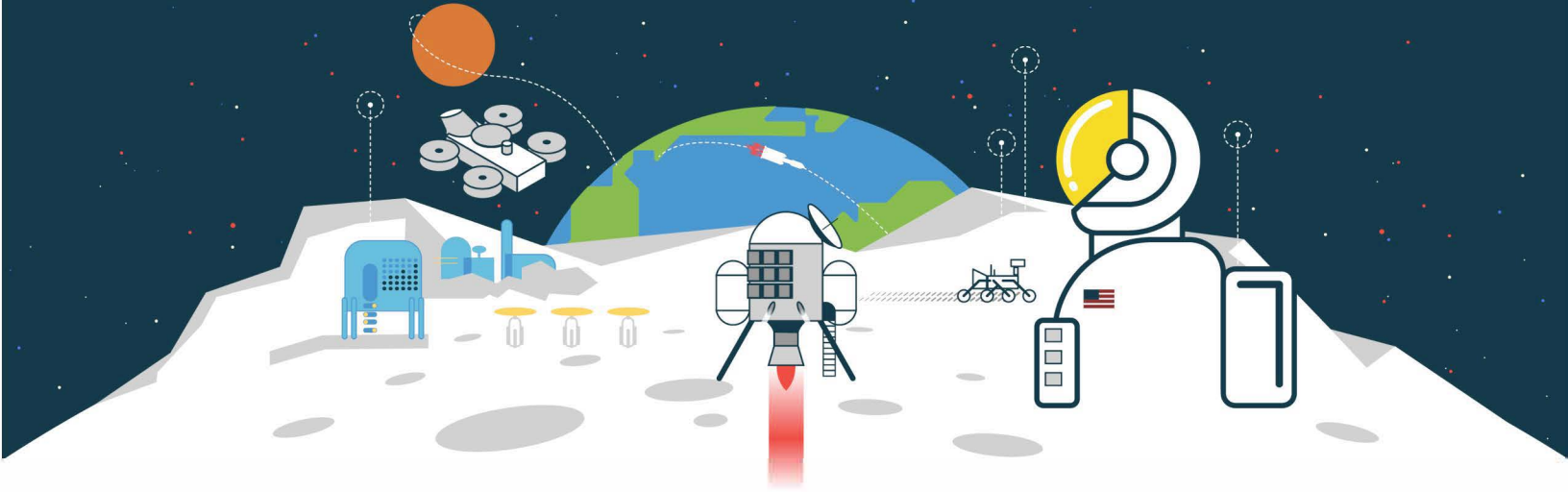


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REINFORCEMENT LEARNING IN SIMULATED REALITIES FOR AUTONOMOUS TASKS IN HOSTILE ENVIRONMENTS

Mark C. Patterson,¹ Seth Cohen¹, Joel Bjornstad¹, Robert Amaro¹, Chanler Cantor², Michael Yohe², William Marx² and Gavin Richardson², Venugopal Varma³

¹*Southern Research, 757 Tom Martin Drive, Birmingham AL 35211(256) 581-2000*

²*Intuitive Research and Technology Corporation, 5030 Bradford Drive, Suite 205, Huntsville, AL 35805, (256) 922-9300*

³*Oak Ridge National Laboratory, 1 Bethel Valley Rd., Oak Ridge, TN 37830, (865) 574-7156*

Mark Patterson (301) 221-8699, mpatterson@southernresearch.org

Abstract.

The next generation of terrestrially based Molten Salt Reactors (MSR) will require autonomous maintenance capabilities due to the extremely hostile radiation and thermal environments that exclude human operators from supporting equipment in close proximity to the reactors. The Advanced Research Program Agency for Energy (ARPA-E) is currently funding efforts to use reinforcement learning technique and train robots to perform maintenance operations necessary to make MSR fission reactors a reality. Since there are no-such reactors currently built and the future designs are still under development, there is no testbed for physical experiments. To overcome this obstacle, we have developed a generalized methodology to train robots in a virtual environment. In this regard, the virtual environment can be created from either 3D mapping of existing, physical components or from components that only exist as engineering specifications as long as their dimensions and behaviors can be represented in the virtual world. Our approach creates an integrated software and algorithm architecture with the ability to “teach” automated systems successful tasks from simulated data sets with minimal human oversight. A well-defined process is being developed that connects the Virtual Reality/Extended Reality (VR/XR) training environment with reinforcement learning algorithms alongside interface software that will enable the system to adapt to any task that can be physically performed autonomously.

As the capability is developed, it is clear that an approach using a virtual environment has extensive applications not only terrestrial based nuclear plant maintenance, but for space based tasks that are difficult or impossible to replicate for the necessary training data set. Autonomous systems, including robots, will support Artemis and many other human activities in space, including establishing a permanent residency on the Lunar surface. Every physical component that will build up the numerous systems supporting space travel and lunar habitats will be accurately defined well in advance, and the desired robotic tasks that require automation can be trained and demonstrated prior to missions taking place. While this technology is currently in its infancy, it is expected that autonomous systems will be able to mature rapidly and undertake complex and dynamic tasks using reinforcement learning derived algorithms.

Keywords: Reinforcement learning derived algorithms,
Virtual reality/Extended reality (VR/XR), Robots,
Autonomous, Simulated data sets.

COMPARING EXPERIMENTALLY VALIDATED COMPUTATIONAL THERMAL RADIATION SOLUTION METHODS AS IT PERTAINS TO NUCLEAR THERMAL PROPULSION

Tyler R. Steiner¹ and Richard H. Howard^{1,2}

¹ *University of Tennessee, Knoxville, Department of Nuclear Engineering, TN, 37996*

² *Idaho National Laboratory, Idaho Falls, ID, 83415*

Primary Author Contact Information: tsteine1@vols.utk.edu

Abstract. In a non-participating medium (i.e. a medium that does not absorb, emit, or scatter thermal radiation), radiative heat transfer between surfaces is a function of the surface characteristics and the optical view exchanged between the surfaces. The proportional quantity of thermal radiation that can be transmitted from an emitting surface to a target surface is called the view factor (also referred to as the configuration factor, shape factor, or form factor). For complex geometries, several numerical methods have been developed to evaluate the view factor. This work seeks to compare existing thermal radiation solution methods. These solution methods include the ANSYS hemi-cube method, the COMSOL hemi-cube method, and the COMSOL ray shooting method. Solution time, accuracy, and various sensitivities will be investigated. This work will utilize the Out-of-Pile Experiment Set Apparatus (OUTSET) developed at Oak Ridge National Laboratory to generate high temperatures in a vacuum environment. OUTSET has been developed to reach prototypical Nuclear Thermal Propulsion temperature conditions. The numerical solution methods will be assessed using the results from the experiment.

Keywords: thermal radiation, experiment, computational,
nuclear thermal propulsion

OPERATIONAL CONSIDERATIONS FOR FISSION REACTORS UTILIZED ON LUNAR *IN-SITU* RESOURCE UTILIZATION MISSIONS

Andrew Klein¹, Allen Camp², Patrick McClure³ and Susan Voss⁴

¹352 NE Fircrest Place, McMinnville, OR, 97128, 541-760-6134, kleina55@yahoo.com

²13405 Quaking Aspen Pl NE, Albuquerque, NM 87111, 505-239-8624, acamp32@comcast.net

³Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM 87545, 505-667-9534, pmmclure@lanl.gov

⁴Global Nuclear Network Analysis, LLC, 1013 Witt Rd, Taos, NM 87571, 505-690-6719, svoss@gnnallc.com

Primary Author Contact Information: 541-760-6134, kleina55@yahoo.com

Abstract. This study examined the operational aspects of a sequence of nuclear reactors that could be utilized to supply increasing amounts of electrical and thermal power for In-Situ Resource Utilization (ISRU) missions on the lunar surface. The missions could facilitate the production of raw materials for use on the Lunar surface and for vehicle propellant material for crew and cargo transportation back to Earth and potentially on to Mars. The full radiation fields surrounding the three reactors utilized to support these mission concepts will have to be analyzed during the design of the system and mapped once the reactors are on the surface and operating. Any reactor shielding can be designed to accommodate crew approaches to the reactors, if astronauts will be working in the vicinity of these reactors. For any reactor system that may be human rated, it is important to consider not only the planned maintenance, but also any projected emergency maintenance. Contingency plans for approaching these reactors under various scenarios will need to be developed. An array of possible maintenance scenarios for these reactors may exist, ranging from no planned maintenance on a pilot plant reactor to possible complicated maintenance scenarios, both planned and unplanned, for a commercial production plant. Reactor startup will need to be fully considered during the system design process for each reactor. The inherent simplicity of operation of self-regulating reactors during the early phases of the lunar ISRU outpost establishment and keeping these missions as simple as possible will help build operational confidence. Restart of the reactors following shutdown also needs early consideration and is especially important if a reactor is providing life support and other critical functions. The existence of any time delay (on the order of a few seconds) between a Lunar outpost and an Earth-based mission control room implies that ground operators may only be able to transmit simple and straightforward commands to the Lunar-based reactors, making rapid operator response challenging. Additionally, while the astronauts on these missions may need to be able to shut down the reactors locally, having one local crew member constantly monitoring a reactor control board is impractical and to be avoided. Thus, it is expected that these reactors will need to utilize considerable amounts of autonomous control and its consideration early in the reactor design process will be critical to mission success. The aim for these control systems should be to design them to setup, startup, make power level changes, operate, and shut them down as simply as possible. Lunar reactors present unique possible abnormal operational hazards. The full, detailed analysis of these highly unlikely events and malfunctions will need to be accomplished. Utilizing the simplest, self-regulating reactor and system designs will build important experience to enable effective operations of more functional systems. Planetary protection impacts of these reactors are expected to be minimal, and the probability of accidents causing interference with other Lunar activities can be minimized. Post-operational decommissioning and disposal (D&D) should ensure that the shutdown reactors do not interfere with other planned activities. Exclusion areas can be established, and radiation monitoring can continue until the radiation levels are benign and permanent shutdown status is confirmed. In the event of abnormal reactor termination, other D&D measures may be necessary.

Keywords: Lunar resource utilization, nuclear reactor operations, operational considerations, decommissioning and disposal

OPERATIONAL CONSIDERATIONS FOR FISSION REACTORS UTILIZED ON NUCLEAR THERMAL PROPULSION MISSIONS TO MARS

Andrew Klein¹, Allen Camp², Patrick McClure³ and Susan Voss⁴

¹352 NE Fircrest Place, McMinnville, OR, 97128, 541-760-6134, kleina55@yahoo.com

²13405 Quaking Aspen Pl NE, Albuquerque, NM 87111, 505-239-8624, acamp32@comcast.net

³Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM 87545, 505-667-9534, pmmclure@lanl.gov

⁴Global Nuclear Network Analysis, LLC, 1013 Witt Rd, Taos, NM 87571, 505-690-6719, svoss@gnmallc.com

Primary Author Contact Information: 541-760-6134, kleina55@yahoo.com

Abstract. This study examined the major implications associated with the operation of nuclear reactors utilized for one-way cargo and round-trip crewed Nuclear Thermal Propulsion (NTP) missions to Mars. The mission scenario is based upon data contained within the National Aeronautics and Space Administration's Human Exploration of Mars Design Reference Architecture 5.0 and its further addenda. The scenario assumed that each round-trip crewed mission would be preceded by two one-way cargo delivery missions that would be flown in parallel. All spacecraft would use a common propulsion stage with three 111-kN (25-klbf) Rover/NERVA "Pewee-class" NTP reactor systems using graphite matrix fuel elements in the form of uranium carbide microspheres or as a dispersion of uranium carbide and zirconium carbide within the matrix material. Radiation exposures from natural space sources, including galactic cosmic radiation and solar particle events, are likely to be very high and considerably greater than those that the crew might receive from the NTP engines. Risk mitigation strategies, such as advanced shielding technologies, countermeasures, and individual-based risk assessments may be important to managing these potential risks to the astronauts. Also, minimizing the round-trip time for a human Mars mission, enabled by using NTP, can reduce the overall risk of radiation exposure complications. Potential crew radiation exposures from the NTP engines would primarily occur during the reactor burns or from the dispersion of radioactive materials due to a reactor malfunction. Radiation fields around the reactors may be very complicated and affected by the reactor internal structures, the shielding design, and the propellant remaining in the tanks at any given time. Docking maneuvers should be able to be carried out relatively soon after an engine burn; however, EVAs and maintenance activities may need to remain behind shielding for a significant time after the burn. NTP reactors should generally be designed to avoid the need for maintenance near the reactors. Robotic maintenance can be considered if any are activities required in a high-radiation environment. Robotic maintenance capabilities would need to be sent with the mission at a cost of additional mass in robotics and spare parts. While considerable engine design, control and testing was accomplished during the Rover/NERVA development programs, modern instrumentation and control methods should be applied to the advancements of NTP engine technology. Full sequence of event analysis, failure mode and effects analysis, detailed probabilistic risk assessment and other techniques now common in terrestrial nuclear facility safety analysis need to be developed to enable the application of modern probabilistic safety analysis techniques to NTP engines. Options for final reactor disposal may have significant consequences and the likelihood of inadvertently impacting Mars and the Earth should be determined for both the cargo and crewed nuclear propulsion mission scenarios.

Keywords: Nuclear thermal propulsion, Mars, nuclear reactor operations, operational considerations

AN ALFVENIC RECONNECTING PLASMOID THRUSTER

Fatima Ebrahimi.¹

¹*Princeton Plasma Physics Laboratory, and Department of Astrophysical Sciences
Princeton University, Princeton, NJ 08544, USA*

Phone: 609-243-2637, ebrahimi@pppl.gov

Abstract. A new concept for the generation of thrust for space propulsion is introduced. Energetic thrust is generated in the form of plasmoids (confined plasma in closed magnetic loops) when magnetic helicity (linked magnetic field lines) is injected into an annular channel. Using a novel configuration of static electric and magnetic fields, the concept utilizes a current-sheet instability to spontaneously and continuously create plasmoids via magnetic reconnection. The magnetic reconnection process here converts magnetic energy of the applied fields to kinetic energy of the plasmoids, accelerating them to a velocity of tens to hundreds of km/s, adjustable by varying the magnetic field's strength. Our novel electromagnetic thruster concept, the Alfvénic reconnecting plasmoid thruster, has been shown to produce an exhaust velocity in the range of 20 to 500 km/s controlled by the coil currents in our first sets of three-dimensional simulations. The plasmoids carry large momentum, leading to a thruster design capable of producing thrusts from tenths to tens of newtons. The optimal parameter range for this new thruster is expected to be ISP (specific impulse) from 2,000 to 50,000 s, power from 0.1 to 10 MW and thrust from 1 to 100 N. It would thus occupy a complementary part of parameter space with little overlap with existing thrusters, and be suitable for long-distance travel with high Δv , including the solar system beyond the Moon and Mars. Because the Alfvénic plasmoid thruster can use a wide range of gases as fuel, it will be ideal for asteroid mining, since, for example, hydrogen could be extracted from asteroids. The next steps include performing more detailed computer simulations to both develop a reduced-size (50 kW or less) solar-powered thruster version, more suitable for lab testing and with more near-term commercial viability, as well as a larger (tens of MW) mission-powered version.

Keywords: plasma thruster, high-power in-space propulsion, Alfvénic plasmoid

Enabling and Enhancing: Effective Stakeholder Communication about Radioisotope Power Systems

Douglas Isbell¹ and Amruta Mehta¹

¹*NASA Jet Propulsion Laboratory, California Institute of Technology 4800 Oak Grove Drive, Pasadena, CA 91109*

Primary Author Contact Information: douglas.m.isbell@jpl.nasa.gov, 626-318-1488

Abstract: NASA's Radioisotope Power Systems (RPS) Program supports a Stakeholder Engagement task that includes strategic communications products developed by a two-person team at NASA's Jet Propulsion Laboratory (JPL). These products include informational materials for the public and other external stakeholders, internal messaging guidance regarding potentially controversial topic areas, and formal communications effectiveness training for spokespeople, as well as mission-funded radiological contingency planning for the launch of RPS-powered NASA spacecraft, such as the Mars 2020 Perseverance rover launched on July 30, 2020. The core principles of RPS strategic communications include being open, accurate, clear, respectful, well-prepared, and interactive. This talk will discuss the goals and development processes involved in RPS strategic communications, and will share examples of recent tasks and products prepared in support of program activities such as Mars 2020 and renewed plutonium dioxide fuel production for civil space exploration. The talk will also present high-level topics for discussion about the challenges and opportunities ahead regarding the future of RPS, and the general use of space nuclear power systems.

Keywords: communications, radioisotope power systems,
launch nuclear safety

Autonomous Operation Capabilities for Space Reactors

Richard T. Wood¹

¹*The University of Tennessee, Knoxville, TN, 37996-1410*

865-974-8841, rwood11@utk.edu

Abstract. The application of nuclear reactors for space power and/or propulsion presents some unique challenges regarding the operations and control of the power system over a long mission under adverse conditions. For a variety of prospective nuclear fission enabled space missions involving deep space exploration spacecraft or planetary surface power systems, constraints that affect the operational approach for a space reactor are likely to include the following:

- Immediate human interaction for continuous operational control and event management is not feasible,
- No maintenance/refurbishment is possible,
- Reactor power must be available on demand, and
- Reactor scram is not a preferred response to off normal events.

These considerations suggest that the ability to respond to rapidly changing or degraded conditions without immediate human intervention is required for many prospective space reactor applications. Thus, a significant degree of autonomy is necessary to facilitate such applications. This presentation will discuss an approach to autonomous control for a space nuclear power system and identify necessary capabilities that must be developed and demonstrated to achieve the desired operational autonomy.

Keywords: Space nuclear power system, Autonomous operation

⁷Li All Solid-State Batteries for Deep Space Applications

Rebecca D. McAuliffe¹ and Gabriel M. Veith¹

¹*Chemical Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 37831*

Primary Author Contact Information: mcaulifferrd@ornl.gov

Abstract.

Probes for deep space missions are required to do more within a confined space. These probes are powered by radioisotope thermoelectric generators (RTGs) and lead acid/nickel metal hydride batteries. These batteries are heavy and bulky and provide low power. Lithium ion batteries are ideal for this application due to their light weight, higher voltages, and lower volume. However, the radiation emitted from the RTGs induce radiation breakdown in polymer electrolytes and neutron capture/daughter product generation in naturally abundant Li sources. This talk will highlight our ability to fabricate all solid-state batteries using ⁷Li. We have made deposition targets of ⁷LiCoO₂ and ⁷Li₃PO₄ to make thin film batteries using ⁷Lipon as a solid electrolyte. These batteries will be tested along with batteries fabricated using naturally abundant Li using Americium-Beryllium sources to understand how ⁷Li all solid-state batteries perform during irradiation.

Keywords: Lithium ion batteries, LiCoO₂, radiation effects, solid-state batteries

THE CHALLENGE AND PROMISE OF WIRELESS POWER TRANSFER FOR FISSION SURFACE POWER

Ethan S. Chaleff¹

¹ *Ultra Safe Nuclear Corporation Tech*
2356 W Commodore Way, Unit 120, Seattle, Washington, 98199

Phone: 206-906-9741, e.chaleff@usnc-tech.com

Abstract. Wireless power transfer (WPT) such as microwave or laser power beaming, could be a promising means to simplify Fission Surface Power (FSP) reactor operations and theoretically holds significant mass savings. This is especially true for early concept demonstrators where little or no site infrastructure to construct in-situ shielding or lay power cabling is assumed to be available. The major proposed benefit is the ability to significantly increase the distance between user and generator, allowing reductions in shielding requirement and greater flexibility in siting for landing. It also theoretically allows one reactor to serve multiple customers. Wireless power transfer has been demonstrated in terrestrial applications, and studied for orbital solar. However, there are subtleties to the design of these systems that do not lend themselves well to lower power initial FSP concepts. For later stage concepts, WPT may be more viable, since challenges with array construction and non-linear power scaling of RF generators decrease risk and mass. That said, for later stage concepts, shielding mass will be less significant if in-situ shielding can be constructed and if on-site infrastructure exists to lay power cabling.

This talk will discuss lessons learned from a detailed technical assessment of microwave power beaming performed by Second order Effects for USNC-Tech. Generally, it was found that WPT is not promising for near-term concepts. Due to a variety of factors, the optimum frequency for a land-based system is less than 10 GHz, and still has low DC-RF conversion efficiency, poor transmission efficiency, and impractically large rectennas, even at the 10 kWe level. Going to higher frequency enables smaller antennas, but comes at the expense of significant added RF generator mass and decreased generator efficiency, not to mention decrease in TRL. Typical end-end efficiencies are less than 15% across a variety of assumptions, and less if flight-qualified hardware is used. In conclusion, WPT faces challenges in the long run without marked improvements in technology, including deployable rectenna arrays and low-power, high-frequency, high-efficiency RF generators.

Keywords: wireless power transmission, microwave, electromagnetic shielding, fission surface power

UPDATE ON HIGH STRAIN RATE TENSILE TESTS OF PT-RH ALLOYS FOR EUROPEAN RADIOISOTOPE POWER SYSTEM CLADS: PT-20%RH AND PT-10%RH

Emily Jane Watkinson¹, Ronald Hoffman², Richard Ambrosi¹, Steve Goodrich², Keith Stephenson³, Gareth Sheppard⁴ and Hugo Williams⁴

¹*School of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, United Kingdom*

²*University of Dayton Research Institute, Dayton, Ohio, United States of America*

³*European Space Agency, ESTEC TEC-EP, Keplerlaan 1, Noordwijk, 2201AZ, The Netherlands*

⁴*School of Engineering, University of Leicester, Leicester, LE1 7RH, United Kingdom*

Primary Author Contact Information: +44116223 1033 and ejw38@le.ac.uk

Abstract. Since August 2018, the University of Leicester has led a set of high strain rate tensile test investigations with Pt-Rh alloys that have been conducted at and with the University of Dayton Research Institute. European radioisotope power system clads will be made from a Pt-Rh alloy for radioisotope heater units and the radioisotope heat source for the thermoelectric and Stirling generators. Current University of Leicester designs have moved away from Pt-30%Rh to Pt-20%Rh. However, the alloy is still to be decided. The high strain rate tensile material data is essential for impact modelling of the clad systems (see Acknowledgements). In this talk, we present progress into the high strain rate tensile behaviour investigation for Pt-10%Rh and Pt-20%Rh and its modelling. These data will be the first of its kind in the public domain. Strain rates of up to $\sim 2000 \text{ s}^{-1}$ and temperatures of up to $500 \text{ }^\circ\text{C}$ have been investigated.

Acknowledgements: The authors wish to acknowledge European Space Agency (ESA) for funding this study. The impact modelling within the ESA study is being led by Alessandra Barco (University of Leicester). Alessandra Barco will use the data and the model for the data as inputs for her impact models. We also wish to acknowledge initial conversations prior to the initial tests with Ramy Mesalam at the University of Leicester.

Keywords: High strain rate tensile tests, initial progress, Pt-10%Rh, Pt-20%Rh, platinum, rhodium

PROGRESS IN THERMOELECTRIC MODULE DEVELOPMENT FOR EUROPEAN SPACE NUCLEAR POWER SYSTEMS

R. Mesalam¹, R. M. Ambrosi¹, H. R. Williams², K. Simpson³, R. Tuley³, C. L. Bicknell¹, T. Crawford¹, K. Stephenson⁴

¹University of Leicester, School of Physics and Astronomy, Space Research Centre, University Rd, Leicester, LE1 7RH, UK

²University of Leicester, School of Engineering, University Rd, Leicester, LE1 7RH, UK

³European Thermodynamics Ltd, 8 Priory Buisness Park, Kibworth, Leicestershire, LE8 0RX, UK

⁴European Space Agency, ESTEC TEC-EP, Keplerlaan 1, 2201AZ Noordwijk, The Netherlands

Primary Author Contact Information: +44(0)116252 5850, rm558@le.ac.uk

Abstract. To date several generations of bismuth telluride based thermoelectric convertors, in the form of modules, have been produced for the European radioisotope thermoelectric generator (RTG) programme. The thermoelectric module production programme has focused on establishing a complete end-to-end capability in the UK, from material synthesis and processing, through to consolidation, segmentation and module assembly. Successful experimental campaigns have demonstrated that bismuth telluride modules, with high aspect ratio legs, are a viable power conversion option for European RTG systems utilising americium-241 as a heat source. Each module consisted of a 40 mm × 40 mm unit with 161 couples in a 1.2 mm × 1.2 mm cross-section and 6 mm in height. Initially, these custom modules were manufactured by hand using a small volume production platform. Currently, the focus is around the development and testing of processes and procedures which utilise automation for the manufacture of modules. The use of an automated module production line is aimed at maximising reproducibility and reliability associated with the manufacturing process. Especially with the difficulties related to assembling modules with high aspect ratio thermoelectric legs. An automated process will also enable larger volumes to be produced in the future as the programme progresses from a development and demonstration phase to a flight-ready phase. However, to better suit the requirements of the new automated process, a redesign of the modules was found to be necessary. The new module design consists of a 36 mm × 36 mm unit with 127 couples in a 1.2 mm × 1.2 mm cross-section and 5 mm in height. To evaluate and compare their overall system-level performance, the redesigned modules will be tested within a laboratory RTG breadboard. An initial lifetime assessment will also be performed using long duration and cyclic fatigue tests which meet the rigorous quality and reliability standards for space applications. This talk will discuss the outcomes of this campaign.

Keywords: Thermoelectric, Generator, Radioisotope

EMPIRICAL ANALYSIS AND EXTRAPOLATION OF MMRTG F1 PERFORMANCE ON CURIOSITY: AN UPDATE

Christofer E. Whiting

University of Dayton, 300 College Park, Dayton, OH 45469

Primary Author Contact Information: (937) 229-2570; chris.whiting@udri.udayton.edu

Abstract. A Multi-Mission Radioisotope Thermoelectric Generator is currently powering the Mars Curiosity rover. Previously, the power produced by this generator was analyzed from the point of landing on Mars (August 2012) to August 2018. Extrapolations obtained from this analysis suggested that the generator would be producing 75.2 W_e at the end of its design life (i.e. after 13.25 years on Mars). Recently, this analysis was updated to include telemetry through April 2020. This updated analysis suggests that the physical/chemical mechanism that was controlling degradation changed sometime around November 2017. This change in mechanism appears to be similar to a change in mechanism that was observed in Pioneer. The radioisotope thermoelectric generators on Pioneer (i.e. SNAP-19) use thermoelectric conversion technology that is similar to the Multi-Mission Radioisotope Thermoelectric Generator, suggesting that this change in mechanism may be a fundamental property of the thermoelectric materials. If this is true, then future missions that use the Multi-Mission Radioisotope Thermoelectric Generator can expect to observe a similar change in behavior during operations. Based on the new mechanism, the extrapolated end of design life power is now 73 W_e . Certainty, confidence, and precision in this extrapolation should improve as more data is obtained from Curiosity. This is because Martian seasons are known to impact generator power, and the current data set only includes 1.33 Martian years of data under the new mechanism. Several Martian years of data are needed to average out the effect that seasons have on power.

Keywords: Multi-Mission Radioisotope Thermoelectric Generator, power, degradation, Curiosity



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Evaluation of Regenerative Cooling Channels for Nuclear Thermal Propulsion

Keaton Melendez¹, Grant Davis¹, William Mullin¹,
Emmanuel Adu¹, Aaron Bell¹, Ben Stefanko¹, Edward Herderick¹, John M. Horack¹

¹The Ohio State University, Columbus, OH, 43210

Primary Author Contact Information: +1 (440) 662-9595, melendez.65@osu.edu

Abstract. Nuclear Thermal Propulsion (NTP) is identified as a technology well-suited for reducing travel times, increasing payload capability, or both, in future interplanetary space travel across large distances. The primary advantages accrue because of NTP's combination of high specific impulse and high thrust, relative to chemical rocket technology. However, one design challenge of NTP is the extremely high heat-flux experienced at the nozzle throat, where high temperatures can damage the nozzle wall. This issue can be partially addressed by introducing a regenerative cooling system to the nozzle, in which liquid H₂ is passed through the nozzle wall prior to use as propellant, which maintains an acceptable steady-state wall temperature. Such systems have been implemented on a range of chemical rockets. However, these traditional cooling channel geometries generally involve straight cooling channel paths with rectangular cross sections along the contour of the nozzle. These traditional geometries have been typically designed and manufactured within subtractive manufacturing environments. The challenge of higher throat temperatures in NTP incentivizes the exploration of design shift towards more complex geometries that are more conducive to additive manufacturing techniques. This lightning talk explores the potential benefits of sinusoidal cooling channels, including the increase of turbulent flow mixing, and investigates testing results. Turbulent flow from mixing results in a smaller fluid boundary-layer, which increases heat transfer from the walls of the nozzle to the working fluid. Testing and modeling of various sinusoidal cooling channel geometries generates insight into preferred sinusoidal parameters for channels, which can then be additively manufactured using current technologies.

Keywords: Additive Manufacturing
Nozzle Design
Regenerative Cooling
Nuclear Thermal Propulsion

THE RPS MISSION DATABASE

Knut I. Oxnevad¹, David F. Woerner¹, and Bill J. Nesmith¹

¹ Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109-8099

Knut I. Oxnevad: 818-943-7917, knut.i.oxnevad.dr@jpl.nasa.gov

Abstract: As part of the Next-Generation Radioisotope Thermoelectric Generator (Next-Gen RTG) Study, an extensive relational database was developed to analyze, combine, visualize, and present the data in effective and unique ways.

As the database was developed and used, the authors realized that it could be beneficial to a wider audience, such as those engaged in planning missions, and those studying and designing them. We have therefore renamed the database to be the RPS Mission Database. Access to the database will be limited. NASA's Radioisotope Power Systems (RPS) Program Office at Glenn Research Center will be granting access at their discretion.

In this lightning talk, we will give a short overview of the capabilities of the database.

There are three "windows" into the database: the RTG Window, the Destination Window, and the Spacecraft Window. Each window is connected to its own unique table of information. This information is displayed in the respective windows. The windows can be accessed from the "Layout" menu.

Each of these windows have a tab named RELATIONS. Here, selected data in the tables that are connected to the window displayed can be accessed. The RELATIONS tab in the RTG Window will show, for each RTG, which spacecraft it can power. Likewise, in the Spacecraft Window, the RELATIONS tab will show, for each spacecraft, which RTGs can be used for powering that spacecraft. The RELATIONS tab in the Destination Window will similarly show, for each destination, which spacecraft have been or are aiming for that destination. The Mars 2020 and Voyager missions will be used as examples.

The database includes detailed data for 309 RTG concepts (existing and potentially new types); 70 destinations, including 6 generic potential destinations (comets, Trojans, Centaurs, etc.); and 156 spacecraft concepts (65 launched and 80 studied) and 273 missions associated with these spacecraft concepts. A mission is defined as a unique vector of spacecraft, mission type (e.g., lander) /subtype (e.g., rover), and destination. For example, the Cassini spacecraft conducted flybys of Enceladus and the asteroid 2685 Masursky, and a number of orbits around Saturn. Under this definition, these would be considered as three distinct missions conducted by Cassini. RTGs, Destinations, and Spacecraft are characterized through the 300 parameters constituting the database.

Keywords: Radioisotope, spacecraft, mission, space destinations, relational database

NASA's Approach to Nuclear National Environmental Policy Act Compliance

Bethany Eppig¹, Jeffery Cronin², Tina Norwood³, June Zakrajsek¹, and Michelle Rau⁴

¹NASA Radioisotope Power Systems Program, Cleveland, OH, 44135

²Leidos, Twinsburg, OH, 44087

³NASA Environmental Management Division, Washington, DC, 20546

⁴Jacobs, Tampa, FL 33609

Primary Author Contact Information: 216-433-3726 and bethany.m.g.eppig@nasa.gov

Abstract. NASA's Radioisotope Power Systems (RPS) Program is responsible to manage and document NEPA activities for both funded and projected RPS enabled NASA missions. The RPS Program actively looks for improvements in the efficiency of execution of these processes while maintaining regulatory compliance. The implementation of identified process improvements that reduce cost and schedule for utilization of an RPS increases the space exploration community's accessibility for solutions to reliably power and heat spacecraft, further supporting the exploration of our solar system and beyond. NASA's RPS Program, in coordination with NASA's Environmental Management Division, has implemented two such improvements to the RPS NEPA process which include (i) beginning the NEPA process with an Environmental Assessments (EA) and (ii) utilization of NEPA's programmatic opportunities.

Previously, the NEPA approach for RPS enabled missions was initiated with an Environmental Impact Statement (EIS), the most detailed and rigorous level of NEPA review. The EIS approach costed roughly \$2M per mission. To date, NASA has prepared nine NEPA documents for past RPS-enabled missions spanning the past three decades. None of these missions has concluded a significant environmental impact is reasonably foreseeable. By using the knowledge and understanding gained from these previously completed RPS NEPA documents, NASA's RPS Program is taking the approach to begin the NEPA process with an EA for RPS-enabled missions. NASA will continue to examine the likelihood and consequences of a release of nuclear material occurring to determine if the impact threshold would be considered significant per NEPA. The Department of Energy serves as a Cooperating Agency on all of NASA's NEPA analysis for nuclear-enabled missions as they provide the nuclear material and serve as the government's experts on nuclear consequence analysis. DOE leads the development of the nuclear approach in RPS NEPA documents and is instrumental in determining the potential nuclear consequences during an accidental release of nuclear material. The purpose of the EA will be to determine whether or not there may be significant impacts that merit more detailed study and analysis. If no significant environmental impact is reasonably foreseeable as a part of the EA process, the NEPA process is completed with the publication of a "Finding of No Significant Impact" (FONSI), with a direct cost savings of roughly \$1.5M to the mission.

Programmatic NEPA documents allow agencies to evaluate the effects of proposed actions at a broad level and utilize that analysis for subsequent actions. NASA has been using a programmatic NEPA approach for routine payloads since 2002. Following this approach for an RPS system, The Radioisotope Heater Unit (RHU) Programmatic Environmental Assessment (PEA) was completed in 2019 and a FONSI published in 2020. RHUs are small devices that use the decay of plutonium-238 to provide heat to keep spacecraft components and systems warm. The PEA provides a principal NEPA assessment on the RHU system, under certain bounding parameters. This system-based consequence analysis allows NASA to utilize the programmatic approach for an RPS, streamlining the NEPA process and saving time and resources for all agencies involved. This system-based approach is a one-time Program investment of roughly \$400K, and if the mission falls within the bounds of the PEA, can reduce mission specific RPS NEPA process costs by an additional \$350K. The potential final result is future mission specific NEPA process costs of \$50K as opposed to \$2M. NASA's RPS Program plans to continue this approach and is in the process of developing a programmatic NEPA document for the General Purpose Heat Source (GPHS), the system specific building block for the radioisotope generators used by NASA.

Keywords: Radioisotope Power System, Programmatic NEPA

Design Basis for Nuclear Thermal Propulsion Testing using a Hot Hydrogen Test Loop

William Searight¹ and Leigh Winfrey¹

¹*Pennsylvania State University, University Park, PA, 16802*
Primary Author Contact Information: (720) 382-6108, wts36@psu.edu

Abstract: Nuclear Thermal Propulsion (NTP) systems offer great near-term promise for enabling deep space missions, owing to significant efficiency improvements over chemical propulsion systems and much greater thrust than electric propulsion systems. While historical NTP designs have been tested extensively, all using Highly Enriched Uranium (HEU) cores, modern designs incorporating High Assay Low Enriched Uranium (HALEU) and ultra-high temperature materials must be validated experimentally¹. To this end, a hot hydrogen test loop capable of producing circulating hydrogen at temperatures up to 1000 Kelvin is being designed and constructed at the Pennsylvania State University, with the immediate intent to characterize the damage NTP components will experience during exposure to hydrogen plasma. While testing facilities for NTP components exist outside of academia^{2,3}, this facility provides the opportunity to examine the plasma-material interactions in NTP systems with experience drawn from fusion energy research and other related disciplines. This work will detail the current preliminary design work behind the loop, as performed using ANSYS Fluent to simulate the fluid behavior in the test section. The design studies performed show laminar flow behavior in the hydrogen and deliver temperatures of 1000 K to the test section. This design work will provide the basis for the loop's construction and operation when laboratory spaces become available.

Keywords: Nuclear Thermal Propulsion, Hydrogen, Testing, High Temperature Materials, Plasma-Material Interaction

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SELECTION OF ALTERNATIVE FIBER TO REPLACE NARC-RAYON FOR THE PRODUCTION OF CBCF

Nidia C Gallego¹, Glenn Romanoski¹, and George Ulrich¹

¹*Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37830*

865-241-9459, gallegonc@ornl.gov

Abstract. A unique Carbon Bonded Carbon Fiber (CBCF) insulation was developed to provide thermal protection to plutonia-fueled clads in General Purpose Heat Source modules used in radioisotope power systems for space applications. The microstructure of CBCF is comprised of chopped and carbonized rayon fibers bonded at intersections by carbonized phenolic resin. Production of CBCF insulation at ORNL has been sustained for the past three decades by a single lot of aerospace grade rayon purchased from North American Rayon Corporation (NARC) of Elizabethton, TN in 1987. NARC is no longer in business; thus, we initiated a search for a suitable replacement fiber that can meet the stringent purity levels required by the CBCF specification. ORNL has complete the evaluation of three rayon or cellulose-based fibers alternatives. A summary of the results and the recommended path forward will be presented.

Keywords: Radioisotope Power Systems, Carbon Bonded Carbon Fiber, CBCF, Insulation, Rayon Fiber

EFFECT OF TIME AND TEMPERATURE ON HELIUM FLOW RATE THROUGH SINTERED PLATINUM POWDER

Brian Friske¹, Bart Murphy¹, Roger Miller¹, and George Ulrich¹

¹*1 Bethel Valley Rd, Oak Ridge, TN, 37830*

Primary Author Contact Information: (865) 576-1417 and friskeb@ornl.gov

Abstract. Effect of sintering temperature and time on the helium flow rate, thickness, and diameter of platinum powder frits was investigated. The platinum powder was cold pressed and processed through an air burn-off operation prior to sintering. Sintering was completed in two separate high temperature vacuum furnaces; one with a metal hot zone and one with a graphite hot zone while on a graphite fixture. Platinum frits are part of Light Weight Radioisotope Heater Unit (LWRHU) clad production at the Oak Ridge National Lab (ORNL).

Keywords: Platinum Powder, Sintering, Light Weight Radioisotope Heater Unit, Frit

FABRICATION OF MO30W BASED CERMETS FOR NUCLEAR THERMAL PROPULSION USING SPARK PLASMA SINTERING

Neal Gaffin¹, Caen Ang¹, Justin Milner², Kelsa Palomares³, and Steven Zinkle¹

¹University of Tennessee, 1412 Circle Dr., Knoxville, TN, 37996

²NASA Glenn Research Center, 21000 Brookpark Rd, Cleveland, OH, 44135

³Advanced Projects Group, Analytical Mechanics Associates Inc., Huntsville, AL, 35806

Primary Author Contact Information: (702) 734-3355 and ngaffin@vols.utk.edu

Abstract. Ceramic Metallic (CERMET) fuels composed of a refractory metal matrix and ceramic fuel particles have been considered a viable option for nuclear thermal propulsion (NTP) fuel systems due to their capability for hydrogen compatibility and high melting temperatures. Original cermet fuels developed through the Argonne National Laboratory's Nuclear Rocket Program and the General Electric 710 Gas Reactor programs were composed of spherical uranium dioxide fuel kernels dispersed in a tungsten metal matrix. Lessons learned through historic programs pointed to increased fuel performance with microstructures that were high density and ensured uniform coating of fuel particles to prevent interconnectivity and exposure to the hydrogen propellant. Under NASA's current space nuclear propulsion project, molybdenum-tungsten alloy cermets are being investigated for use in moderated, low enriched uranium NTP reactors. For the initial study into this alloy, 30 weight percent tungsten with the balance of molybdenum (Mo30W) was selected to test the fabricability and viability of a molybdenum tungsten alloy for NTP.

To support ongoing SNP material development and characterization activities, Mo30W cermet samples were successfully fabricated at the University of Tennessee – Knoxville using spark plasma sintering (SPS). A comprehensive study examining the effects of hold temperature, applied pressure, and sintering time was conducted to determine the optimum sintering conditions to enable the production of high density (> 90% theoretical density) Mo30W coupons and Mo30W surrogate cermets. Samples were analyzed using Energy Dispersive X-ray Spectroscopy and X-ray diffraction to determine whether a solid solution of Mo30W was achieved for different Mo30W alloy feedstocks and sintering conditions. Process scalability was assessed for sample sizes of 20 and 40 mm diameters. For both sizes, samples were found to be isotropic, with similar properties and microstructure observed throughout the entire sample when sintered under the same processing conditions. Initial sintering studies with surrogate fuel materials (zirconia and hafnium nitride) are ongoing, to evaluate the impact of surrogate feedstock morphology and volume loading on optimal sintering parameters. Powder coating techniques are being evaluated to determine optimal pre-processing conditions to ensure uniform particle dispersions without particle interconnectivity.

Keywords: CERMET, NTP, Spark Plasma Sintering, Mo30W

Aerogel Production by Critical Point Drying for RTG Thermoelectric Modules and Other Applications

Ying Song¹, Russ Bennett¹, Steve Keyser¹ and Bob Sievers¹

¹10707 Gilroy Road, Hunt Valley, MD 21031

Phone: (410)891-2304; Email: Ying.Song@Teledyne.com

Abstract. Many spacecraft, satellites and landers require the use of thermal insulation that will provide isolation from the extreme environments encountered in space and on extraterrestrial bodies. Critical point dried aerogel (CPDA) exhibits superior properties to other existing commercial insulation materials, possessing exceptionally porous structure with high specific surface area, extremely lower density and thermal conductivity. It may effectively reduce heat loss through a wide temperature range. CPDA is also proved to prolong the operational lifetime of thermoelectric couples due to its ability to suppress the sublimation of volatile constituents of the thermoelectric material in a high temperature environment. These features make CPDA attractive for both RTG thermoelectric modules and also for low temperature applications. Critical point drying has been considered as a conventional method to approach the synthesis of aerogel to eliminate capillary stresses in order to produce uniform nanostructured pore network of aerogel. Teledyne Energy Systems, Inc. (TESI) with the support of NASA, has designed and completed installation of a critical point drying autoclave system with the ability to operate using either carbon dioxide or acetonitrile as supercritical fluid for producing different types of aerogel to meet different requirements. The system can be operated fully automatically with precisely controlled pressure, temperature, and flow. Manufacturing capability has been successfully demonstrated for a wide variety of size and shape of CPDA. The progress in developing and optimizing drying process for a custom geometric and thermal application will be presented.

Keywords: Aerogel, Critical Point Drying, Thermal Insulation, RTG

Device Performance and Characteristics of SiGe and SiMo Materials Synthesized by Spark Plasma Sintering at Multiple Laboratories

Rama Venkatasubramanian^{1#}, Jonathan Pierce¹, Richard Ung¹, Meiyong Himmtann¹, Joseph Poon², Sriparna Bhattacharya³, Apparao Rao³, Scott Misture⁴, Tim Erickson¹ and Paul Ostdiek¹

¹Johns Hopkins University Applied Physics Laboratory (APL), Laurel, MD; ²University of Virginia (UVa), Charlottesville, VA; ³Clemson University, Clemson, SC; ⁴Alfred University (AU), Alfred, NY

rama.venkatasubramanian@jhuapl.edu

Abstract: SiGe and SiMo materials are key component materials in the building of general-purpose heat source – radioisotope thermoelectric generator (GPHS-RTG) unicouples. In this presentation, we will describe a collaborative effort that APL has undertaken recently with UVa, Clemson, and AU in the spark plasma sintering (SPS) synthesis of SiGe and SiMo materials and their characterization, and device validation at typical GPHS-RTG operating temperatures. We will report on the maturity of the SPS process, as inferred by the ability to get comparable results from materials made at various university labs using comparable experimental synthesis parameters. *Early measurements indicate that the thermoelectric properties (electrical resistivity and Seebeck) as well as grain structure of SPS SiGe are meeting the acceptance criteria of heritage SiGe materials.* When we did observe small deviations in SiGe uni-couple performance, using different SPS SiGe materials from different labs, it was consistent with small differences in respective material characteristics. SPS has been used for the first time to produce SiMo materials and demonstrating reproducibility and internal consistency. Demonstration of SiGe and SiMo materials at multiple facilities using similar SPS processes could reduce capital investment and transition risks to the Next Gen industry contractor. Going forward, we need lifetime validation of SPS SiGe material properties and the unicouple performance for mission-life reliability; these studies are being undertaken next. The reported developments are essential first steps to mature a robust manufacturing pathway for the sustainment and advancement of SiGe GPHS-RTG technology for future outer-planetary missions.

Keywords: Silicon Germanium, Silicon-Moly, GPHS-RTG, spark plasma sintering, thermoelectric

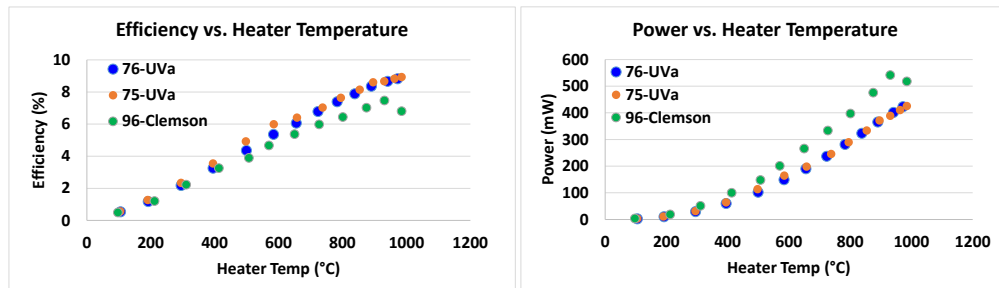


Figure 1 Experimental SiGe unicouple converter efficiencies and power outputs made from SPS Si₇₈Ge₂₂ materials made at UVa and Clemson with similar experimental parameters for synthesis of materials ($T_{\text{cold}} \sim 100^\circ\text{C}$ at a $T_{\text{hot}} \sim 1000^\circ\text{C}$)

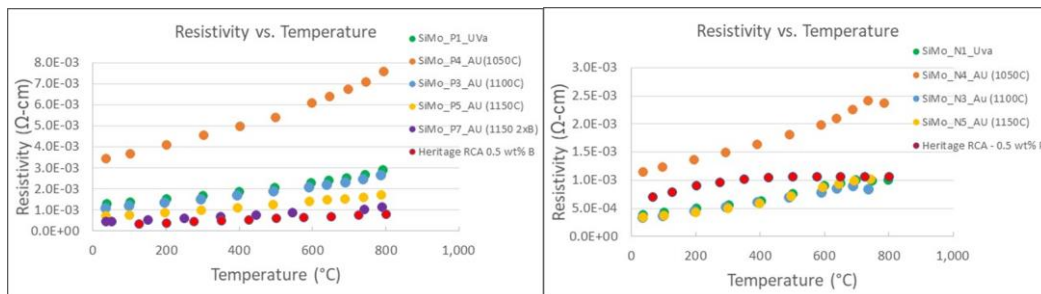


Figure 2 Electrical resistivity of P-type and N-type SiMo materials prepared by SPS at AU and UVa, and compared to that of heritage SiMo materials

Acknowledgement: The authors acknowledge the support of NASA Next Gen RTG Project and the NASA/RPS Program Office for the development of SPS SiGe/SiMo materials and early device test results.

Exploring Lunar Seismic Hazards for Future Base Camp Nuclear Installations

Michelle T. Bensi¹, Constantinos D. Frantzis¹, Maria E. Banks², Lisa S. Schleicher³, Nicholas C. Schmerr⁴, Thomas R. Watters⁵, and Renee C. Weber⁶

¹University of Maryland, Dept. of Civil and Environmental Engineering, College Park, MD 20742, USA

²NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA (maria.e.banks@nasa.gov)

³Research Geophysicist (lisaschleicher.org), Rockville, MD 20850, USA

⁴University of Maryland, Department of Geology, College Park, MD 20742, USA

⁵Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560, USA

⁶NASA Marshall Space Flight Center, Huntsville AL, USA.

With most of the world's space agencies starting to implement plans for longer-term surface operations and permanent manned lunar installations, it is becoming increasingly important to accurately characterize the hazards faced by these installations. Permanent lunar bases would almost certainly require some form of nuclear energy to offset the intermittent availability of solar power. Probabilistic seismic hazard analysis (PSHA) is a key tool used around the world to inform the development and application of seismic design criteria for nuclear installations. A key component required for a PSHA is the characterization of a magnitude-frequency distribution (MFD) for seismic events. Seismometer data from the Apollo seismic stations, which were active from 1969 to 1977, is limited by the distribution of the instrument locations on the lunar surface. Nonetheless, this data provides essential information about lunar seismic events. Combining the seismometer data with Lunar Reconnaissance Orbiter mapping of young, possibly active faults, we can start to characterize the MFD across the entire lunar surface. In this study, we provide insights into development of preliminary probabilistic seismic hazard assessments of relevance to lunar base design considerations and identify what knowledge gaps exist to be addressed in the future.

PYROLYTIC GRAPHITE – AN ENABLING MATERIAL FOR RADIOISOTOPE SPACE POWER SYSTEMS

Glenn Romanoski¹, Nidia Gallego¹, Frederic Vautard¹, Ryan Paul¹, Hsin Wang¹, Roger Miller¹ and George Ulrich¹

¹*Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37830*

865-574-4838, romanoskigr@ornl.gov

Abstract. Pyrolytic graphite (PG) has served an enabling role in current and legacy radioisotope power systems. This unique material is one of the allotropic forms of carbon and exhibits highly anisotropic structure and properties that lead to its usefulness. PG is formed by high temperature decomposition of hydrocarbon gasses onto substrates in a such manner that the graphitic planes within individual grains become aligned with the deposition surface and each other. Consequently, the resulting material embodies the unique anisotropic nature of PG on the macro scale of engineering components. The anisotropic nature of graphite is defined by its crystal structure with very strong covalent bonds in the basal plane of the hexagonal unit cell and very weak Van der Waals bonding between these parallel planes. The attendant anisotropy in bonding leads to very high strength and thermal conductivity in the direction of basal planes and very low strength and thermal conductivity perpendicular to them. PG has been chosen as an insulating material to protect the isotopic fuel in space power systems in potential accident scenarios. Over the past decade ORNL has been engaged with PG vendors in specifying, characterizing and qualifying this unique material. A description of PG enabling attributes and challenges associated with fabricating components will be presented.

Keywords: Radioisotope Power Systems, Pyrolytic Graphite, Insulation

**Safeguards And Proliferation Protections (SAPPs): A Way to Protect and Defend
U.S. HEU-Fueled Space Power & Propulsion Reactors**

Joseph A. Sholtis, Jr.

Sholtis Engineering & Safety Consulting, 2 Oso Drive, Suite 200, Tijeras, NM 87059-7632

Phone: (505) 281-4358; E-Mail: Sholtis@aol.com

Abstract. This presentation highlights a way to protect U.S. High-Enriched Uranium (HEU) fueled space reactors by means of protective functions that Safeguards And Proliferation Protections (SAPPs), proposed herein, can provide. Efforts to prescribe High Assay Low-Enriched Uranium (HALEU) for U.S. space reactors have advanced recently; largely driven – justifiably – by proliferation concerns. There are, however, valid arguments for retaining HEU as an option for U.S. space reactors. They include: 1) Reactor system and space vehicle size and mass, and associated trip times, are less for HEU-fueled systems; 2) Launch, nuclear, and astronaut safety are generally easier to ensure for HEU-fueled systems; and 3) Schedule (particularly development schedule), together with fuel availability, are currently more certain for HEU. Potential diversion of HEU, as a result of a launch or reentry accident away from U.S. territory, is a low probability event. And, future launches involving on-board space reactors, particularly to the Moon or Mars, are likely to be rare events receiving global attention. Based on the above, it is important to retain HEU as an option for mission managers and system designers - if possible. SAPPs, akin to Permissive Action Links (PALs) for U.S. nuclear weapons, could allow U.S. HEU-fueled space reactor systems to be considered as a normal matter of course - if SAPPs are functionally established judiciously, designed creatively, and incorporated carefully throughout mission/system development. Generic functions of SAPPs, for example, might be to: 1) Ensure the system will only function when properly called upon; 2) Ensure the system will not function, unless expected/specified actions and/or external environmental conditions are satisfied; 3) Ensure unimpeded access to the reactor internals/fuel is precluded unless specified external actions occur, as/when expected; 4) Ensure unimpeded access to the reactor internals/fuel is precluded if unexpected/unspecified external actions/conditions occur; and 5) Ensure the system and its fuel are protected against potential diversion. Certainly, the specifics of such SAPPs would require protection against disclosure, since such knowledge would serve as a cookbook for their defeat. The objective here is to stimulate further discussions on this topic among policy makers, mission managers, and system designers in appropriate settings.

Keywords: High Assay Low Enriched Uranium (HALEU)
High Enriched Uranium (HEU)
U.S. space nuclear power and propulsion reactors
Safeguards And Proliferation Protections (SAPPs)
Permissive Action Links (PALs)

LIMITS ON FUSION PROPULSION FOR EXOPLANET EXPLORATION

Gerald P. Jackson, Ph.D.¹

¹*1275 W. Roosevelt Rd., Suite 132, West Chicago, IL, 60185*

Cell: 630-710-7079, gpj@beamalpha.com

Abstract. The concept of fusion-based propulsion is often invoked for deep-space missions. Congressional guidance calls for an interstellar mission to a nearby habitable exoplanet to be launched by July 20, 2069, the 100th anniversary of the Apollo 11 moon landing. The guidance required a spacecraft peak velocity of 10% of the speed of light (0.1c). In order to achieve such spacecraft velocities exhaust velocities commensurate with particle energies of approximately 1 MeV/nucleon are required. Assuming a 10 kg dry mass for a probe at Proxima b, prior work has investigated the use of antimatter-induced fission to generate sufficient thrust and spacecraft power to support such an unmanned mission. In that work electrostatic containment of antimatter and electrostatic focusing of fission daughters were envisioned to create a propulsion system and power plant with a mass commensurate with the probe. In this talk the concept of electrostatic plasma confinement and reaction byproduct focusing are investigated for a variety of fuels in the same context of a 10 kg dry mass and 0.1c cruising velocity. Missions with and without the stopping of byproduct neutrons are considered.

Keywords: fusion energy, high-power in-space propulsion,
in-space power plant, exoplanet mission

BETAVOLTAIC POWER SYSTEM FOR PLANETARY EXPLORATION

Marc Litz¹, Randy Tompkins¹, Brenda Smith² and Chris Thomas³

¹*Army Research Laboratory, Adelphi, MD 20783*

²*ORNL, Oak Ridge, TN 37831*

³*Widetronix Inc., Ithica, NY 14850*

Marc.s.litz.civ@mail.mil, 301-394-5556

Abstract. The goal of planetary science exploration is to seek to reach targets of broad scientific interest across the solar system. Solar power is limited beyond Saturn, energy storage battery systems are limited by chemical energy density, and extreme planetary environments push the operating conditions of components while demanding long lived operation. Extreme pressures, temperatures, and ionizing radiation are conditions leading to degradation of materials. Betavoltaic power systems are composed of a beta emitting radioisotope adjacent to a semiconductor that converts beta kinetic energy into electrical output in a process similar to that of photovoltaics. Ultra-wide bandgap semiconductor materials have higher radiation tolerance than commonly used photovoltaic semiconductors Si and GaAs. SiC and GaN devices have been developed with beta energy conversion efficiency (8-20%) and low cost manufacturing processes. While energy conversion efficiency of betavoltaics greater than 10% are common, a higher beta energy radiation source can increase power density of the device. Betavoltaic power sources have been demonstrated using tritium and ⁶³Ni, and continue to be developed with the goal of increasing the power density by using higher energy radioisotopes (⁹⁰Sr and ²⁴¹Am). GaN, AlGaIn and Diamond energy converters are being designed and developed to take advantage of the >10% energy conversion efficiency while also providing higher power density by virtue of more energetic radioisotopes. We review the progress of liquid format ⁶³Ni radioisotope on textured (etched or pillared) SiC energy converters that have been shown to provide x8 increase in power output over planar devices. Initial experiments describing the material degradation of SiC and GaN to alpha exposure and the impact on power source lifetime is also discussed.

Keywords: betavoltaic, direct energy conversion, alphavoltaics, UWBG semiconductors

THERMAL CONDUCTIVITY MEASUREMENTS OF NEPTUNIUM-ALUMINUM CERMET PELLETS WITH VARIOUS NEPTUNIUM LOADINGS

Gretchen K. Toney¹, Chris L. Jensen¹, Artem Trofimov², Hsin Wang²

¹Radioisotope Science and Technology Division, ²Materials Science and Technology Division
Oak Ridge National Laboratory
1 Bethel Valley Rd, Oak Ridge, TN, 37831-8364, USA

e-mail: toneygk@ornl.gov, ph: 865 574 1710

Thermal conductivity measurements of neptunium-aluminum cermet pellets were carried out recently at Oak Ridge National Laboratory to investigate the potential viability of increasing the neptunium loading in the pellets. Currently, a typical NpO₂-Al cermet target used in the Plutonium-238 Supply Program contains 20 vol% NpO₂, 70 vol% aluminum, and 10 vol% void. Those concentrations were chosen conservatively to ensure that heat transfer within the target during irradiation is sufficient to prevent melting the aluminum (mp=660 °C). At this loading of NpO₂, ~400 targets per year are required to produce enough ²³⁸Pu to meet the production goal. Better utilization could be made of the finite irradiation positions available in research reactors if the neptunium oxide loading per target could be increased. An increase from 20% to 30% could result in an approximate 25% decrease in the number of targets necessary to produce comparable amounts of ²³⁸Pu. The first parameter to consider when increasing the concentration of NpO₂ in the target is thermal conductivity. Thermal conductivity is a property used to determine target survival through the necessary cycles of irradiation in the reactor. To investigate the feasibility to increase the concentration of NpO₂ in the target, special pellets dedicated for thermal conductivity measurements were manufactured via the current production pellet preparation process with up to 35 vol% NpO₂ loading. The thermal conductivity of the higher NpO₂ loaded pellets was determined using a transient plane source (TPS) system procured from Hot Disk AB. The system is designed to nondestructively measure the thermal conductivity using a Wheatstone bridge with a disk-shaped sensor. To aid in obtaining the best results, a one-dimensional method was used to measure thermal conductivity of a single pair of stacked pellets. The thermal conductivity testing for 20 vol% NpO₂ aligned with previously measured data. Promising thermal conductivity values were obtained for 25, 30, and 35 vol% NpO₂. Additional thermal and mechanical analysis is needed to determine if cermet pellets with those composition would be acceptable for the irradiation cycles in the reactor.

Keywords: neptunium, plutonium-238 production,
thermal conductivity, cermet pellets

**MONOAMIDES LIGANDS FOR PLUTONIUM-238 PRODUCTION
PROCESS IMPROVEMENT FROM PHOSPHORUS-FREE EXTRACTANTS**

Lætitia H. Delmau, Robert M. Wham, Luke R. Sadergaski, David W. DePaoli, and Dennis E. Benker

*Radioisotope Science and Technology Division, Oak Ridge National Laboratory,
1 Bethel Valley Rd, Oak Ridge, TN, 37831-8364, USA*

e-mail: delmaulh@ornl.gov, ph: 865 576 2093

Abstract. As part of the fifth ^{238}Pu production campaign, neptunium was recovered quantitatively by solvent extraction without the need for further purification by anion exchange. The anion exchange step, which is labor and reagent intensive, was required during the previous campaigns because the solvent extraction step carried out in the mixer-settler banks was based on a tributyl phosphate (TBP) extractant. Although TBP is a good extractant for extracting neptunium from fission products, its use presents the major drawback of subsequently having to remove phosphorus compounds from the neptunium product. These phosphorus compounds are commonly TBP degradation products, and their presence has been shown to create neptunium cermet issues, such as cracking upon calcination. For this recent campaign, the solvent extraction process was based on a monoamide, a phosphorus-free molecule originally developed in France in the early 1980s to replace TBP in the Plutonium Uranium Redox EXtraction (PUREX) process. The monoamide diethylhexyl butanamide (DEHBA) was used in two banks of mixer-settlers. The first bank was dedicated to extracting neptunium and scrubbing the loaded organic phase, and the second bank was solely used for stripping. Two preliminary runs were carried out to establish the proper conditions for optimized hydraulics and quantitative neptunium recovery. The third run was done on the remaining neptunium feed and allowed for the separation of 2,150 g of neptunium from the fission products. The use of monoamides requires a feed at higher acidity, which led to an increase in ^{106}Ru , ^{95}Zr , and ^{95}Nb fission products in the neptunium compared to products obtained using TBP. Further purification was obtained by running the product through a second cycle of solvent extraction. Upcoming runs for the next campaigns will use a monoamide that exhibits stronger extraction performance at lower acidity, which should improve throughput and alleviate the fission product issues.

Keywords: monoamides, neptunium, plutonium, solvent extraction, mixer-settlers