA, consulted on November 2, 2021.

missions[20]. BWXT is a nuclear fuel and solutions design company, including manufacturing the fuel rods for the US Navy's aircraft carrier and submarine reactors.

On July 13, 2021, NASA Space Technology Administrator Jim Reuters announced 3 contracts, each worth about $5 million over a year, for concept studies of a nuclear thermal engine:

- One contract with BWXT and Lockheed Martin.
- A second with General Atomics Electromagnetic Systems, in collaboration with X-energy and Aerojet Rocketdyne.
- And one with Ultra Safe Nuclear Technologies. This company will work with its parent company Ultra Safe Nuclear Corporation, as well as with Blue Origin, General Electric Hitachi Nuclear Energy, General Electric Research, Framatome and Materion[21].

It is worth noting the presence here of companies that are not necessarily historical players in American nuclear technologies, testifying to the maturity of the American New Space.

However, NASA is not the only U.S. agency committed to nuclear thermal propulsion. On April 12, 2021, the Defense Advanced Research Projects Agency (DARPA) launched the DRACO program, for Demonstration Rocket for Agile Cislunar Operations. The ambition is clear and the fact that it comes from an agency of the Department of Defense is not insignificant. The goal of the program is to launch a nuclear thermal-powered spacecraft as early as 2025. Commander Nathan Greiner, head of the DRACO program, sums up the interest of this propulsion system for defense activities: « *Rapid maneuver in the space domain has traditionally been challenging because current electric and chemical space propulsion systems have drawbacks in thrust-to-weight and propellant efficiency, respectively* [22]».

To carry out the first studies, DARPA has selected three companies for an 18-month period. General Atomics, a historic player in nuclear space propulsion, is getting $22 million, Lockheed Martin $2.9 million, and Blue Origin $2.5 million. Blue Origin's presence is emblematic of New Space companies working on increasingly sensitive technologies historically reserved for states alone. The fact that several contractors are common to both NASA and DARPA initiatives allows us to grasp the duality of space nuclear developments in the United States.

The challenge of all these programs is to articulate the nuclear thermal and nuclear electric options for future explorations in a coherent roadmap, taking into account international safety and security issues.

Technological developments at the heart of international safety and security issues

A specific aspect of the political issues facing American space developments is the management of environmental risk. This is closely related to the issue of nuclear proliferation in space, particularly from a legal perspective.

[20] LISOIR Hugo et LISOIR Maxime, « Moteur plasma / Tau Ceti / Le retour de Nerva ? », *Dernières Nouvelles des Etoiles*, August 15, 2017, www.youtube.com, https://www.youtube.com/watch?v=u0-Tk46waI0&t=358s, consulted on November 2, 2021.

[21] FOUST Jeff, « NASA considering flight test of space nuclear reactor technology », article, published on May 3, 2018, *spacenews.com*, https://spacenews.com/nasa-considering-flight-test-of-space-nuclear-reactor-technology/, consulted on 2 November, 2021.

[22] ERWIN Sandra, « DARPA selects Blue Origin, Lockheed Martin to develop spacecraft for nuclear propulsion demo », article, published on April 12, 2020, *spacenews.com*, https://spacenews.com/darpa-selects-blue-origin-lockheed-martin-to-develop-spacecraft-for-nuclear-propulsion-demo/, consulted on 2 November, 2021.

Risk management, some commentators argue, is more of a public relations problem than an engineering one. In 1997, the launch of the Cassini probe, equipped with a Radioisotope Thermoelectric Generator (RTG)[23] for its energy supply, had provoked important demonstrations of opponents to nuclear power. This, even though the RTGs had been designed and tested to withstand the possible explosion of the launch vehicle at lift-off. Nevertheless, it is certain that when the current nuclear space developments leave the drawing boards, the management of the relationship with the different components of civil society will be a central subject of American space policy. The outcome of the debates will most certainly depend on the structuring of public opinion. In this matter, the United States has a certain lead over the other Western space powers, with a growing involvement of federal structures in the maintenance and mobilization of the popular passion for space. The US Space Force, beyond its military command function, is also a formidable tool of internal and external influence. Its centralizing power positions it as the official defender of the space sector alongside NASA, engaging in the necessary political and bureaucratic battles, while maintaining a community of space experts in its own right[24].

In any case, the technology will adapt to political requirements. This will concern the critical phases of the reactor launches, for which the risks are known, the possible foreseeable consequences, and the trainable teams. The question of the orbits on which the systems will be stationed will certainly also be the subject of political arbitration. On this subject, the studies carried out by Boeing in the framework of President George H. W. Bush's Space Exploration Initiative in 1989 give an idea of what the American approach could be: one report in particular, concerning a mission architecture for an ion propulsion spacecraft powered by a 40 MW reactor, foresees an elliptical orbit with a perigee[25] at 400 km of altitude. Such a positioning, although more expensive to achieve during the launch, minimizes the risks of risky atmospheric re-entry.

The problem of the degree of fuel enrichment for the reactor core will be more delicate to deal with. If there is a technical interest[26] using highly enriched uranium (designated HEU, from 20 to 85%), most of the designs proposed in the United States today focus on low-enriched uranium (from 2 to 20% for Low Enriched Uranium (LEU), and from 5 to 20% for High-Essay Low-Enriched Uranium (HALEU)). This direction is confirmed by SPD-6 in its section 3 (b), which, without excluding the use of HEU, conditions it on the respect of a certain number of criteria[27]. The Executive Order of January 12, 2021, further directed the Department of Energy to transfer technology for the production of low-enriched uranium to the commercial sector in order to

[23] A Radioisotope Thermoelectric Generator (RTG) produces electricity from the heat resulting from the radioactive decay of materials rich in one or more radioisotopes, usually plutonium 238. However, no fission reaction occurs. RTGs have the advantages of being simple and of allowing power supply at distances where solar energy is too far away to be exploited.

[24] PENENT Guilhem, « *Space Force*, une mise en contexte », *Défense & Sécurité Internationale*, n°138, November – December 2018, pp. 96-100, p. 99

[25] The point in the orbit of an object that is closest to the Earth.

[26] Pour une étude comparative exhaustive des enjeux techniques et politiques du degré d'enrichissement des cœurs des réacteurs nucléaires spatiaux, voir National Academies of Sciences-Engineering-Medicine, *Space Nuclear Propulsion for Human Mars Exploration*, 2021, https://www.nap.edu/catalog/25977/space-nuclear-propulsion-for-human-mars-exploration, consulté le 2 novembre 2021.

[27] « *Before selecting HEU or, for fission reactor systems, any nuclear fuel other than low-enriched uranium (LEU), for any given SNPP design or mission, the sponsoring agency shall conduct a thorough technical review to assess the viability of alternative nuclear fuels.* » White House, *Memorandum on the National Strategy for Space Nuclear Power and Propulsion (Space Policy Directive-6)*, doc. Cit.

expand it (Section 6)[28]. The LEU NTP Engine System Trades and Mission Options report published in 2019 by Aerojet Rocketdyne[29] facilitates an understanding of the performance of such a propulsion system.

There are many political and technical reasons for this choice, and the one that attracts our attention here is non-proliferation considerations. It is generally considered that safety requirements should be higher for highly enriched uranium (HEU) cores, especially because of the use of the same fuel in nuclear weapons. Internationally, the use of HEU by the United States in its space reactors would imply complications for its postures with respect to civilian uses of HEU by other countries. Finally, at the domestic level, non-proliferation issues have an impact on program costs and schedules, as well as on the ability of commercial actors to participate in reactor development. The choice of LEU or HALEU therefore has industrial relevance, in addition to being a domestic policy argument in obtaining launch approval.

Insofar as nuclear space technologies are a common objective of the American, Russian, and Chinese space programs, but these three countries will probably not make the same technical choices, it is to be expected that international space law will take up the issue. This is all the more true since there is no lack of dual use of these developments, which will certainly stimulate a generalized need for a legal framework for these developments.

A possible capacity extension in low earth orbit and beyond

The possibility of designing spacecraft capable of very high acceleration in a short period of time presents « *advantages and opportunities* » as General David Thompson stated on July 28, 2021[30]. By referring to the DRACO program as a technology "test bed," the deputy chief of the U.S. Space Force appears to be acquiescing to the recommendations of the report « A Primer on Cislunar Space » published on June 23, 2021[31]. In this report, the Space Vehicles Directorate advises the US Space Force to prepare for operations between the Earth and the Moon. One of the scenarios envisaged by the US Space Force is to be able to deploy and move satellites or other vehicles in cis-lunar Space[32]. This ambition should be put in perspective with the Western and Chinese ambitions to establish permanent bases on the Moon during the 2030s. Thus, prospectively, these developments augur a progressive extension of military surveillance operations to lunar orbits by 2040.

Over the same 20-year horizon, the revival of design work for on-board space reactors, as a propulsion system and as a source of energy, allows the re-examination of anti-satellite and anti-ballistic missile weapon positioning projects initially envisaged for the Strategic Defense Initiative of the Reagan era. The high energy density and low mass of nuclear solutions make it

[28] White House, *Executive Order on Promoting Small Modular Reactors for National Defense and Space Exploration*, Doc. Cit.

[29] Aerojet Rocketdyne, *LEU NTP Engine System Trades and Mission Options*, 2019, http://anstd.ans.org/NETS-2019-Papers/Track-2--Mission-Concepts-and-Logistics/abstract-29-0.pdf, consulted on November 2, 2021.

[30] ERWIN Sandra, « Space Force sees « advantages and opportunities » in nuclear-powered space missions », article, published on October 19, 2021, *spacenews.com*, https://spacenews.com/space-force-sees-advantages-and-opportunities-in-nuclear-powered-space-missions/, consulted on November 2, 2021.

[31] Air Force Research aboratory – Space Vehicules Directorate, *A primer on Cislunar Space*, June 23, 2021, https://www.afrl.af.mil/Portals/90/Documents/RV/A%20Primer%20on%20Cislunar%20Space_Dist%20A_PA2021-1271.pdf?ver=vs6e0sE4PuJ51QC-15DEfg%3d%3d, consulted on November 2, 2021.

[32] ERWIN S. Op. cit. e.

possible to power systems with very high energy requirements, but which generate little or no debris: high-power lasers[33] or neutral particle beams[34]. In the field of lasers, it is possible to directly use the extremely radioactive environment of a nuclear reactor core as a generating medium for lasers[35].

These space systems, often colossal in size (of the order of a hundred meters long and weighing a hundred tons), require heavy launchers for their takeoffs. Of the six launchers with more than 50 tons of launch capacity into low Earth orbit currently under development worldwide, three are American: Space X's Starship, Boeing's Space Launch System, and Blue Origin's New Glenn[36]. The conjunction of these two capability ruptures, launchers and nuclear technology, renews the field of possibilities for the weaponization of space. In this context, a technical-capability analysis of heavy launchers currently under development would be relevant.

Conclusion

U.S. nuclear space ambitions are now benefiting from a policy environment not seen since the 1960s, both domestically and internationally. The U.S. government has decided to commit its administrations to two complementary directions: the first is reactors for energy supply applications for surface operations (Kilopower program) and the second is the development of a nuclear thermal propulsion system (DRACO program). These developments are primarily intended for lunar exploration, but their applications remain dual. The systems will be based on low-enriched uranium cores, for both technical and political reasons. However, it will be interesting to observe the extent to which the Biden administration will modify the policy framework for these programs, particularly the December 16, 2020 SPD-6 and the January 12, 2021 Executive Order that complements it.

The structuring of American civil society around space issues will be a sensitive element in the shaping of nuclear space policy, both for environmentally and militarily. Developments in this area will be interesting to follow, as well as international legal initiatives to establish a legal framework for nuclear infrastructures in orbit and on celestial bodies. Indeed, nuclear proliferation issues will be a growing topic in space law.

The deployment of nuclear-powered solutions makes it possible to extend civilian and military space operations beyond low Earth orbit. The maturity of new private players in the space sector and the renewed global confrontation of ideologies make the renewal of U.S. nuclear space programs long-term. The obvious interest of the US Space Force illustrates the credibility of technological breakthroughs that must be carefully analyzed.

Strategic studies should exchange ideas1 more closely with the engineering sciences in the aerospace sector in order to reinforce the technical credibility of capability thinking. Cis-lunar operations and non-debris-generating ASAT technologies, coupled with orbital and energetic capability disruptions, should be the main fields of major evolution in the next two decades.

33 An example is Martin Marietta's "Zenith Star" anti-ballistic missile orbital laser project. CHUNG Winchell, "Martin Marietta Zenith Star", article, *www.projectrho.com*, http://www.projectrho.com/public_html/rocket/planetaryattack.php#zenithstar, consulted on November 2, 2021.

34 CHUNG Winchell, « SDI Neutral Particule Beam », article, *www.projectrho.com*, http://www.projectrho.com/public_html/rocket/spaceguncon vent2.php#id--Particle_Beams--SDI_Neutral_Particle_Beam, consulted on November 2, 2021.

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