72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021.

IAC-21-C3,3,X67114

Space Nuclear Power for Terrestrial Utilities

Peter J. Schubert

Indiana University-Purdue University Indianapolis, Indianapolis, Indiana, U.S.A. pjschube@iupui.edu

Abstract

Solar power satellites must be large because sunlight is diffuse. Recent advances in developing fission fuel on the Moon raise the possibility of a nuclear powersat. Modest payloads of uranium oxide, transmuted from lunar thorium, and delivered to GEO are inserted into fission reactors. Eighty such reactors attached to a spacetenna can provide GW-class baseload power to terrestrial utilities. This paper studies the size, logistics, and safety considerations for Space Nuclear Power. A particular technical concern is the thermal management required of a heat engine. The delivery of fuel pins from the Moon is studied, and various transport methods are compared. The transfer of power wirelessly is studied, as it impacts terrestrial communications. Of prime concern to all are the safety considerations, which are partly ameliorated by the use of U-233 as the fissile material. A Risk Analysis is presented, and the highest ranking solutions presented. Life Cycle Analysis considerations demand a practical end-of-life treatment. The design of the nuclear powersat aims to strictly minimize any use as a weapon, with the goal being no greater threat to earth than an inert body of similar mass. Through lunar resource utilization, the time may be advanced when utilities can provide baseload (always on) electric power, which is free of pollution.

Keywords: space power, clean energy, lunar, thorium, ISRU, fission, power beaming

1. Introduction

Space Solar Power is the concept of gathering photovoltaic energy in Earth orbit and delivering this power wirelessly to terrestrial receivers. A major challenge to traditional SSP is the diffuse nature of sunlight, at about 1350 W/m^2. This demands vast collection areas that must remain aligned with the Sun as they orbit. An alternate SSP concept uses mirrors or Fresnel lenses to concentrate sunlight onto a vessel containing a working fluid. The hot fluid is used to turn a turbine in a thermodynamic cycle (e.g. Brayton or Stirling) to run a dynamo and generate electric power. This alternate approach requires large, rotating optics, and also requires large area radiative heat exchangers (HEXs) to cool the fluid and to regenerate the cycle.

A new approach, explored here, is to use nuclear fission reactors as the source of electric power. There remains a need for large area HEXs, however, the concentrated nature of nuclear power conveys advantages in mass and size.

The obvious objection to Space Nuclear Power (SNP) is the risk of launching nuclear reactors from Earth. To completely avoid this concern, the current study assumes the production of fissile fuel rods on the surface of the Moon [1,2,3]. Uranium-233 that has been transmuted from thorium on the lunar surface makes a desirable fission fuel because it is already enriched. U-233 is also a desirable fuel because the radioactive byproducts decay to safe levels within one century. Disposal issues are not eliminated, however, the hazards to human health are significantly reduced relative to traditional U-235 fission reactors.

The concept of SNP studied herein involves a collection of separate, modular reactors arrayed across a transmitting antenna (“spacetenna” [4]) for energy delivery to utility customers on Earth. The HEXs must be large, but can be arranged so that they face solar north and solar south. Such a configuration avoids the need for rotating connectors and moving parts, and obviates the need for precise alignment.

Deployment of SNP is a third generation technology for in situ resource utilization (ISRU) as it depends on the extraction and transmutation of thorium, plus the assembly of large area structures (spacetenna and HEXs). Intermediate applications of fission fuel from the Moon include surface power to support ISRU operations, and nuclear thermal rockets (NTR) to facilitate rapid transit to main belt asteroids [3,5]. These earlier outcomes support the increasing fraction of SNP components that can be sourced in space, further reducing launch costs and risks compared to delivery from the Earth.

2. Approach

The US Department of Energy reviews advanced small modular reactors (SMRs) [6] which are generally shaped as a cylindrical prism, making them ideally-suited to fit within a rocket fairing. The reader is reminded that the present SNP concept envisions such SMR machines to be launched with *zero* radioactive materials – these being supplied from the Moon once they are integrated on-station in orbit. Only then is the nuclear reaction initiated [2]. This approach protects Earth.

This is the author's manuscript of the article published in final edited form as:

Schubert, P. J. (2021, October). Space Nuclear Power for Terrestrial Utilities. 72nd International Astronautical Congress, Dubai, United Arab Emirates.

Cylindrical SMR developers in 2020 include NuScale Power (US), CNNC (China), Mitsubishi Heavy Industries (Japan), and many others [7]. Power output ranges from 10s of MWe electric) to 100s of MWe. For this study, a single SMR output of 60 MWe is assumed, with a thermal-to-electrical efficiency of 40 percent, or a total of 150 MWth generated. Each such reactor must reject 90 MWth from the HEX system.

Wireless power transfer (WPT) refers to the use of electromagnetic radiation across a free space region between transmitter and receiver. Far-field WPT which must pass through the Earth's atmosphere preferentially uses frequencies which are minimally attenuated by gases and vapors in the air. Common frequencies are 2.45 GHz and 5.8 GHz. These frequencies are captured and converted to DC power via rectifiers, which use diodes and capacitors at each receiving antenna element. Such a device is called a rectenna, as a portmanteau of rectifying antenna. Higher frequencies require smaller antennas, thereby reducing mass. Components at higher frequencies are generally more costly.

Another frequency studied is 270 THz, using lasers in the infrared range. The beam can be significantly smaller, and is converted to DC via photovoltaic cells, which are generally lower in RF-to-DC conversion efficiency relative to a rectenna. Two important drawbacks to IR lasers are (a) their near-complete attenuation in clouds, and (b) the potential to be used as a weapon. These considerations rule out lasers for commercial, baseload power operations. This study employs 2.45 GHz as the WPT reference case because the power electronics are relatively easier to fabricate from ISRU materials [8].

Many orbits have been proposed for space power systems. The original concept by P. Glaser [9] uses the Clarke orbit, or geostationary earth orbit (GEO) in which an orbiting powersat moves at the same angular velocity as the spinning of the Earth. The result is that the powersat remains fixed over a single spot around the equator, which is a considerable advantage because of the very large size required of the terrestrial rectenna. Other orbits lacking this natural station-keeping must employ trains or fleets of satellites to provide nearly-continuous power to a given location on the ground. Such constellations have the advantage of redundancy and avoid the need to assemble large unitary structures in orbit. This work begins by assuming a single monolithic powersat in GEO, but can be applied with minimal changes to a lower-orbit constellation.

Delivering fuel rods from the Moon to GEO can be accomplished with traditional chemical rockets. As a third generation technology, one can assume water ice harvesting in permanently-shadowed regions at the lunar poles can be electrolyzed into hydrogen and oxygen, which are then used as fuel and oxidizer. Electromagnetic catapults are another option, presuming that first-generation stationary fission plants can provide the energy needed to launch ferrous payload canisters [10]. Ballistic payloads require slow-down upon reaching GEO, and such a system has been studied to show technical feasibility [11,12].

Assembly of large structures on orbit is a challenge, and will probably be conducted by human-operated waldos or autonomous robots. The spacetenna for 2.45 GHz is approximately 950 m in diameter [13], and can be assembled from modular components [14]. The phased array spacetenna will require a "pencil beam" of highly-collimated energy to avoid desensitization of communications and radio astronomy instruments on earth and in orbit [15,16]. Terrestrial rectenna must be large, on the order of 7 to 10 km in diameter, depending on the lattitude north or south of the equator. These large structures can follow terrain, and can be elevated to avoid undergrowth, snow accumulation, and to allow ruminant grazing. Costs and environmental considerations for such megastructures have been studied in [17].

3. Results

A 5,000 MW SNP powersat system suitable for a major metropolitan statistical district such as Indianapolis, Indiana will require 83 SMRs. Assuming 3 ºK background temperature at solar north and south, the area A required for radiative heat transfer of the thermal power P_{th} of 90 MWth can be computed by the Stefan–Boltzmann law:

$$P_{th} = \sigma A T^4 \qquad (1)$$

where $\sigma = 5.67\times10^{-8}$ W/m$^2\cdot$K^4. Assuming a thermodynamic system with an easily-designed exit temperature of 287 ºC, and the total area required is $1.34\text{x}10^6$ m^2, so that each reactor needs a HEX of 72 m diameter. For 2.45 GHz, a 475 m spacetenna is needed, so the area for radiative heat transfer is approximately double the area of the transmitter. Figure 1 shows the composite beam, computed using AWR Microwave Office.

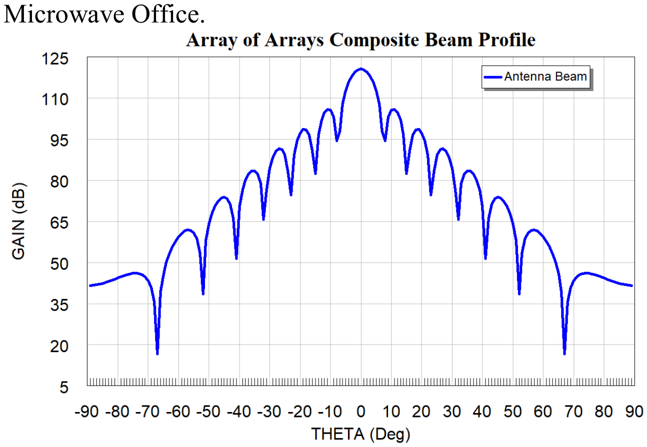

Figure 2. Array of arrays [18,19] spacetenna beam profile for 83 non-continguous but co-planar modular units showing unacceptable off-axis sidelobe levels.

This mismatch would require long runs with fluid, which is inefficient in mass and volume. Instead, an exit temperature of at least 384 ºC is required to match the size of the HEX to the area of the transmitter associated with that portion of the power. Each module could thus be close-packed together in tiled hexagons. This arrangement would have a much-improved beam profile, as shown in Figure 2.

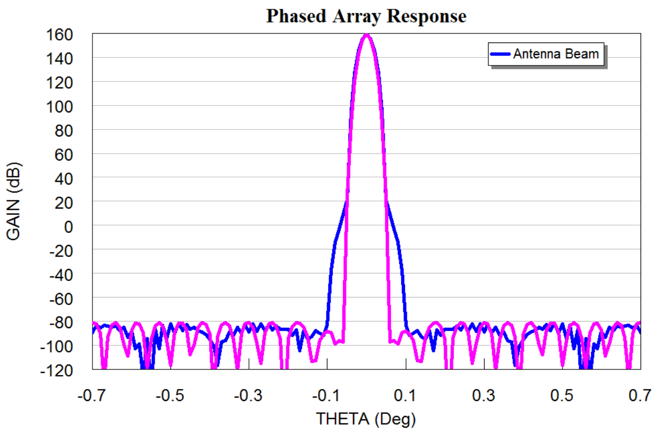

Figure 2. Desired GEO-to-Earth beam profile for contiguous co-planar spacetenna (2.45 GHz) with Dolph-Chebychev power density schedule achieved with 384 ºC exhaust temperature for Space Nuclear Power.

This derived temperature requirement may dictate the use of molten salts as the primary working fluid between the reactor and the Brayton cycle turbine. A secondary HEX using, for example, helium, would then be needed to convey heat to the radiators.

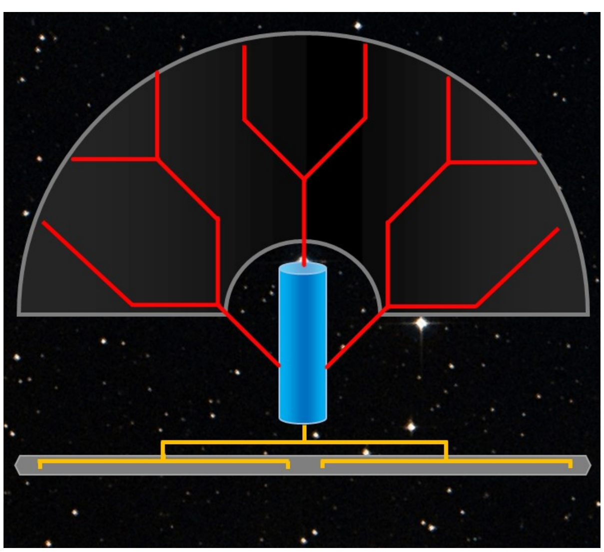
Figure 3. View from solar north of the Space Nuclear Power powersat arrangement. The blue cylinder is the Small Modular Rector. Red lines are secondary coolant distributed through the semi-circular radiator, and orange lines are corporate feed of power to the spacetenna at the bottom of the figure, which appears edge-on. Earth is down.

The radiators in figure 3 are advantageously aligned in the plane of the ecliptic, which is 0.41 radians tilted relative to the inclination of the Earth's axis. This allows the majority of the area of the radiators to face cool regions of the deep sky. Because the Earth's axis is tilted relative to the solar ecliptic, there will be a glancing exposure of the HEX to reflected sunshine from the Earth during daytime. From the cosine law, this would demand an increase in area of 8.3 percent. However, because the temperature of the Earth is much less than that of the sun, the overall impact of earthshine will be minor.

The useful life of a SNP installation is dominated by the SMR, and can be taken as 30 years. The total energy delivered is 1.3 billion MWh, and at a competitive rate of 25 USD/MWh amounts to 32 billion USD in revenue. Operation and maintenance will have been conducted on the spacetenna and the HEX, predominantly by robotic or waldoed apparatuses. The spacetenna will still be viable due to the perpectual scheme developed in [14], and can be re-used. The HEX will likely have patches over patches and will need to be recycled or scrapped.

Disposal of the SMR to the "graveyard" orbit is not recommended, as is normal for defunct GEO satellites. Because these are electricity-generating machines, the last remnants of useful power can be used for electric rocket motors. These will slowly raise the orbit until the assemblage exits Earth's gravity well. A safe and non-controversial final resting place for an aged SMR will be to send it into the Sun.

Risk Analsysis is a formalized means by which to identify hazards to operators and to passersby during the operation of a machine or asset. Some of the standards and tools available include: (1) MIL-STD-882D 10 February 2000, Department of Defense, "Standard Practice for System Safety"; (2) ISO 14121-1:2007, "Safety of Machinery Risk Assessment—Part 1: Principles"; (3) "Failure Mode Effects and Analysis (Design FMEA) and Potential Failure Mode, Effects, and Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA), Society of Automotive Engineers standards document SAE J1739 (August 2002).

Figure 4 shows a risk analysis applied to SNP. Ten primary hazards are identified, and a brief description is included. The evaluation and comparison of each risk is given by the multiplicative product of three metrics. Occurrence indicates the probability, where a score of 10 means that the hazard is inevitable during the life of the asset. Severity is the harm expected, where 10 is likely to cause permanent disability or loss of life. Detection measures the difficulty of determining if the hazard is happening so that mitigation steps may be taken. A score of 10 means it is impossible to detect. The product is the Risk Priority Number (RPN) which is then ranked to determine which harms to lessen first.

ID	HAZARD	DESCRIPTION	OCCURANCE	SEVERITY	DETECTION	RPN	ACTIONS
RISK-001	Failed Seals	Fluid loss from degraded or failed seals	8	8	1	64	Redundancy, testing, fail-safe seals, frequenty maintenance
RISK-002	Debris Penetration (small)	Point puncture by meteorites or space junk	10	8	7	560	Hull protection, redundancy, energy absorption, repairbots, radar with laser deflectors
RISK-003	Collision (large-scale)	Distributed impact from spacecraft, asteroid, or other large body	4	10	1	40	Avoidance radar and annunciate, safe shut-down
RISK-004	Loss of Station-Keeping	Run out of fuel to maintain correct attitude towards customers	4	4	1	16	Sensors and scheduled maintenance
RISK-005	Solar Flare or CME	Extreme electromagnetic or particle flux that damages electronics, harms humans	10	8	1	80	Electrostatic protection, rad-hard electronics, redundancy
RISK-006	Mishandled Spent Fuel	Theft or loss of used radioactive fuel pellets	3	10	5	150	Clear disposal guidelines, government oversight
RISK-007	Control Malfunction	Software code error, computer glitch, or operator error	4	9	6	216	Red-team testing, redundancy, error-checking, sensors, team decision-making
RISK-008	Insider Sabotage	Deliberate damage done by knowledgeable person(s)	3	10	8	240	Personnel selection, psychological monitoring, team decision-making
RISK-009	Abandonment (Kessler Syndrome)	Resupply interrupted and runs past scheduled maintenance schedules	5	5	1	25	Automation of control and maintenance functions, safet shut-down
RISK-010	Too-bright Background	Proliferation of space assets impair radiative heat transfer	4	5	1	20	Pre-emptive regulation, turn-down.

Figure 4. Top-level risk assessment for Space Nuclear Power (SNP) at GEO location.

4. Discussion

The SMR size is taken conservatively, assuming that space-rated machines are de-rated in performance in favor of safety relative to terrestrial reactors. Performance improvements can be realized with larger electric outputs per module. The design presented here can certainly be accomplished with only Earth-launched components. However, to address concerns for safety and protection of the homeworld biosphere, the U-233 fuel can be produced on the lunar surface. With fission power available on the Moon, there is power available for electromagnetic launch [12]. In this way, fuel pins can be delivered to GEO, captured electromagnetically, and then inserted into an otherwise non-radioactive SMR delivered from Earth. The use of beryllium initiators, creating hot neutrons via deep sky gamma rays sill start the chain reaction for each reactor.

The concept of Space Solar Power has motivated research for many decades. However, the idea of Space Nuclear Power has only cecome a possibility with the discovery of a means for fission fuel production via in situ resource utilization on the lunar surface [1]. A SNP powersat will be smaller than a SSP powersat, and can be made less reflective so as to have a lesser impact on the night sky for astronomers. The risks to humans on Earth for SNP is low, and may be realized with lower costs and simpler logistics. This can provide pollution-free, baseload power to Earth.

5. Conclusions

Presented here for the first time is a novel space power architecture for delivering carbon-free around-the-clock power to terrestrial utilities. This requires a mature ISRU capability including excavation and soil handling, a transmutation operation based on the UREX/THOREX process [3], and delivery of fuel rods to GEO. Space Nuclear Power with fissile fuel from the Moon is less of a risk to people on Earth than terrestrial nuclear power. The greatest risk is debris penetration, which will require double hulls and other means of mitigation. Other risks involve software or people, such that redundancy of control and command will be crucial. This study presents initial technical feasibility that indicates further study and development is warranted. The eventual outcome could be a highly-profitable space business which serves the needs of a majority of the population of Earth for all time to come.

6. Conflicts of Interest

The author declares no competing interests. This work was unfunded.

7. References

1 Schubert, P., "Nuclear Power from Lunar ISRU", Insights in Mining Science & Technology, vol. 1, no. 1, Aug 2019.

2 Schubert, P.J., Doshi, J., Kindomba, E.M., Conaway, A., Bhaskaran, A., "Baseload Fission Reactor for Lunar Operations," Proc. 2020 Int'l Astro. Conf., paper IAC-20/C3/5-C4.10, 12-15 Oct. 2020.

3 Schubert, P.J., Marrs, I., Daniel, E, Conaway, A., Bhaskaran, A., "Ultra-Safe Nuclear Thermal Rockets using Lunar-Derived Fuel", The Journal of Space Safety Engineering, v. 8, no. 3, September 2021, Pages 185-192. DOI: https://doi.org/10.1016/j.jsse.2021.07.001

4 Love, A.W., "Basics of SPS Power Transmission from Space," IEEE Ant. Pro. Soc. Newsletter, Dec. 1980.

5 Schubert, P.J., Marrs, I., Daniel, E., Conaway, A., Bhaskaran, A., "Nuclear Thermal Rocket with Fissile and Reaction Fuel from Lunar ISRU," Proc. 2020 Int'l Astro. Conf., paper IAC-20/C4/10-C3.5, 12-15 Oct. 2020.

6 US Department of Energy https://www.energy.gov/ne/advanced-small-modular-reactors-smrs (accessed 14 Aug 21)

7 Schubert, P.J., Finnell, AJ., "Efficiency Equations for Long-Distance Wireless Power Transfer using Phased Array Antennas," Proc. 2020 Int'l Astro. Conf., paper IAC-20/C3/2, 12-15 Oct. 2020.

8 Schubert, P., "Doubly-Self-Aligned Hole-Within-a-Hole Structure in Semiconductor Fabrication Involving a Double LOCOS Process Aligned with Sidewall Spacers," U.S. Patent number: 4,758,530.

9 Glaser, Peter E., "The Future of Power from the Sun," Intersociety Energy Conversion Engineering Conference, Boulder, CO, 13 Aug 1968.

10 Schubert, P., Simpson, N., Lin, M., "Technical Feasibility of a Novel Method for Station Keeping," AIAA SPACE 09, Pasadena, CA, 14-17 Sept 2009.

11 Schubert, P., "Apparatus and Method for Maneuvering Objects in a Low/Zero Gravity Environment, US 6,994,296, 2006

12 Duncan, S., Schubert, P., Delaurentis, D., "System for Electromagnetic Capture of Lunar-launched Payloads into GEO," 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cincinnati, OH 8-11 July 2007.

13 Dietz, R.H., "Solar Power Satellite Workshop on Microwave Power Transmission and Reception," NASA-TM-84064, 1980.

14 Finnell, A.J., Heng, P., Powell, S.H., Schubert, P.J., "Spacetenna Flatness and Error Correction," Proceedings of the Int'l Astro. Cong. 2019, Washington, D.C., 22-25 Oct. 2019.

15 Schubert, P.J., , "Sidelobe Reduction for GEO to Earth Wireless Power Transfer," Int'l. Astro. Conf. 2016, Guadalajara, Jalisco, Mexico, 26-29 Sept 2016.

16 Finnell, A.J., Schubert, P.J., "Antenna Arrangement Verification for Low Sidelobe Levels," IEEE WiSEE 2019, Ottawa, CN 16-19 Oct. 2019.

17 Schubert, P., "Energy and Mass Balance for a Cislunar Architecture supporting SSP," AIAA SPACE 09, Pasadena, CA, 14-17 Sept 2009.

18 Wen, C., et. al., "Reconfigurable Sparse Array Synthesis with Phase-only Control via Consensus-ADMM-Based Sparse Optimization," IEEE Trans. Vehicular Tech., 24 Sept 2021, DOI 10.1109/TVT.2021.3089418,

19 Abdellatif, A.S., Zhai, W., Patula, H.K., Repeta, M., "Array of Arrays: Optimizing Phased Array Tiles,"Ant. And Wireless Prop. Lett., 8 March 2021, AWPL-01-21-006, DOI 10.1109/LAWP.2021.3061281.