CONFERENCE PROCEEDINGS

NUCLEAR and **EMERGING TECHNOLOGIES** for **SPACE**

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Lightening Talk Abstracts

Oak Ridge National Laboratory

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Author	Title
Benensky, Kelsa	An Affordable Approach to Bridging Critical Gaps in Near Term Nuclear Thermal Propulsion Fuel and Component Maturation
Bowers, Jessica	Development of the Material Property Handbook for Space Nuclear Applications
Caffrey, Jarvis	Polymer Irradiation Testing for NTP Systems
Carver, Faith	RPS Ball Mill container Loading Process Improvement
Cendro, Samantha	Simulation and Experimental Validation of an Inductively Heated Solid-Core Nuclear Thermal Rocket
Cheikh, Mohamed A.	Coatings for Protection Against Hot Hydrogen Environments
Friske, Brian R.	Light Weight Radioisotope Heater Unit Pilot Production
Gallego, Nidia C.	Evaluation of Alternative Fibers to Replace NARC-RAYON for the Production of CBCF
Howard, Richard	Getting NTP Off the Ground
Isbell, Douglas	Enabling and Enhancing: Effective Public Communication about Radioisotope Power Systems
Jackson, Gerald P.	Limitations of Fusion Propulsion for Exoplanet Exploration
Joyce, Michael	Structural Integrity of Nuclear Fuel Rods During Earth-to-Orbit Launch
Kohlhorst, Noah	On the Quantitative Characterization of Dop26 Iridium Weld Microstructures
Kowalski, William	Spacecraft and Mission Design Drive Earth-Orbit Nuclear Safety
Lorenz, Ralph D.	Hydrogen Prospecting on Titan Exploiting MMRTG Neutron Flux
Maydan, Jack	Combined Cycle Nuclear Power and Propulsion: Complexity Reductions to Enable Human Mars Mission Architectures in 2020
Mesalam, R.	Progress in Thermoelectric Module Development for Eurpeans in Space Nuclear Power Systems
Myhre, Kristian G.	Implementation of Mediated Electrochemical Oxidation for Inclusion in the Plutonium-238 Supply Program to Dissolve Plutonium Dioxide
O'Connor, Andrew	Simulation-Guided Design of Neutron Absorbing Composites
Oriol, Stephane	Limits of Fusion Propulsion for Exoplanet Exploration
Plank, Jack	NERVA-Derived Bimodal Reactors as a Mass-Saving Strategy for Mars Missions
Raj, S. V.	Development of Multilayered Coatings for NERVA-Type Graphite Fuel Elements
Reed, Mark	The Ultra-Safe Nuclear Software Architecture for Rapid, Intuitive, Parameterization and Optimization of Fission Reactor Designs
Riemer, B. W.	SEEMS - A New Facility For Single Event Effects Testing and Muon Spectroscopy
Searight, William	Nuclear Thermal Rocket Tie Tube Testing using a Hot Hydrogen Test Loop
Sherman, Steven R.	Integrated Scheduling of Hot Cell Operations to Increase 238Pu Production Rates
Sholtis, Joseph A.	Safeguards And Proliferation Protections (SAPPs): A Way to Protect and Defend U.S. HEU-Fueled Space Power & Propulsion Reactors
Smith, Michael B. R.	Modern Techniques for Visualizing Radiation Data in Nuclear Space Scenarios
Steiner, Tyler R.	Comparing Experimentally Validated Computational Thermal Radiation Solution Methods as it Pertains to Nuclear Thermal Propulsion
Watkinson, E. J.	Progress in Characterising an Am-U Oxide as a Potential Fuel for Future European Radioisotope Power Systems: Thermal Properties and Initial Helium Outgassing Experiments
Watkinson, Emily Jane	High Strain Rate Tensile Tests of Pt-Rh Alloys for European Radioisotope Power System Clads: Pt-20%Rh and Pt-10%Rh
Wozniak, N. R.	Surrogate Testing of New Hot Press Capability
Yazawa, Kazuaki	Thermionic Energy Conversion for Next Generation Heat-Driven Battery
You, Setthivoine	Helicity Drive: A Novel, Scalable Magneto-Inertial Fusion Concept for Space Propulsion

Nuclear and Emerging Technologies for Space
Knoxville, TN, April 6 – April 9, 2020, available online at https://nets2020.ornl.gov

AN AFFORDABLE APPROACH TO BRIDGING CRITICAL GAPS IN NEAR TERM NUCLEAR THERMAL PROPULSION FUEL AND COMPONENT MATURATION

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Abstract. An in-space propulsion technology, nuclear thermal propulsion (NTP) is capable of enabling fast transit times beyond low earth orbit (LEO) due to its capacity for high specific impulse (850+ s) and thrust (~10^1 – 10^2 klbf). The successful development of NTP technologies relies upon the development and qualification of a robust reactor subsystem design capable of operating under the conditions required for high specific impulse, namely a high temperature, hydrogen environment for relatively short durations (1 – 2 hours). Development of the reactor is primarily contingent upon demonstrating the repeatable and predictable performance and integrity of NTP fuels under prototypic conditions (time, temperature, irradiation spectrum/burnup, and hydrogen flow). In historic programs, performance demonstration of the reactor was proven through full scale reactor ground testing. However, this approach may be perceived as costly and requires long-lead facilities development. Although ground test reactor facilities provide many benefits to demonstrate the integrated system performance and reactor reliability testing, near-term maturation of low technology readiness level (TRL) fuels and other in-reactor components may be pursued by leveraging pre-existing facilities. This lightning talk defines a testing methodology to improve the TRL of NTP fuels and in-reactor components, identifies critical facilities gaps, and provides insight on near term developments needed to enable irradiation and combined effects testing for NTP fuels.

Keywords: nuclear thermal propulsion, technology maturation, fuels, testing

Nuclear and Emerging Technologies for Space
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Development of the Material Property Handbook for Space Nuclear applications

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Abstract. NASA is reestablishing a materials handbook document and companion electronic database for component materials relevant to nuclear thermal propulsion (NTP). This talk will summarize the first phase effort to (1) Create a central repository of space nuclear materials data in the form of a written data book and GRANTA style database, and (2) Identify gaps in the collective knowledge about how materials respond under extreme conditions similar to those in an NTP system. Design and analysis of complex NTP systems requires accurate materials data for the components of interest at the conditions of interest. Since NTP operating requirements are atypical compared both to terrestrial reactors and chemical propulsion, much of the needed data is time consuming to find, at best, or nonexistent, at worst. To amend this situation, data has been consolidated and digitized from a collection of historical NTP documents, as well as general literature. A draft handbook document has been prepared to summarize and illustrate the material properties. In parallel, the data has been integrated into an online database for readily accessible information. This will provide modelers and designers a standard reference data source, enable more robust designs, and facilitate comparison between design groups. Through this data consolidation process, substantial gaps were identified in mechanical property and thermophysical property data especially at the temperature ranges of interest for current nuclear thermal designs. This talk will summarize the material systems scrutinized, the data found, and the gaps identified. Additional discussion will cover recommendations for prioritized material testing.

Keywords: Database, Materials Handbook, Materials Properties

Nuclear and Emerging Technologies for Space
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POLYMER IRRADIATION TESTING FOR NTP SYSTEMS

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Abstract. A set of candidate polymer materials with spaceflight heritage were selected for radiation exposure and mechanical testing to evaluate their effectiveness for use within a nuclear thermal propulsion (NTP) system. The selected polymers will see possible use as sealing surfaces for low leakage valve hardware, which is a primary motivation for this testing, however many other applications of these polymers exist for spaceflight hardware. These tests are intended to provide a broad scope evaluation of five candidate materials, including polytetrafluoroethylene (PTFE) Teflon®, perfluoroalkoxy alkane (PFA) Teflon®, polychlorotrifluoroethylene (PCTFE), polyamide-imide (PAI), and ethylene propylene diene monomer (EPDM). Radiation levels were selected to range across the anticipated radiation intensities nearby a NTP reactor core and in the likely vicinity of associated valve hardware, as evaluated by MCNP6 radiation transport analysis. Two separate exposure experiments were performed: a larger experiment in the Gamma Irradiation Facility (GIF) at Sandia National Laboratory in Albuquerque, NM, and a smaller subset experiment exposed to combined neutron/gamma radiation at the Oregon State TRIGA Reactor (OSTR) in Corvallis, OR. Gamma irradiation was performed for total ionizing dose (TID) levels between 10^6 and 10^8 rad, while neutron/gamma samples targeted 10^{16}-10^{17} n/cm^2 (fast neutron fluence). Gamma exposed samples were subjected to two thermal conditions during irradiation. Half were exposed while submerged in liquid nitrogen and half were exposed at ambient temperature. Most gamma exposed samples were sealed within argon-purged mylar/foil bags to minimize oxidative effects, and a smaller subset were left exposed to oxygen to quantify the possible impact of oxidation. Gamma exposed samples are currently being evaluated using ASTM standard procedures for the following properties of interest: tensile strength and elongation (ASTM D638 Type I and Type V), compressive strength and modulus (ASTM D695), hardness (ASTM D2240), shear strength (ASTM D732), flexural strength (ASTM D790), static and kinetic friction (ASTM D1894), and friction wear (ASTM F2357). Each condition and test type included five replicates, yielding a total of 1400 gamma irradiated samples (including controls). Mechanical testing of the gamma irradiated samples is performed by National Test Services (NTS) in Baltimore, MD, and is near completion at the time of writing this abstract. Additional samples were fabricated using the candidate materials for direct function testing within a low-leakage valve test apparatus. A smaller set of ASTM D638 Type V 'microdogbones' were used for the OSTR reactor experiment to minimize activation and evaluate tensile strength and elongation to be assessed at NASA Marshall Space Flight Center. Completion of this suite of experiments will provide significant value to the NTP feasibility assessment by supporting down-selection of candidate heritage polymer materials, by bracketing their viable radiation operating environments, and by evaluating the impacts of cryogenic thermal conditioning and oxygen exposure during irradiation.

Keywords: radiation, material, polymer, propulsion, valve

Nuclear and Emerging Technologies for Space
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RPS BALL MILL CONTAINER LOADING PROCESS IMPROVEMENT

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Abstract. Working with $^{238}PuO_2$, an alpha radiation emitter, provides the operator with a significant amount of neutron exposure during daily operations. As a protective measure, yearly exposure it closely monitored, with a maximum allowable total effective dose of 2 rem per year. During the fuel fabrication process of $^{238}PuO_2$, processes which require significant hands on processing time are large contributors to occupational dose accumulation, and are therefore a focus for time reduction activities. During the granule formation process, after the $^{238}PuO_2$ fuel lot is formed, it under goes ball milling to reduce the particle size to a small, repeatable mixture. The ball mill jar is loaded with both 110 stainless steel balls and $^{238}PuO_2$ fuel for the slow milling operation. After which, the fuel must be removed and successfully separated from the ball bearings. This requires removal of both the fuel and the ball bearings from the jar and subsequent reloading of the ball bearings for future operations. Currently, when a ball is dropped while reloading the ball bearings from the screen back into the ball mill jar, the operator must remove all the previously loaded balls and count all of the balls to ensure 110 are loaded to ensure the process is both repeatable and reliable. This is both time consuming and ergonomically taxing. The timed tests utilized assume the operator has dropped a ball and must therefore individually count each ball while loading back into the jar. This scenario is the most dose intensive case of the procedure and is, therefore, the focus of the process improvement.

To improve efficiency and reduce dose intensive time, a ball mill reloading apparatus counts exactly 55 ball bearings per loading and deposits them directly into the ball mill jar. Two rounds of loading are required to reach and count a total of 110 ball bearings. After initial process proving, timed trial was held in a cold laboratory glovebox line. For the timed tests, the operators performed first normal counting and loading sequence in 30 millimeter lead lined gloves and then a ball mill loader apparatus assisted loading in the same 30 millimeter lead lined gloves. All participants were members of fuel fabrication team. The skill and levels of experience loading the ball mill jar in line varied from novices to process specific trainers, however, all participants were experienced glovebox workers. The ball mill loader apparatus reduced the hands on time required by 2-3 times. During this trial, comments on the design itself were taken and used to further improve the process, including the shape of the grabber/stopper for releasing the ball bearings. These comments were incorporated in a subsequent remachined stopper for operator ease. With the reduced time and ergonomic effort associated with the ball mill apparatus, the process improvement is available for use, with data collection and potential improvements continuing.

Keywords: Radioisotope Power System, Ball Mill, Process Improvement

Nuclear and Emerging Technologies for Space
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SIMULATION AND EXPERIMENTAL VALIDATION OF AN INDUCTIVELY HEATED SOLID-CORE NUCLEAR THERMAL ROCKET MODEL

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Abstract. Nuclear thermal propulsion allows for thrust performance akin to liquid bi-propellant rockets along with efficiency close to ion propulsion drives. The objective of the Hyperion-I project is to model nuclear thermal propulsion and experimentally validate the numerical model. A coupled magnetic and computational fluid dynamic model for a single-channel test article was created using ANSYS Maxwell and ANSYS Fluent and subjected to experimental testing conditions. A test stand capable of meeting the testing requirements of a .00025 kg/s mass flow rate at 500 psi for 15 minutes was built. Four Omega K-type thermocouples and four Omega PX309 pressure transducers were utilized pre-regulator, post-regulator, pre-test-article, and post-test-article to acquire pressure and temperature data. The outlet flow temperature of 66.85 °C was validated with an experimental temperature of 66±2 °C. Future testing includes a multi-channel test core and a full-scale core for Phases II and III of the Hyperion-1 project, respectively.

Keywords: Solid Core Nuclear Thermal Rocket
Induction Heating
Multiphysics ANSYS Modeling
Hardware Testing
Experimental Validation

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COATINGS FOR PROTECTION AGAINST HOT HYDROGEN ENVIRONMENTS

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Advanced carbon-based heat exchangers (carbon/carbon composite or graphite) used in solar-thermal propulsion engines must be protected for extended periods from the ≥3000 K hydrogen propellant. In previous work for NASA and DoD, Ultramet successfully fabricated and demonstrated the hot hydrogen survivability of rhenium-based solar-thermal engines, and of refractory metal carbide coatings on open-cell foam components for nuclear-thermal propulsion. The potential exists to combine these technologies by using ductile rhenium as an interlayer between a carbon heat exchanger and a high melting point outer metal carbide layer with well-established survivability in high temperature hydrogen. Relative to rhenium, the carbides are lower in density and cost. This combination has the potential to alleviate issues related to thermal expansion mismatch between the substrate and protective coatings, maximize adhesion, minimize the potential for cracking, and maximize component use temperature and lifetime. In current work for the NASA Jet Propulsion Laboratory (JPL), Ultramet has fabricated a matrix of coated coupon test specimens, including various coating materials and layered coatings, and performed initial hot hydrogen performance testing in the Compact Fuel Element Environmental Test (CFEET) facility at NASA Marshall Space Flight Center (MSFC). Material fabrication and test results will be presented.

Keywords: heat exchanger, hot hydrogen protection, rhenium, niobium carbide, zirconium carbide

Nuclear and Emerging Technologies for Space
Knoxville, TN, April 6 – April 9, 2020, available online at https://nets2020.ornl.gov

LIGHT WEIGHT RADIOISOTOPE HEATER UNIT PILOT PRODUCTION

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Abstract. Light Weight Radioisotope Heat Unit (LWRHU) production development activities have been ongoing at the Oak Ridge National Laboratory. These activities have included procurement and qualification of the raw materials and tooling, either reproduced or further developed from legacy Mound Laboratories' procedures and drawings. New quality control and inspection procedures were also developed. These development activities have culminated in a pilot production run to show our ability to produce LWRHU. The pilot production was completed in fiscal year 2019 with the fabrication and shipping of ten Clad Body Subassemblies, Closure Caps, and Shims. This talk discusses the results of the pilot production along with any issues identified during production. Continued steady state production plans for fiscal year 2020 and beyond will be discussed.

Keywords: LWRHU, Pilot Production

Nuclear and Emerging Technologies for Space
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EVALUATION OF ALTERNATIVE FIBERS TO REPLACE NARC-RAYON FOR THE PRODUCTION OF CBCF

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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. Three rayon or cellulose-based fibers have been evaluated and a summary of findings with a path forward to qualification will be presented.

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

Nuclear and Emerging Technologies for Space
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Getting NTP Off the Ground

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Nuclear thermal propulsion (NTP) has great potential for enabling crewed missions within our solar system and is widely considered by the technical community as the only advanced propulsion technology that is mature enough to support missions in the next decade. However, its technical readiness level is only around 3 or 4 (technology development stage). Given the domestic drive to hold an NTP flight demonstration by 2024, there is much to do to literally get NTP off the ground. This talk discusses current development efforts, including modeling and experimentation, that are underway and intended to rapidly mature NTP technology. However, in many ways, these current efforts may not be sufficient to meet the National Aeronautics and Space Administration's aggressive timelines. The discussion also attempts to provide suggestions on how to also successfully overcome this immense challenge.

Keywords: Nuclear thermal propulsion (NTP), flight demonstration, technical readiness level

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Enabling and Enhancing: Effective Public Communication about Radioisotope Power Systems

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Abstract: The two-person risk communication team at NASA's Jet Propulsion Laboratory (JPL) supports NASA's Radioisotope Power Systems (RPS) Program with a variety of public information products, internal messaging guidance, and formal communications effectiveness training, as well as radiological contingency planning for the launch of RPS-powered NASA missions. The core principles of RPS risk communication include being open, accurate, clear, respectful, well-prepared, and interactive. This talk will discuss the strategic goals of RPS risk communication, and will share examples of recent RPS risk communication tasks and products prepared in support of renewed plutonium dioxide fuel production for civil space exploration, and NASA's upcoming Mars 2020 rover mission. 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 nuclear power systems in space.

Keywords: risk communication, launch nuclear safety

Nuclear and Emerging Technologies for Space
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LIMITS OF FUSION PROPULSION FOR EXOPLANET EXPLORATION

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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 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

Nuclear and Emerging Technologies for Space
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Structural Integrity of Nuclear Fuel Rods during Earth-to-Orbit Launch

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Abstract. This lightning talk will focus on ongoing research into the effects of forces acting on inactive nuclear fuel rods during launch. Much research has gone into studying effects on nuclear fuel rods while active in a nuclear thermal propulsion engine; however, there have been no tests to confirm that they will survive the initial launch from Earth before they are in use. As part of my research, I am investigating nuclear fuel rod designs used by the previous Nuclear Engine for Rocket Vehicle Application (NERVA) program and BWXT who is contracted to build an engine for NASA. A finite element analysis will be used on these fuel rod designs to model if any fractures or cracking will result from the acceleration and vibrational forces of a launch. Physical tests will then be conducted on prototype rods made from a non-nuclear material with similar properties to uranium and will include a launch in a rocket from the university's rocket club.

Keywords: nuclear thermal propulsion, nuclear fuel rods,
structural integrity

Nuclear and Emerging Technologies for Space
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On the Quantitative Characterization of Dop26 Iridium Weld Microstructures

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Abstract. DOP26 is an iridium alloy consisting nominally of 0.3 weight percent tungsten, 60 parts per million (ppm) thorium, and 50 ppm aluminum. The material is used to make clad vent sets for radioisotope thermoelectric generators (RTGs). The clad vent set is composed of two DOP26 cups gas tungsten arc welded together around a fuel pellet, functioning as a shield protecting the fuel pellet against extreme conditions. Since these welds could be exposed to high temperatures and high mechanical stresses, they must have superior microstructural stability and mechanical properties at high temperatures. The mechanical properties of welds are related to their microstructures which are influenced by the weld processing parameters and post weld heat treatments. Thus, there is a need to quantitatively characterize the microstructure of iridium welds and correlate these to weld processing conditions. In this work, we present a new technique to quantitatively characterize the grain size, grain shape, and grain boundary curvature of iridium welds. We will show that this technique can be used to quantitatively describe the spatial variations in these characteristics as a function of weld processing conditions. Quantitatively characterizing the grain size, grain shape, and grain boundary curvature ultimately provides us the ability to correlate mechanical properties of the welds with microstructure evolution influenced by weld processing conditions and post weld heat-treatments.

Keywords: Microstructure evolution, Quantitative analysis, Grain Shape, Grain boundary curvature, Dop26 Iridium

Nuclear and Emerging Technologies for Space
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SPACECRAFT AND MISSION DESIGN DRIVE EARTH-ORBIT NUCLEAR SAFETY

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Abstract. The Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems released August 20, 2019 stated that "[a]dditional safety guidelines may be appropriate for the non-terrestrial operation of nuclear fission systems." With respect to orbital operation, the authors believe spacecraft and mission design drive safe outcomes significantly more than reactor design. The length of natural decay drives public exposure to radioactivity in an uncontrolled reentry. Spacecraft mass, surface area, and starting altitude affect decay duration exponentially, and balancing these factors in spacecraft and mission design should be primary considerations for space nuclear systems in Earth orbit. With proper failure modes and redundancies, public exposure risk can be reduced by orders of magnitude.

Keywords: CONOPS, Safety, Spacecraft Design

Nuclear and Emerging Technologies for Space
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Hydrogen Prospecting on Titan Exploiting MMRTG Neutron Flux

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Abstract. Titan's compositionally-diverse surface is expected to comprise units of ice-rich material (water and ammonia) as well as organic-rich deposits of hydrocarbons with some nitrogen-bearing compounds. Sample acquisition for detailed chemical analysis a billion miles from Earth carries a significant operations overhead, and so 'quick-look' local reconnaissance data to broadly classify composition is useful to inform sampling decisions, especially on a mobile platform where many such operations may occur. Neutron spectroscopy, yielding a quick (<~1 hr) estimate of the bulk hydrogen abundance in a volume 1-2m around the vehicle, is a powerful tool in this respect. Unlike airless bodies like the moon, however, Titan's thick atmosphere (with a column mass equivalent to 100m depth of water on Earth) screens out the bulk of cosmic rays from space, such that the ambient neutron flux is minimal.

On Mars, the Curiosity rover has demonstrated that the combination of neutrons from its MultiMission Radioisotope Thermoelectric Generator (MMRTG), and neutrons from cosmic rays penetrating Mars' thinner atmosphere, can permit passive hydrogen abundance measurements. It is estimated the contributions there from the MMRTG and cosmic rays are about equal.

Monte-Carlo N Particle (MCNP) simulations for Titan show that the neutron energy distribution from the MMRTG and reflected by the ground is usefully sensitive to the surface composition (much more hydrogen-rich than Mars), with different spectra for pure water ice, water-ammonia mixtures, and carbon-nitrogen material representative of potential Titan surfaces. The Dragonfly New Frontiers mission will use a dedicated pulsed neutron generator (PNG) in conjunction with neutron detectors and a high signal-to-noise gamma ray spectrometer to measure carbon, oxygen and nitrogen abundances as well as hydrogen and potential minor species such as sodium, sulfur and chlorine. However, passive measurements will also be taken to determine background radiation, and MMRTG neutrons reflected by the surface and atmosphere will comprise a significant contribution. These passive measurements provide an independent means to quickly characterize the hydrogen content of Titan's surface via the neutron energy spectrum, even without PNG operation. The radioisotope power system (RPS) therefore provides a useful secondary capability: RPS-stimulated neutron measurements are possible on other landed missions (e.g. Ceres) but are particularly significant at Titan owing to the atmospheric screening.

Keywords: Titan, Hydrogen, Neutron Spectroscopy, MMRTG

Nuclear and Emerging Technologies for Space
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Combined Cycle Nuclear Power and Propulsion: Complexity Reductions to Enable Human Mars Mission Architectures in 2020

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Abstract:

The solution to slow transport times, constrained consumables, and exorbitant propellant budgets associated with Human Mars Missions has often been to employ nuclear propulsion. The increase in specific impulse, and possibility for continuous thrust, improves delta-V capabilities which serves to alleviate transport time and mass constraints while providing substantial flexibility to other mission limitations. The canonical problems for nuclear propulsion in a Human Mars Mission have always been that its benefits are shadowed by its complexities and the system's high uncertainty in mass due to its low test readiness level. This talk serves to present research on a Human Mars Mission Architecture which combines power production with thermal propulsion through the same nuclear core to enable feasibility within the 2020 decade. By using the core for constant power production, complexities associated with restarting a cold reactor are averted, and the ability to quickly power up for an emergency burn is provided. The combined cycle also reduces radiator mass substantially because while the system's peak thermal output (100s of MW) used during propulsion would require city-block sized radiators, the core is instead cooled by the propellant which is then exhausted through the nozzle, and conversely the electrical power production operates at much more manageable thermal levels (100s of kW). Because it surmounts complexities, reduces uncertainty, and provides additional benefits to the crew, a combined cycle nuclear thermal rocket becomes a feasible choice for enabling nuclear technologies on the journey to Mars.

Keywords:

combined-cycle, human, mars, propulsion, power

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PROGRESS IN THERMOELECTRIC MODULE DEVELOPMENT FOR EUROPEAN SPACE NUCLEAR POWER SYSTEMS

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Abstract. To date several generations of bismuth telluride based thermoelectric generators (TEGs), in the form of modules, have been produced for the European radioisotope thermoelectric generator (RTG) programme. The TEG 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 TEGs, 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 TEGs 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 TEGs. The use of an automated TEG 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 TEGs 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 TEGs 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

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IMPLEMENTATION OF MEDIATED ELECTROCHEMICAL OXIDATION FOR INCLUSION IN THE PLUTONIUM-238 SUPPLY PROGRAM TO DISSOLVE PLUTONIUM OXIDE

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Abstract. A capability to dissolve calcined plutonium oxide at the tens of grams per batch scale has been successfully implemented in Oak Ridge National Laboratory's hot cell facilities to support the Plutonium-238 Supply Program mission. Furthermore, online monitoring of the dissolution process was successfully accomplished using *in situ* absorption spectroscopy and real-time data analysis. The newly developed online monitoring capability enabled streamlined determination of the dissolution progress. The process used to dissolve the plutonium oxide, called mediated electrochemical oxidation, relies on highly oxidizing silver(II) ions to oxidize the plutonium oxide into a dissolved liquid form. This process enables the dissolution of plutonium oxide without the use of hydrofluoric acid, which is not compatible with chemical processing infrastructure in Oak Ridge National Laboratory's Radiochemical Engineering Development Center hot cells. This Lightning Talk will discuss the completed successful efforts to implement mediated electrochemical oxidation dissolution of calcined plutonium oxide as well as plans to dissolve legacy plutonium oxide currently stored at Oak Ridge National Laboratory.

Keywords: Pu-238 Supply Program; Mediated Electrochemical Oxidation; Online Monitoring

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SIMULATION-GUIDED DESIGN OF NEUTRON ABSORBING COMPOSITES

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Abstract. Simulating neutron radiation attenuation by a metal matrix and neutron-absorbing, reinforcing particles for neutron absorbing composites can guide design and optimize future experimentation. Neutron transmission simulations using the Japan Atomic Energy Agency's Particle and Heavy Ion Transport System radiation code predict the macroscopic cross-section for neutron absorption. Previous work in neutron transport through particle-reinforced composites has relied on approximate analytical techniques or computational techniques that use non-physical, non-random distributions of particles within the matrix. The present work uses a more physically representative shield consisting of a random distribution of particles with modifications to reduce computational complexity and time. The results illustrate how particle size and associated volume fraction affect neutron shielding performance of such composites. Whereas increasing volume fraction should increase neutron attenuation, increasing particle size deleteriously affects neutron shielding performance. This particle size dependence arises from the neutron channeling effect, wherein neutrons may stream through a composite without encountering sufficiently absorbing particles provided a sufficiently large particle size and concomitant excessive interparticle spacing. Various metals and their alloys are evaluated as the matrix with respect to neutron shielding ability. These data can be used to select an appropriate metal matrix and particle size and associated particle volume fraction for structural materials used in aerospace and other high radiation environments. To enable the use of a systems design framework, an appropriate metric to evaluate neutron shielding performance must be selected; others have proposed boron-10 areal density previously. This metric decomposes a boron-containing composite into a scalar quantity based on the mass of boron-10—the primary neutron-absorbing isotope—per unit area of the material. However, this calculation does not respect the influence of particle size and associated neutron channeling. As such, the boron-10 areal density metric is re-proposed with added terms to respect both the relative efficiency of each particle size and the cumulative distribution of particle sizes. This modified metric can be employed to tailor the properties of a neutron absorbing composite to the energies encountered and performance required in various environments.

Keywords: neutron absorbing composites, simulation-guided materials design, systems design framework, boron-10 areal density, neutron channeling

Nuclear and Emerging Technologies for Space
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LIMITS OF FUSION PROPULSION FOR EXOPLANET EXPLORATION

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Abstract. The French Space Agency (CNES) together with the French Commissary for Atomic and Alternative Energies (CEA) are studying a preliminary concept for a space vehicle propelled with antimatter. This paper details recent results about this preliminary concept, with a focus on the main systems needed to create the thrust, starting from the reaction chamber basic simulations, and going further with the magnetic fields, and ending with considerations about the propellant storage. Some potential technological solutions are identified and a rough order of magnitude is calculated for the vehicle main performances such as the thrust, the specific and total impulse, as well as the spacecraft's shape and its overall mass.

Keywords: in-space propulsion, spacecraft design

NERVA-Derived Bimodal Reactors as a Mass-Saving Strategy for Mars Missions

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Abstract. Bimodal Nuclear Thermal Propulsion (BNTP) has been of interest to those who work on space nuclear systems since it was first proposed as an accessory to standalone nuclear thermal propulsion (NTP) near the end of the Rover/NERVA program. It involves the inclusion of an electrical power generation cycle, often a Brayton cycle, into a reactor whose primary function is providing thermal power for propulsion. One of the many beneficial functions of BNTP is helping to reduce post-burn H_2 cooling requirements, since the reactor does not have to shut down completely, but rather only reduces thermal power to the input level required by the power generation cycle. This report attempts to quantify the significance of this effect over a range of the design space for BNTP by developing a simplified analytical reactor shutdown heat transfer model and applying it across several NERVA-derived reactor designs. Preliminary findings suggest that the realistic H_2 coolant mass savings from BNTP implementation are not enough on their own to completely offset the mass of the power cycle components across one conjunction-class Mars mission, contrary to some historical estimates. However, coolant mass savings can be more significant under certain conditions, which, when combined with the mass saved by removing the solar panel system and reducing battery backups, can make BNTP competitive as a power generation system for human deep space missions.

Keywords: Bimodal, Propulsion, Heat, Cooling, Power

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Development of Multilayered Coatings for Nerva-Type Graphite Fuel Elements

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Abstract. Nuclear thermal propulsion (NTP) has twice the specific impulse of chemical rockets, which makes it attractive for manned missions to Mars and other planets. Although the Nuclear Engine for Rocket Vehicle Application (NERVA)/Rover programs demonstrated the viability of NTP, it was also observed that the engine life was severely limited by "mid-passage corrosion" (MPC) of the fuel, where cracks in the chemical vapor deposited (CVD) coating allowed the hot hydrogen propellant to react with the graphite-based substrate to form hydrocarbon reaction products. The present research proposes a new multilayered coating concept designed to solve the midrange corrosion problem. The concept envisions designing either a functionally graded or multilayered coatings to minimize the thermal expansion mismatch between the NbC or ZrC outer coating and the Gr/(U,Zr)C fuel matrix while acting as compliant layers as well as diffusion barriers separating the carbon and hydrogen. Single and multilayered coatings were deposited on Gr substrates by CVD. Graphite disks, as well as the inner channels of 19-hole hexagonal rods 152.4 and 304.8 mm long, were coated by CVD in proof-of concept demonstration studies. The results of the cross-sectional microstructures are discussed. These trials have established that it is possible to deposit multilayered coatings by CVD in 19-hole hexagonal rods similar to the NERVA fuel rod design although the quality of the coatings and the uniformity of their thicknesses require further improvement.

Keywords: Midrange corrosion; multilayered coatings; NERVA; ZrC; chemical vapor deposition.

Nuclear and Emerging Technologies for Space
Knoxville, TN, April 6 – April 9, 2020, available online at https://nets2020.ornl.gov

CURSOR:

The Ultra-Safe Nuclear Software Architecture for Rapid, Intuitive Parameterization and Optimization of Fission Reactor Designs

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Abstract. Creating new reactor core geometries and material definitions is arduous and tedious, the "99% perspiration" that requires most effort in reactor design endeavors.

USNC's proposed perspiration panacea is Cursor, a software architecture for generic reactor design with coupled neutronic, thermal hydraulic, and material performance analysis. When the user creates a new geometry type, Cursor automatically parameterizes it to rapidly explore parameter spaces and optimize physics parameters. Available physics includes neutronics (with gamma heating), thermal hydraulics for any fluid and flow geometry for which thermal data and valid correlations exist (for both power and propulsion reactors), depletion neutronics, shielding and dose distribution both during operation *and after shutdown*, thermal conduction for any material and geometry for which thermal resistance is known, and hydrogen loss from hydrides through diffusion barriers.

Cursor automatically generates Monte Carlo neutronic inputs for MCNP, Serpent, and MAVRIC from a single intuitive input file via subclassing techniques that allow different reactors to share common geometry. Thus, adding and parameterizing new geometries requires minimal effort and *zero* knowledge of MCNP or Serpent input syntax. Cursor utilizes this same subclassing framework for thermal hydraulics. Power and propulsion reactors share the same flow channel solver with different boundary conditions.

Cursor relies upon the stand-alone software package Alexandria, a suite of libraries for material composition definitions, thermal hydraulic correlations, and flow channel solution kernels. Alexandria automatically generates material composition definitions for (1) *any* standard chemical formula with optional isotopic enrichment and (2) any complex composition in public libraries.

While many organizations have developed software to couple diverse physics for reactor design, Cursor is unique in its *breadth* – its generality and usability for a diverse potpourri of reactor types. A novice user can learn how to use Cursor in an hour and can create arbitrary new material definitions in seconds. An experienced developer can add a new core geometry type, with both neutronics and thermal hydraulics, in one day.

Cursor is USNC's baseline software for all space reactor designs (including Versatile NTP, Pylon, and LEU Kilopower) and some crucial design tasks for the MMR™ terrestrial design currently undergoing regulatory licensing in Canada.

USNC welcomes collaboration opportunities.

Keywords: reactor, design, modeling, software, NTP

Nuclear and Emerging Technologies for Space
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SEEMS – A NEW FACILITY FOR SINGLE EVENT EFFECTS TESTING AND MUON SPECTROSCOPY

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A third target station using the Spallation Neutron Source (SNS) accelerator is proposed to serve two distinct user communities. Electronics researchers and industrial users investigating single event effects (SEE) need greater test facility capacity and capabilities for atmospheric high-energy neutron radiation originating from cosmic and solar rays. Technology trends in digital electronics used in aviation and spaceflight technologies are increasing the risk of unexpected and possibly hazardous behavior when subjected to cosmogenic radiation. The regulatory landscape in the aircraft industry is evolving to require assurances that critical systems meet appropriate reliability criteria. Existing facilities in the U.S. are at capacity and lack the desired feature of large, *meter*-scale neutron beams to test complete systems (neutron fluxes 10^4 n/cm^2/s) in addition to small, millimeter-scale beams for device irradiation (to ~10^7 n/cm^2/s). SEEMS can also be highly suitable for space and terrestrial electronic test applications. Irradiation capabilities with protons up to 1.3 GeV is possible. SEEMS will be fully featured for SEE users and offer more than 4,500 hours of annual test time to multiple test areas for decades to come. It will be situated close to the SNS First Target Station (Fig. 1) but not interfere with its neutron scattering science function.

The SEEMS target station concept is a low-power spallation neutron source using a helium-cooled tungsten target. A small fraction (~0.2%) of the SNS proton beam is diverted by a process known as laser stripping. The diverted protons are directed to the SEEMS target before the accumulator ring injection point; they can alternatively be sent to a dedicated proton test area. The ideal high-energy neutron spectrum is obtained at +/- 30° off the proton forward direction (from top down in Fig. 2). This configuration is highly compatible with providing muons that emanate at +/- 90°. A stripping laser can be operated with very short pulses (< 50 ns) at a repetition rate that will produce muon beams with exceptionally high resolution for muon spectroscopy. This second user community of condensed matter research with muons is highly complementary to neutron scattering techniques used at ORNL.

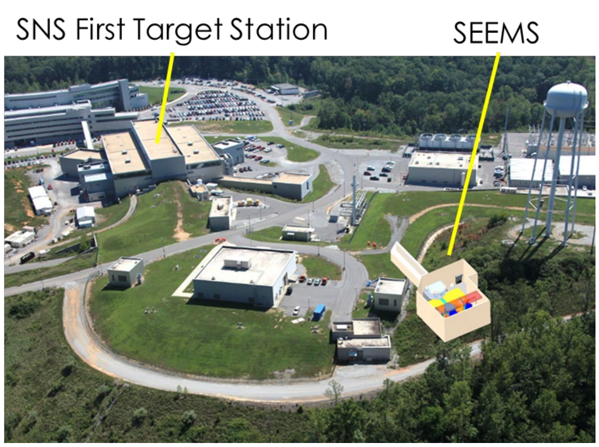

Fig. 1. SEEMS facility location at the SNS.

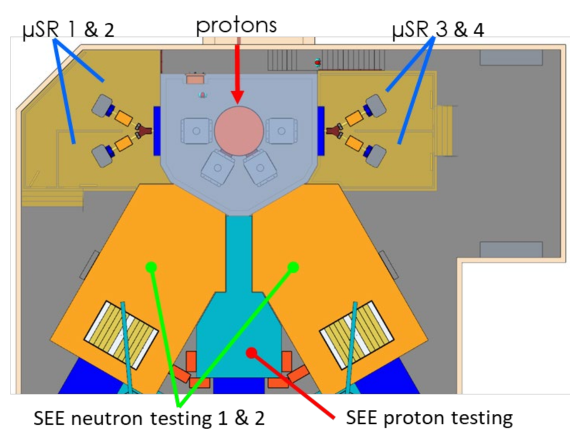

Fig. 2. Layout of SEEMS experiment areas.

Keywords: Single event effects; radiation testing; electronics; high-energy neutrons; muon spectroscopy

Nuclear and Emerging Technologies for Space
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Nuclear Thermal Rocket Tie Tube Testing using a Hot Hydrogen Test Loop

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Abstract:

One of the most promising propulsion systems for deep space exploration is the Nuclear Thermal Rocket (NTR), with a fuel that contains much greater energy density than traditional chemical propulsion systems and with an overall thrust much greater than an electric propulsion system. In order to validate the design and ensure a long rocket engine lifetime as required for a deep space mission, a hot hydrogen test loop capable of producing circulating hydrogen plasma at temperatures up to 3000 Kelvin is being designed and constructed at the Pennsylvania State University, with the immediate intent to study the plasma-material interactions of plasmas with component materials. In this work specifically, the components of interest are the NTR's tie tubes, through which the hydrogen plasma coolant and propellant is channeled through the reactor core and heated by fission neutrons.

This work will detail the current and ongoing progress in construction of this tabletop sized experiment, and preliminary data on the test loop's performance will be presented and summarized.

Keywords: Nuclear Thermal Rocket, Hot Hydrogen Test Loop, Tie Tubes, material performance

Nuclear and Emerging Technologies for Space
Knoxville, TN, April 6 – April 9, 2020, available online at https://nets2020.ornl.gov

INTEGRATED SCHEDULING OF HOT CELL OPERATIONS TO INCREASE ^{238}Pu PRODUCTION RATES

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Abstract. The ^{238}Pu Supply Program at Oak Ridge National Laboratory is working to improve and scale up a process for producing heat source PuO_2 (HS PuO_2) for NASA. Currently, ~400 g HS PuO_2/year can be produced, and production must be increased to 1.5 kg HS PuO_2 per year by 2025. The work is being performed in existing multiuser nuclear facilities, and the ^{238}Pu work must compete with other nuclear programs for resources and time. Although rates can be increased somewhat by process improvements, full-scale operations cannot be achieved without the careful scheduling of overlapping hot cell operations. Many constraints affect operating schedules, including inherent equipment operating rates, resource and equipment availability, nuclear inventory limits, reactor operating schedules, facility maintenance schedules, and physical storage capacities. Unplanned delays can also occur as a result of equipment failures, employee absences, and interferences with unrelated work. The ^{238}Pu Supply Program is using Microsoft Excel and Microsoft Project to develop scheduling scenarios. The program also uses the discrete event simulation packages GPSS/H, Process Simulator, and SIMUL8 to analyze the scenarios in light of constraints, to identify potential operating policies and sequences that might best increase production. Proposed schedules are then discussed with stakeholders to converge on a subset of schedules that is acceptable to both developmental and operational personnel. Once a schedule is agreed upon, regular schedule updates and corrections are issued by the program as work progresses and circumstances change. This scheduling approach was pioneered this year to identify an optimal ^{238}Pu operating schedule for calendar year 2020, and operations management has adopted an initial schedule as a baseline plan. Process observations will be used to update expected durations and recognize previously unaccounted for delays and opportunities for parallel work.

Keywords: ^{238}Pu, NASA, scheduling

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

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Abstract. This presentation highlights the importance of the High-Enriched Uranium (HEU) fuel option for U.S. space power and propulsion reactors, and the protective functions that Safeguards And Proliferation Protections (SAPPs), proposed herein, can provide. Efforts to preferentially prescribe Low-Enriched Uranium (LEU) in U.S. space reactors have advanced recently; largely driven – justifiably – by proliferation concerns. There are, however, valid arguments for retaining HEU for space reactors. They include: 1) Reactor system and space vehicle size (diameter & volume) and mass, (including mass for astronaut shielding), and their associated trip times, are less for HEU-fueled systems; and 2) Launch, nuclear, and astronaut safety (associated with faster Mars transport) are much easier to ensure for HEU-fueled systems. Also, space reactor launches, which represent vulnerable times for proliferation, are not likely to be commonplace. When we return to the Moon, and send crewed missions to Mars, space reactor launches are likely to be rare events; with each launch receiving global attention. Based on the above, it is important to retain HEU as a viable 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 functionally established judiciously, designed inventively, and incorporated carefully throughout mission/systems development. Generic functions of SAPPs, for example, might be to: 1) Ensure the system will only function as designed, when properly called upon; 2) Ensure the system will not function as designed, unless expected/specified 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/specified external conditions or actions 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-Enriched Uranium (HEU)
U.S. space power and propulsion reactors
Safeguards
Proliferation
Safeguards And Proliferation Protections (SAPPs)
Low-EnrichedUranium (LEU)
Launch safety
Nuclear safety
Astronaut safety
Permissive Action Links (PALs)
U.S. nuclear weapons

Nuclear and Emerging Technologies for Space
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Modern Techniques for Visualizing Radiation Data in Nuclear Space Scenarios

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Abstract. Effective presentation of technical information in the science and engineering fields is a constant balancing act of quantitative and qualitative data, yet communication of highly specialized data within diverse working groups is a necessary skill for successful research and engineering projects. In projects requiring the confluence of nuclear and aerospace disciplines, the opportunities for specialized, or niche, analyses and data are countless.

One example of complex analyses in space-nuclear disciplines is the modeling, estimating, and presenting of the impact of ambient radiation fields over spatial and temporal regions of a given system. Radiation in spaceflight scenarios can originate from natural sources like galactic cosmic rays (GCR), solar particle events (SPE), and trapped radiation belts along with power or propulsion systems like radioisotope power systems (RPS), fission power systems, or nuclear thermal propulsion (NTP). Each one of these sources offer unique and complex radiation fields with composite primary particle spectra, broad energy regimes, and numerous secondary particle interactions that all play a role in any individual radiation analysis.

Efforts at Oak Ridge National Laboratory (ORNL) to better illustrate radiation phenomena in scientifically useful formats has been underway for many years, and recent efforts to support the nations space-nuclear interests with various radiation analyses has driven a need to couple state of the art radiation transport techniques with sophisticated visualization software. This talk will present efforts underway to link data generated by the ORNL-developed, SCALE® nuclear software suite with the Unreal Engine® 3D video game development software. The opportunities awarded by this convergence are the ability to map physics-based radiation data from particle transport simulations onto 3D computer aided design (CAD) models. While these methods are not intended to supplant existing radiation visualization techniques, they do intend to supplement current approaches and tools for communicating and presenting complex radiation data for spaceflight applications.

Keywords: Data visualization, radiation, radioisotope power systems, nuclear thermal propulsion, space radiation, GCR, SPE, RPS, NTP

Nuclear and Emerging Technologies for Space
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COMPARING EXPERIMENTALLY VALIDATED COMPUTATIONAL THERMAL RADIATION SOLUTION METHODS AS IT PERTAINS TO NUCLEAR THERMAL PROPULSION

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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 conditions, such as temperatures above 2500 K. The numerical solution methods will be assessed using the results from the experiment.

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

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**PROGRESS IN CHARACTERISING AN AM-U OXIDE AS A POTENTIAL FUEL FOR FUTURE EUROPEAN RADIOISOTOPE POWER SYSTEMS:
THERMAL PROPERTIES AND INITIAL HELIUM OUTGASSING EXPERIMENTS**

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Abstract. Since 2018, the University of Leicester and the European Commission Joint Research Centre (JRC), Karlsruhe have been collaborating on a number of investigations via an Unpaid Visiting Scientist Agreement. The objectives are to characterise a range of properties of the sintered Am-U oxide developed by JRC. This material is now being considered as one of the fuel options for the European radioisotope power systems being designed and developed by the University of Leicester. In this talk, we present progress on two of the four joint experiments to characterise this Am-U oxide material: an investigation to determine its thermal properties and the preliminary results of a helium outgassing study using a set-up unique to JRC Karlsruhe. We also highlight a third study that will commence shortly regarding thermal expansion (The fourth study is presented as a NETS 2020 summary paper: an interaction/compatibility study between the Am-U oxide with Pt-20%Rh and Pt-30%Rh.).

Acknowledgements. Emily Jane Watkinson wishes to acknowledge the Unpaid Visiting Scientist Agreement with European Commission Joint Research Centre Karlsruhe. The University of Leicester wishes to acknowledge the funding provided by the European Space Agency via the National Nuclear Laboratory (United Kingdom) to enable the travel to conduct these collaborative experiments.

Keywords: Americium-Uranium Oxide, Thermal Properties, Helium Outgassing.

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

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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 initial 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.

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

SURROGATE TESTING OF NEW HOT PRESS CAPABILITY

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Abstract. A new, modern hot press is being brought online to facilitate and ensure the production of plutonium-238 dioxide ($^{238}PuO_2$) General Purpose Heat Sources (GPHS). This will modernize the hot press systems and control systems, while increasing the functionality of the system. Following initial set-up and testing of the system, a series of surrogate ceria (CeO_2) pellets were pressed under varying temperature, pressures, and pressure ramp rates. These parameters were chosen to determine their effect on the pellets. The CeO_2 powder was prepared using the same process used for GPHS production. The resulting pellets were analyzed both before and following a sintering step. The sintering process is crucial for oxidizing the pellet back to the correct stoichiometry following hot pressing, and for reaching the desired theoretical density. The analysis included density determination and comparison of microstructures. Results indicate that the sintering step is successful in achieving the correct stoichiometry and the correct theoretical density. The series of CeO_2 pellets pressed and analyze prove that the new hot press is capable of producing the necessary temperatures and pressures, resulting in pellets that will be able to be proven to be flight quality.

Keywords: Hot press, ^{238}Pu, GPHS

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Thermionic Energy Conversion for Next Generation Heat-Driven Battery

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Abstract: Thermionic energy conversion (TEC) is a promising technology for the on-board power generators of space vehicles. TECs in comparison to thermoelectrics such as the multi-mission radioisotope thermoelectric generators (MMRTGs) have a simpler structure and work at higher hot side temperature (>1000K), which is beneficial for thermodynamic processes. Thermionic effect follows Richardson's law, where the electron emission exponentially increases with increasing hot side temperature and reduced electrode work function, hence the energy flux allowed to flow in the thermionic device drastically increases until reaching material breakdown. For the cold side, there is an optimum temperature to generate the maximum power depending on the hot side temperature and the electrode work functions. Such optimum cold-side temperature overlaps the range of the hot-side temperature of the alkali metal thermal electric converters (AMTECs) or thermoelectric generators. Hence cascading the TEC as a topping cycle of these converters is reasonable but thermal impedance match between these distinct devices remains a design challenge. If TEC is designed for standalone, a high-performance cold side heat sink at such uncommon elevated temperature is required. Despite the significant efforts historically spent on TEC devices, their practical implementation has not been successfully demonstrated for spaceflight hardware. There are several technical breakthroughs required for a new generation of thermionic technology. Advanced materials and cesium plasma chemistry enhances the performance with relatively wider gap spacing between the electrodes. Heat conduction through the physical contacts between the emitter and collector dictates the heat flow and the thermodynamic efficiency. This irreversible energy transport by thermal crosstalk is likely larger than the useful energy transport by emitting electrons. Thanks to the high heat flux adaptability, the expected power output density of TEC device could achieve 5 kW/kg. This value is an order of magnitude larger than fuel cells and more than comparable to Li-ion batteries or aircraft jet engines. The Li-ion battery supports a limited range by its energy density, which is much smaller than that of fuels for heat-driven power generation. This talk will present the latest modeling/testing efforts to optimize TEC performance with advanced materials and technologies for spaceflight power conversion systems.

Keywords: Thermionic energy conversion, cesium plasma, heat flow, power density,

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Helicity Drive: A Novel, Scalable Magneto-Inertial Fusion Concept for Space Propulsion

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Abstract. Fusion energy holds tremendous promise for enabling high-power space propulsion and power applications once breakeven is achieved. Conventional approaches to fusion have favored the steady-state magnetic confinement or the short-pulse inertial confinement approaches that each present significant challenges for space applications. Our Helicity Drive concept is a novel intermediate approach based on decades of magneto-inertial fusion work, and presents a simplified solution adapted for high-power in-space propulsion. The new concept exploits magnetic reconnection as a fast, high-power ion heating mechanism; natural plasma self-organization as a robust, stable, magnetic confinement scheme; and modest peristaltic magnetic compression to increase the plasma triple product. The result is a simplified design with favorable triple product scaling, no auxiliary heating systems, no dynamic compression liners, reduced magnetic compression challenges, and the ability to independently control density, temperature, and magnetic energy to compensate for uncertainties in confinement time. The primary innovation of the concept is the ability to reconnect more than two stable magnetic plasma configurations, which gives a fusion power output that is uniquely scalable with input geometry, significantly simplifying the engineering of the whole system. The concept can potentially scale from a fusion-enhanced solar electric propulsion system to a self-sustained fusion power plant and propulsion system, simply with the number of identical plasma guns. This is analogous to scaling an engine with the number of cylinders instead of increasing the size of one cylinder. HelicitySpace was recently formed to assemble interest in the concept with a focus on addressing the spaceflight and energy applications, leading a Project Team that includes the California Institute of Technology, Swarthmore College, the University of Maryland at Baltimore County, and the Space Sciences Institute.

Keywords: fusion energy, magneto-inertial confinement,
high-power in-space propulsion, in-space power plant