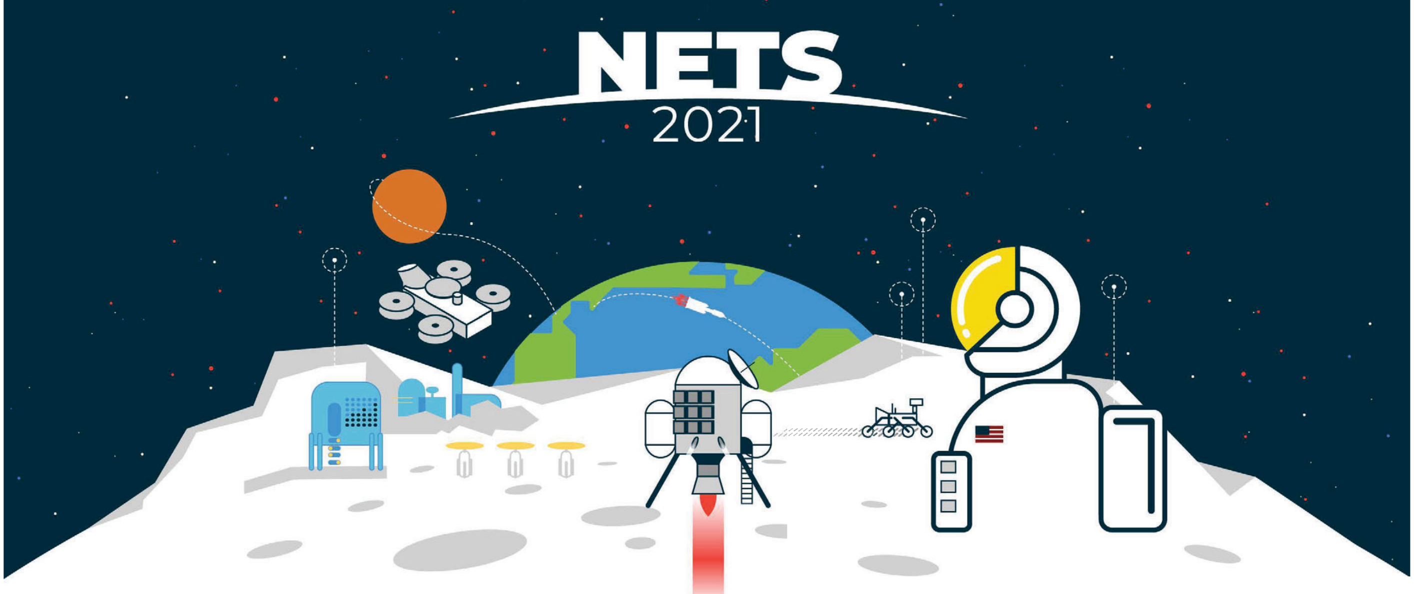

NUCLEAR and EMERGING TECHNOLOGIES for SPACE

Technical Program: Back to the Moon and on to Mars through advancing nuclear technologies and innovation.

NETS 2021 is sponsored by the Oak Ridge National Laboratory, and will be held from April 26th-30th, 2021. This conference will be held virtually so that the entire NETS community may participate in this exciting meeting.

U.S. DEPARTMENT OF ENERGY

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Nuclear and Emerging Technologies for Space 2021 –

Schedule at a Glance

SUNDAY, APRIL 25

NETS 2021 "Registration and Check In" Plenary Hall and Track Rooms open for presenter practice, NETS Help Desk Open	4:00 - 6:30 PM ET	Gathertown NETS Virtual Conference Hall
NETS Student Professional Development Event	5:00 - 6:30 PM ET	Gathertown Student Lounge

MONDAY, APRIL 26

Conference Registration and NETS Help Desk Open	8:00 – 10:00 AM ET	Gathertown NETS Virtual Conference Hall
Opening Plenary Balendra Sutharshan (ORNL), Matthew Mench, (UTK), Craig Piercy (ANS)	10:00 - 10:45 AM ET	Gathertown Plenary Hall
Keynote address: Sen. Blackburn and Rep. Fleischman	10:45 - 11:30 AM ET	Gathertown Plenary Hall
Break	11:30 - 11:45 AM ET	
Lightning Talks	11:45 AM - 12:30 PM ET	Technical Session Rooms
Break	12:15 - 12:30 PM ET	
Track 4 panel - Technology Challenges	12:30 - 1:30 PM ET	Track 4 Technical Session Room
Lunch on your own	12:30 - 1:30 PM ET	
Technical Sessions	1:30 - 3:15 PM ET	Technical Session Rooms
Break	3:15 - 3:30 PM ET	
Technical Sessions	3:30 - 5:00 PM ET	Technical Session Rooms
Track 2&3 panel - Industry Perspectives on Space Reactor Development	3:30 - 4:30 PM ET	Track 3 Technical Session Room

TUESDAY, APRIL 27

Conference Registration and NETS Help Desk Open	8:00 – 10:00 AM ET	Gathertown NETS Virtual Conference Hall
Darryl Gaines (Commercial Lunar Payload Services)	10:00 - 10:45 AM ET	Gathertown Plenary Hall
Tracey Bishop (DOE) and June Zakrajsek (NASA) Powering the Next Generation of Space Exploration)	10:45 - 11:30 AM ET	Gathertown Plenary Hall

Break	11:30 - 11:45 AM ET	
Lightning Talks	11:45 AM - 12:30 PM ET	Technical Session Rooms
Distinguished Speaker: Tim Tinsley (Updates from the UK National Laboratory)	12:30 - 1:30 PM ET	Gathertown Plenary Hall
Lunch on your own	12:30 - 1:30 PM ET	
Technical Sessions	1:30 - 3:15 PM ET	Technical Session Rooms
Break	3:15 - 3:30 PM ET	
Technical Sessions	3:30 - 5:00 PM ET	Technical Session Rooms
Track 2&3 panel - National Academy of Sciences, Engineering, and Medicine on Nuclear Propulsion for Crewed Mars Missions	3:30 - 4:30 PM ET	Track 2 Technical Session Room

WEDNESDAY, APRIL 28

Conference Registration and NETS Help Desk Open	8:00 – 10:00 AM ET	Gathertown NETS Virtual Conference Hall
Aaron Miles (Office of Science and Technology Policy)	10:00 - 10:45 AM ET	Gathertown Plenary Hall
Jeffery Merrifield (Advanced reactors)	10:45 - 11:30 AM ET	Gathertown Plenary Hall
Break	11:30 - 11:45 AM ET	
Lightning Talks	11:45 AM - 12:30 PM ET	Technical Session Rooms
Lunch on your own	12:30 - 1:30 PM ET	
Technical Sessions	1:30 - 3:15 PM ET	Technical Session Rooms
Break	3:15 - 3:30 PM ET	
Technical Sessions	3:30 - 5:00 PM ET	Technical Session Rooms
Track 3 panel - Update on Launch Approval	3:30 - 4:30 PM ET	Track 3 Technical Session Room

THURSDAY, APRIL 29

Conference Registration and NETS Help Desk Open	8:00 – 10:00 AM ET	Gathertown NETS Virtual Conference Hall
Keynote address: Ralph Lorenz (Overview of the Dragonfly Mission)	10:00 - 10:45 AM ET	Gathertown Plenary Hall
Keynote address: Ralph McNutt (Concepts for an Interstellar Probe)	10:45 - 11:30 AM ET	Gathertown Plenary Hall
Break	11:30 - 11:45 AM ET	
Lightning Talks	11:45 AM - 12:30 PM ET	Technical Session Rooms
Lunch on your own	12:30-1:00 ET	

Distinguished Speaker: Jon Neuhoff, The Department of Energy Isotope Program	1:00 - 1:30 PM ET	Gathertown Plenary Hall
Technical Sessions	1:30 - 3:15 PM ET	Technical Session Rooms
Break	3:15 - 3:30 PM ET	
Technical Sessions	3:30 - 4:30 PM ET	Technical Session Rooms
Track 1 panel - How Thermoelectric and Dynamic RPS can enable solar system discoveries in the next 20 years	3:30 - 4:30 PM ET	Track 1 Technical Session Room
Closing Announcements and Awards	4:30 - 5:30 PM ET	Gathertown Plenary Hall

Nuclear and Emerging Technologies for Space 2021 – Technical Sessions and Panels By Track

Sessions	Date	Time	Location
Lightning Talks			
Lightning Talk Session I.A	Apr 26	11:45 AM – 12:15 PM ET	Track 4 Room
Lightning Talk Session I.B	Apr 26	11:45 AM – 12:15 PM ET	Track 3 Room
Lightning Talk Session II.A	Apr 27	11:45 AM – 12:15 PM ET	Track 1 Room
Lightning Talk Session II.B	Apr 27	11:45 AM – 12:15 PM ET	Track 2 Room
Lightning Talk Session III	Apr 28	11:45 AM – 12:15 PM ET	Track 2 Room
Lightning Talk Session IV.A	Apr 29	11:45 AM – 12:15 PM ET	Track 1 Room
Lightning Talk Session IV.B	Apr 29	11:45 AM – 12:15 PM ET	Track 4 Room
Track 1: Radioisotopes and Power Conversion Systems			
RPS Fuels and Constant Rate Production	Apr 26	1:30 – 3:15 PM ET	Track 1 Room
Target and Fuel Production	Apr 26	3:30 – 5:00 PM ET	Track 1 Room
European Radioisotope Power Systems Development	Apr 27	1:30 – 3:15 PM ET	Track 1 Room
Thermoelectric Technology Development	Apr 27	3:30 – 5:00 PM ET	Track 1 Room
Radioisotope Thermoelectric Generators	Apr 28	1:30 – 3:15 PM ET	Track 1 Room
Mission & Power Conversion	Apr 28	3:30 – 5:00 PM ET	Track 1 Room
Dynamic Power Conversion	Apr 29	1:30 – 3:15 PM ET	Track 1 Room
Panel: "How Thermoelectric and Dynamic RPS can enable solar system discoveries in the next 20 years"	Apr 29	3:30 – 4:30 PM ET	Track 1 Room
Track 2: Nuclear Fission Power and Propulsion			
Space Fission Power I	Apr 26	1:30 – 3:15 PM ET	Track 2 Room
Nuclear Propulsion I	Apr 26	1:30 – 3:15 PM ET	Track 3 Room
Joint Panel: "Industry Perspectives on Space Reactor Development"	Apr 26	3:30 – 4:30 PM ET	Track 3 Room
Space Reactor Analysis and Testing I	Apr 27	1:30 – 3:15 PM ET	Track 2 Room
Nuclear Propulsion II	Apr 27	1:30 – 3:15 PM ET	Track 4 Room
Joint Panel: "National Academy of Sciences, Engineering, and Medicine on Nuclear Propulsion for Crewed Mars Missions"	Apr 27	3:30 – 4:30 PM ET	Track 2 Room
Nuclear Propulsion III	Apr 28	1:30 – 3:15 PM ET	Track 2 Room
Space Fission Power II	Apr 28	3:30 – 5:00 PM ET	Track 2 Room
Space Reactor Fuels and Materials	Apr 29	1:30 – 3:15 PM ET	Track 2 Room

Space Reactor Analysis and Testing II	Apr 29	3:30 – 5:00 PM ET	Track 2 Room

Track 3: Mission Concepts and Policy for Nuclear Space Systems

Joint Panel: "Industry Perspectives on Space Reactor Development"	Apr 26	3:30 – 4:30 PM ET	Track 3 Room
Mission Concepts and Policy I	Apr 27	1:30 – 3:15 PM ET	Track 3 Room
Joint Panel: "National Academy of Sciences, Engineering, and Medicine on Nuclear Propulsion for Crewed Mars Missions"	Apr 27	3:30 – 4:30 PM ET	Track 2 Room
Mission Concepts and Policy II	Apr 28	1:30 – 3:15 PM ET	Track 3 Room
Panel: "Update on Launch Approval"	Apr 28	3:30 – 4:30 PM ET	Track 3 Room

Track 4: Advanced and Emerging Technologies for Nuclear Space Applications

Panel: "Technology Challenges"	Apr 26	12:30 – 1:30 PM ET	Track 4 Room
Advanced and Emerging Technologies for Nuclear Space Applications I	Apr 26	3:30 – 5:00 PM ET	Track 4 Room

Nuclear and Emerging Technologies for Space 2021 – Lightning Talk Final Program

Monday, April 26, 2021

Lightning Talk Session I.A

11:45 AM
Betavoltaic power system for planetary exploration (36030)
Presenting Author: Marc S. Litz

11:50 AM
Limits on fusion propulsion for exoplanet exploration (35993)
Presenting Author: Gerald Jackson

11:55 AM
^{7}Li All Solid-State Batteries for Deep Space Applications (35642)
Presenting Author: Rebecca McAuliffe

12:00 PM
An Alfvenic reconnecting plasmoid thruster (35441)
Presenting Author: Fatima Ebrahimi

Lightning Talk Session I.B.

11:45 AM
NASA's Approach to Nuclear National Environmental Policy Act Compliance (35942)
Presenting Author: Bethany Eppig

11:50 AM
Autonomous Operation Capabilities for Space Reactors (35639)
Presenting Author: Richard Wood

11:55 AM
Exploring Lunar Seismic Hazards for Future Base Camp Nuclear Installations (35966)
Presenting Author: Michelle Bensi

12:00 PM
The promise and challenge of wireless power transfer for Fission Surface Power (35643)
Presenting Author: Ethan Chaleff

12:05 PM
Reinforcement learning in simulated realities for autonomous tasks in hostile environments (34963)
Presenting Author: Mark Patterson

Tuesday, April 27, 2021

Lightning Talk Session II.A

11:45 AM
Enabling and Enhancing: Effective Stakeholder Communication about Radioisotope Power Systems (35494)
Presenting Author: Douglas Isbell

11:50 AM
Empirical analysis and extrapolation of MMRTG F1 performance on Curiosity: an update (35914)
Presenting Author: Christopher Whiting

11:55 AM
Progress in thermoelectric module development for European space nuclear power systems (35906)
Presenting Author: Ramy Mesalam

12:00 PM
RPS mission database (35929)
Presenting Author: Knut I. Oxnevad

12:05 PM
Modern techniques for visualizing radiation data in nuclear space scenarios (35394)
Presenting Author: Michael B. R. Smith

Tuesday, April 27, 2021

Lightning Talk Session II.B

11:45 AM
Operational considerations for fission reactors utilized on lunar in-situ resource utilization missions (35187)
Presenting Author: Andrew C. Klein

11:50 AM
Safeguards And Proliferation Protections (SAPPs): A Way to Protect and Defend U.S. HEU-Fueled Space Power & Propulsion Reactors (35989)
Presenting Author: Joseph Sholtis

11:55 AM
Operational considerations for space fission power and propulsion platforms (35182)
Presenting Author: Andrew Klein

12:00 PM
Operational considerations for space fission reactors utilized on nuclear thermal propulsion missions to Mars (35188)
Presenting Author: Andrew Klein

Wednesday, April 28, 2021

Lightning Talk Session III

11:45 AM
Monoamides ligands for Plutonium-238 production – process improvement from Phosphorous-free extractants (36051)
Presenting Author: Laetitia Delmau

11:50 AM
Development of the Material Property Handbook for Space Nuclear Applications
Presenting Author: Jessica Bowers

11:55 AM
Selection of alternative fiber to replace NARC-Rayon for the production of CBCF (35950)
Presenting Author: Nidia C. Gallego

12:00 PM
Fabrication of Mo30W Based Cermets for Nuclear Thermal Propulsion Using Spark Plasma Sintering (35957)
Presenting Author: Neal Gaffin

Thursday, April 29, 2021

Lightning Talk Session IV.A.

11:45 AM
Pyrolytic Graphite - an Enabling Material for Radioisotope Space Power Systems (35972)
Presenting Author: Glenn R. Romanoski

11:50 AM
Update on high strain tensile tests of Pt-Rh alloys for European radioisotope power system clads: Pt-20%Rh and Pt-10%Rh (35904)
Presenting Author: Emily J. Watkinson

11:55 AM
Device Performance and Characteristics of SiGe and SiMo Materials Synthesized by Spark Plasma Sintering at Multiple Laboratories (35960)
Presenting Author: Rama Venkatasubramanian

12:00 PM
Thermal conductivity measurements of neptunium aluminum cermet pellets with various neptunium loadings (36050)
Presenting Author: Gretchen K. Toney

12:05 PM
Aerogel Production by Critical Point Drying for RTG Thermoelectric Modules and Other Applications (35959)
Presenting Author: Ying Song

Thursday, April 29, 2021

Lightning Talk Session IV.B (Continued)

11:45 AM
Comparing experimentally validated computational thermal radiation solution methods as it pertains to nuclear thermal propulsion (34973)
Presenting Author: Tyler R. Steiner

11:50 AM
Design Basis for Nuclear Thermal Propulsion Testing using a Hot Hydrogen Test Loop (35944)
Presenting Author: William Searight

11:55 AM
Evaluation of Regenerative Cooling Channels for Nuclear Thermal Propulsion (35925)
Presenting Author: Keaton Melendez

12:00 PM
Effect of time and temperature on helium flow rate through sintered platinum powder frits (35951)
Presenting Author: Brian Friske

Nuclear and Emerging Technologies for Space 2021 – Track 1 Final Program

Monday, April 26, 2021

RPS Fuels and Constant Rate Production

1:30 PM
Mitigation of ^{208}Tl gamma dose from ^{236}PU decay chain via removal of ^{232}U (34912)
Presenting Author: Joshua H. Rhodes

1:50 PM
Online monitoring of radiochemical processing streams for the Plutonium-238 supply program (34942)
Presenting Author: Luke Sadergaski

2:10 PM
Microsphere Plutonium-238 oxide fuel to revolutionize new radioisotope power systems and heat sources for planetary exploration (35943)
Presenting Author: Jeff Katalenich

2:30 PM
Overview of recent Pu-238 production activities at Idaho national laboratory (35945)
Presenting Author: Andrew Zillmer

Target and Fuel Production

3:30 PM
Optimization of Plutonium-238 Production in the Advanced Test Reactor (35948)
Presenting Author: Emory Colvin

3:50 PM
Using N,N-Dihexylhexanamide for Plutonium-238 Purification (35956)
Presenting Author: Jarrod Gogolski

4:10 PM
Results, implications, and projections from irradiation and examination of initial NpO_2 test targets for improved ^{238}Pu production (36049)
Presenting Author: E.D. Collins

Tuesday, April 27, 2021

European Radioisotope Power Systems Development

1:30 PM
Americium-based oxide and Pt-Rh alloys compatibility/interaction tests in the context of European space radioisotope power systems (35415)
Presenting Author: Emily Jane Watkinson

1:50 PM
A facile polymetric templating route towards fabricating RTG and RHU vent hole filters (35426)
Presenting Author: Ramy Mesalam

2:10 PM
Impact studies for the ESA radioisotope power systems (35889)
Presenting Author: Alessandra Barco

2:30 PM
European Radioisotope Power Systems Programme: Recent Updates (35937)
Presenting Author: Richard M. Ambrosi

2:50 PM
A concept study on advanced radioisotope solid solutions and mixed oxide fuel forms for future space nuclear power systems (35938)
Presenting Author: Richard M. Ambrosi

Tuesday, April 27, 2021

Thermoelectrics Technology Development

3:30 PM
Developing Production Life Cycle (PLC) Levels Based on Production Factors and their Application in Determining the Production Readiness of a Heritage RTG Component (SiGe Unicouples) (34971)
Presenting Author: Daniel Kramer

3:50 PM
Preliminary testing of commercially available silicon germanium based thermoelectric modules (35079)
Presenting Author: Daniel Kramer

4:10 PM
Bipolar couple assembled module (BCAM) design for scalable and rugged architecture for TEG applications (35901)
Presenting Author: Rama Venkatasubramanian

4:30 PM
Spark Plasma Synthesis of SiGe Materials and Performance of Unicouples (35977)
Presenting Author: Jonathan Pierce

Wednesday, April 28, 2021

Radioisotope Thermoelectric Generators

1:30 PM
Empirical analysis of the MMRTG qualification unit operated at a low thermal inventory (35907)
Presenting Author: Christofer E. Whiting

1:50 PM
Multi-mission thermoelectric generator assembly testing and launch operations for Mars 2020 (35921)
Presenting Author: Eric S. Clarke

2:10 PM
Next generation radioisotope power for space exploration (35986)
Presenting Author: Robert D. Overy

2:30 PM
Manufacturing Development of Chargeable Atomic Batteries, an Affordable Alternative to Plutonium-based Radioisotope Heater Units and Thermoelectric Generators (35974)
Presenting Author: Andrew Lesh

2:50 PM
Chargeable atomic batteries – commercial radioisotope power systems for space and terrestrial missions (35975)
Presenting Author: Christopher G. Morrison

Missions & Power Conversion

3:30 PM
Mission concept considerations for ocean world exploration using RPS inside a pressure vessel (34982)
Presenting Author: Young H. Lee

3:50 PM
Advancements in low temperature, mid-temperature and high temperature heat-to-electric conversion devices (35899)
Presenting Author: Rama Venkatasubramanian

Thursday, April 29, 2021

Dynamic Power Conversion Technology Development

1:30 PM
Convertor development for dynamic radioisotope power systems (35896)
Presenting Author: Scott Wilson

Thursday, April 29, 2021

Dynamic Power Conversion Technology Development (Continued)

1:50 PM
Stirling convertor extended testing in support of dynamic RPS maturation (35940)
Presenting Author: Daniel D. Goodell

2:10 PM
Turbo Brayton converter for radioisotope power systems (35967)
Presenting Author: Jeffrey Breedlove

2:30 PM
Design of a 1 kW simplified Stirling controller using capacitor-based power factor correction (36001)

Presenting Author: Christopher B. Barth

2:50 PM
Sunpower Robust Stirling Converter (SRSC) Phase II Overview

Presenting Author: Josh Collins

Nuclear and Emerging Technologies for Space 2021 – Track 2 Final Program

Monday, April 26, 2021

Space Fission Power I

1:30 PM
Design of a low enrichment uranium nuclear reactor to power a future Martian colony - neutronic aspects (35996)
Presenting Author: Joffrey Dorville

1:50 PM
Design of a low enrichment uranium nuclear reactor to power a future Martian colony - thermal hydraulics (35997)
Presenting Author: Jacob A. Tellez

2:10 PM
Design of a low enrichment uranium nuclear reactor to power a future Martian colony - heat rejection (35998)
Presenting Author: Conner Glatt

2:30 PM
PYLON: scalable power for the emerging space economy (35999)
Presenting Author: Wesley R. Deason

2:50 PM
Mass optimization of a convective heat exchanger for Mars surface reactor waste heat rejection (35965)
Presenting Author: Nathan Colgan

Nuclear Propulsion I

1:30 PM
Dual moderator space reactor cores
Presenting Author: Jesus A. Mendoza

1:50 PM
Design and Modeling of a Centrifugal Nuclear Thermal Rocket
Presenting Author: Bryce T. Cornell

2:10 PM
In-situ alternative propellants for nuclear thermal propulsion
Presenting Author: Dennis Nikitaev

2:30 PM
Parametric evaluation of alternative nuclear propulsion cores using curved fuel plates
Presenting Author: Abdalla Abou-Jaoude

Tuesday, April 27, 2021

Space Reactor Analysis and Testing I

1:30 PM
Simulation of an inductively heated multi-channel nuclear thermal rocket model (35931)
Presenting Author: Micah Pratt

1:50 PM
Development of multi-purpose dynamic nuclear thermal rocket system models (35969)
Presenting Author: Jordan D. Rader

2:10 PM
Nuclear space system analysis and modelling (NSSAM): A software tool to efficiently analyze the design space of space reactor systems (35980)
Presenting Author: Kelsa B. Palomares

2:30 PM
Preliminary system framework for the startup analysis of a low enriched nuclear thermal propulsion engine (35683)
Presenting Author: Vigneshwar Manickam

Tuesday, April 27, 2021

Nuclear Propulsion II

1:30 PM
Nuclear power concepts for high-power electric propulsion missions to mars (35913)
Presenting Author: Lee Mason

1:50 PM
Space Nuclear Propulsion fuel and moderator development plan conceptual testing reference design (34986)
Presenting Author: Jeremy L. Gustafson

2:10 PM
Nuclear thermal propulsion demonstrator concept (35981)
Presenting Author: Michael Eades

2:30 PM
Safety design considerations for nuclear reactor powered spacecraft (35985)
Presenting Author: Robert W. Scheichler

2:50 PM
Design of a NERVA-derived HALEU reactor (EMU'') for nuclear thermal propulsion (35295)
Presenting Author: Avery Grieve

Wednesday, April 28, 2021

Nuclear Propulsion III

1:30 PM
Core loading pattern optimization of a tie-tube nuclear thermal propulsion reactor using a simulated annealing algorithm for nodal diffusion solvers (35915)
Presenting Author: Corey Smith

1:50 PM
Alternatives for electrical power production from a nuclear thermal propulsion engine (35917)
Presenting Author: Emily Wood

2:10 PM
Progress on decay heat modeling and mitigation in NTP Systems (35988)
Presenting Author: Aaron Selby

2:30 PM
Increasing cermet fuel thermal margin with thoria for nuclear thermal propulsion (34949)
Presenting Author: Gyutae Park

2:50 PM
Nuclear Thermal Propulsion Immediate Xenon Restart Threshold for Short Burn Durations (35476)
Presenting Author: Mario Mendoza

Space Fission Power II

3:30 PM
Development of key technologies for Korean space heat pipe reactor (35955)
Presenting Author: Chan Soo Kim

3:50 PM
Neutronic analysis of the submersion-subcritical safe space (S^4) reactor using reduced enrichment uranium fuel (35949)
Presenting Author: Takanori Kajihara

4:10 PM
Heat pipe development for space fission demonstration missions (35958)
Presenting Author: Max F. Chaiken

4:30 PM
Shielding analysis for a moderated low-enriched uranium fueled Kilopower reactor (35992)
Presenting Author: Jeffrey C. King

Thursday, April 29, 2021

Space Reactor Fuels and Materials

1:30 PM
Interface and subsurface ceramic behavior in molybdenum cermets for nuclear thermal propulsion (35046)
Presenting Author: Taylor Duffin

1:50 PM
Pulsed electric current sintering for fuel element fabrication (35968)
Presenting Author: Caen K. Ang

2:10 PM
Moderator considerations for space nuclear power and propulsion systems (35982)
Presenting Author: Kelsa B. Palomares

2:30 PM
A survey of high-temperature moderators for space nuclear reactor applications (35995)
Presenting Author: Jaden G. Zymbaluk

2:50 PM
Polymer irradiation testing for NTP systems (35976)
Presenting Author: Jarvis Caffrey

Space Reactor Analysis and Testing II

3:30 PM
Nuclear thermal propulsion subscale experimental testbed using the Ohio State University Research Reactor (35156)
Presenting Author: Tyler R. Steiner

3:50 PM
Upgrading Test Vehicle Capacity to Enable Future Space and Microreactor Testing in TREAT (35918)
Presenting Author: John D. Bess

4:10 PM
MIT reactor irradiation capabilities for space nuclear technology deployment (34959)
Presenting Author: Koroush Shirvan

Nuclear and Emerging Technologies for Space 2021 – Track 3 Final Program

Tuesday, April 27, 2021

Mission Concepts and Policy I

1:30 PM
Decoding Mission Design Problem for NTP Systems for Outer Planet Robotic Missions (35952)
Presenting Author: Saroj Kumar

1:50 PM
Introduction to a Human Mars Campaign Utilizing Nuclear Thermal Propulsion (34944)
Presenting Author: Timothy Kokan

2:10 PM
Modeling of NTP Engine Start-Up, Shutdown, and Cooldown and Their Impact on DV (35318)
Presenting Author: Britton Reynolds

2:30 PM
The Case for a 50+ Year Radioisotope Power Supply (36029)
Presenting Author: Clayton Smith

Wednesday, April 28, 2021

Mission Concepts and Policy II

1:30 PM
Considerations for Implementing Presidential Memorandum-20 Guidelines for Nuclear Safety Launch Authorization for Future Civil Space Missions (34981)
Presenting Author: Yale Chang

1:50 PM
Fission Reactor Inadvertent Reentry (34964)

2:10 PM
Avoiding HEU in Space Reactors: An Emerging Consensus (35922)
Presenting Author: Alan J. Kuperman

Presenting Author: Allen L. Camp

Nuclear and Emerging Technologies for Space 2021 – Track 4 Final Program

Monday, April 26, 2021

Advanced and Emerging Technologies for Nuclear Space Applications I

3:30 PM
A Cool Model to Analyze Heat Deposition on MTV Propellant Tanks (35987)
Presenting Author: Nicholas Albert Morris

3:50 PM
Planned Steady State Irradiation of Characterized Instruments for Nuclear Thermal Rockets using an In-Pile Experiment Apparatus (34972)
Presenting Author: Dan Floyd

4:10 PM
Helicon Injected Inertial Plasma Electrostatic Rocket (35898)
Presenting Author: Rohan Puri

4:30 PM
Antimatter-Based Propulsion for Exoplanet Exploration (35990)
Presenting Author: Gerald Peter Jackson

4:50 PM
Antimatter-Based Spacecraft Power Generation (35991)
Presenting Author: Gerald Peter Jackson

Nuclear and Emerging Technologies for Space 2021 –Full Proceedings Abstract Summary

PULSED ELECTRIC CURRENT SINTERING FOR FUEL ELEMENT FABRICATION (35968)

Presenting Author: Caen Ang, University of Tennessee (**cang@utk.edu)**

ZrC is a candidate material for nuclear thermal propulsion core structures. There has been significant progress in controlling the sintering to produce dense, bulk structures with embedded channels via control of the Zr-C system kinetics and chemical thermodynamics. Preliminary hot hydrogen tests at 2500K illustrate promising performance of ZrC-based materials. Challenges in geometry and design remain when considering Pulsed Electric Current Sintering for near-net shape fabrication.

IMPACT STUDIES FOR THE ESA RADIOISOTOPE POWER SYSTEMS (35889)

Presenting Author: Alessandra Barco, University of Leicester (**ab849@leicester.ac.uk**)

Since 2009, ESA has been conducting R&D activities leading towards the future development of a European capability in radioisotope power systems (RPSs) for space. An important aspect of the overall program is safety, and this involves ensuring that the design of these systems, in particular of the heat source (i.e. fuel and containment layers), meets a set of stringent requirements: it is fundamental to properly design them in order to avoid inadvertently releasing radioactive material into the environment in the event of an accident. Validated heat source accident models are necessary to inform the design iteration of the European 241Am-based RPSs, and to construct a safety case for their launch.

The research project here presented was a collaboration, supported by ESA, between the University of Leicester and ArianeGroup. Its goal was to start the process of understanding the behavior of the fuel containment systems under the most relevant accident conditions by computer modelling, to validate them experimentally given the infrastructure, test facilities and expertise of ArianeGroup in this field, and to characterize the different materials. The data obtained will help to iterate and improve the design of the European RPS heat sources by focusing on the fuel containment systems.

DESIGN OF A 1 kW SIMPLIFIED STIRLING CONTROLLER USING CAPACITOR-BASED POWER FACTOR CORRECTION (36001)

Presenting Author: Christopher Barth, NASA Glenn Research Center (**Christopher.b.barth@nasa.gov)**

Free-piston Stirling convertors provide efficient, reliable thermal to electric power conversion, provided they are paired with a reliable controller. This paper outlines work underway on design concepts for kilowatt- class controllers. Using passive power factor correction (PFC) this design explores the possibility of reducing programmatic risk through system simplification. Efficiency is maximized through incorporating wide- bandgap gallium nitride (GaN) switches, and passive PFC volume is minimized through the use of polymer multi-layer capacitors. This work is aimed at exploring new approaches for future Stirling controllers.

UPGRADING TEST VEHICLE CAPACITY TO ENABLE FUTURE SPACE AND MICROREACTOR TESTING IN TREAT (35918)

Presenting Author: John Bess, Idaho National Laboratory (**john.bess@inl.gov)**

TURBO BRAYTON CONVERTER FOR RADIOISOTOPE POWER SYSTEMS (35967)

Presenting Author: Jeffrey Breedlove, Creare LLC (**jfb@creare.com)**

Creare has teamed with Aerojet Rocketdyne, the University of New Mexico Institute for Space and Nuclear Power Studies (UNM ISNPS), Sest Incorporated (Sest), and West Coast Solutions to develop a turbo-Brayton power converter for future National Aeronautics and Space Administration (NASA) missions that use radioisotope heat sources. NASA has considered the closed Brayton cycle attractive for spaceflight applications since the 1960s, and Creare has developed miniature Brayton technology for over 40 years. Key characteristics include high specific power, high efficiency, long-life operation without wear, undetectable vibration, and flexible packaging. Detailed design results indicate a 300 We-class converter with a turbine inlet temperature of 730°C will have a thermal-to-electric conversion efficiency of nearly 25% and a specific power greater than 20We/kg. Prototype converter testing is scheduled to begin in April to verify these predictions.

MULTI-MISSION THERMOELECTRIC GENERATOR ASSEMBLY TESTING AND LAUNCH OPERATIONS FOR MARS 2020 (35921)

Presenting Author: Eric Clarke, Idaho National Laboratory Eric.Clarke@inl.gov

The Space Nuclear Power and Isotope Technologies (SNPIT) division at Idaho National Laboratory (INL) fuels, performs acceptance testing, and provides spacecraft integration support of Radioisotope Power Systems (RPS) in support of National Aeronautics and Space Administration (NASA) missions. Recently the SNPIT team completed assembly, testing and launch support of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) for the Mars 2020 Perseverance Rover mission.

MASS OPTIMIZATION OF A CONVECTIVE HEAT EXCHANGER FOR MARS SURFACE REACTOR WASTE HEAT REJECTION (35965)

Presenting Author: Nathan Colgan, University of Wisconsin **ncolgan@wisc.edu**

A numerical model of a finned-tube heat exchanger is developed and optimized to determine the mass- optimal heat exchanger geometry for waste heat rejection to the Martian atmosphere for a range of heat exchanger materials, configurations, and power loads. The optimizer uses a non-linear adaptive differential evolution optimization algorithm to find the optimal tube length, tube diameter, and fin pitch while a gradient descent method is used to find the optimal number of tube rows and columns. For a 100 kW stainless steel heat exchanger suitable for use with a supercritical CO2 (sCO2) closed Brayton cycle direct-cooled reactor, the optimal heat exchanger mass is found to be 27.0 kg with a frontal area of 3.94 m2. This is 95% less mass and area than a comparable radiator and requires 638 W of fan power (or 0.6% of the output power) to operate. Optimal geometries are also found for heat rejection loads of 1 kW to 500 kW across a range of coolant and atmosphere temperatures, indicating wide applicability of this technology for Martian heat rejection applications such as cryofuel refrigeration, in-situ resource utilization (ISRU) plant cooling, or large-scale power generation.

RESULTS, IMPLICATIONS, AND PROJECTIONS FROM IRRADIATION AND EXAMINATION OF INITIAL NPO_2 TEST TARGETS FOR IMPROVED ^{238}PU PRODUCTION (36049)

Presenting Author: E.D. Collins, Oak Ridge National Laboratory (**collinsed@ornl.gov)**

An alternative target design with potential improvements—including a major increase in 238Pu production rate and annual capacity; fewer targets to be fabricated, irradiated, and processed; and a significant elimination of aluminum-bearing, radioactive liquid waste—has been conceived and evaluated using reactor physics and thermal hydraulics analyses. The alternative target design uses pressed pellets of 237NpO2 stacked inside a Zircaloy-4 cladding tube. Four test targets were fabricated, irradiated, and examined. No potential problems were indicated. Projections from measured constituents indicated annual production could be increased by a factor of ~2, and the number of targets required to be fabricated, irradiated, and processed could be reduced by a factor of ~5.

DESIGN AND MODELING OF A CENTRIFUGAL NUCLEAR THERMAL ROCKET (34943)

Presenting Author: Bryce Cornell, Auburn University (**btc0027@auburn.edu)**

A computational fluid dynamic model of the Centrifugal Nuclear Thermal Rocket propulsion system is necessary prior to physical experimentation and development. In this paper, a simulation of a rotating centrifugal fuel element is discussed and evaluated. The model was developed and simulated using ANSYS Fluent and will help lay the foundation for future modeling of the system. This task was one of the first needed to kickstart progress towards the optimization of the Centrifugal Nuclear Thermal Rocket.

NUCLEAR THERMAL PROPULSION DEMONSTRATION CONCEPT (35981)

Presenting Author: Wes Deason, USNC-Tech (**w.deason@usnc-tech.com)**

USNC-Tech was honored to participate in the NASA- funded Industry Lead Nuclear Thermal Propulsion (NTP) Fight Demonstrator study managed by AMA. This program surveyed the industry for input into how a near- term NTP demonstration system could be designed and built. Under this project, USNC-Tech produced the R2DTO concept that leveraged USNC-Tech Technology to enable a near-term demonstration of NTP systems. This paper provides a high-level overview of R2DTO that highlights key technology choices and advantages.

PYLON: SCALABLE POWER FOR THE EMERGING SPACE ECONOMY (35999)

Presenting Author: Wes Deason, USNC-Tech (**w.deason@usnc-tech.com)**

USNC-Tech's Pylon space reactor architecture enables a safe and scalable approach to implement nuclear power in space. Pylon leverages USNC's proprietary nuclear fuel technology, FCM^{TM}, to achieve high performance at any power level, from 10's of kilowatts to multi-megawatts. When coupled with a gas-cooled Brayton cycle and solid neutron moderators, no configuration changes are required from initial demonstration to full commercial application.

DESIGN OF A LOW ENRICHMENT URANIUM NUCLEAR REACTOR TO POWER A FUTURE MARTIAN COLONY - NEUTRONIC ASPECTS (35996)

Presenting Author: Joffrey Dorville, Colorado School of Mines (**joffreydorville@mines.edu)**

Moderator, fuel, and core geometry configuration options are reviewed for the preliminary design of a low enrichment uranium megawatt-class nuclear reactor intended to provide 2 MWe to a colony established on the surface of Mars. The initial calculations suggest that using a cylindrical fuel block and yttrium hydride as moderator could be beneficial to achieve desired neutronic performance and reduce the mass of the system. The cylindrical design using yttrium hydride, dimensioned from this analysis, has a total diameter of 90 cm and a total height of 126.4 cm for the core and the reflector. The total mass of the core with the reflector is 2,900 kg. The control drum worth, the shutdown margin, and the excess reactivity, calculated for cold clean conditions with MCNP6.2, are \$15.0 ± \$0.5, \$9.94 ± \$0.33, and \$5.10 ± \$0.15, respectively.

NEXT GENERATION RADIOISOTOPE POWER FOR SPACE EXPLORATION (35986)

Presenting Author: Jean-Pierre Fleurial, Jet Propulsion Laboratory

Corresponding Author: Robert Overy (**Robert.D.Overy@nasa.gov**)

Radioisotope Thermoelectric Generators (RTGs) have been a key power source technology to enable NASA science and exploration missions exploring the surface of the Moon and Mars, the outer planets, and interstellar space since the 1960's. The Radioisotope Power Systems Program in partnership with the Department of Energy, plans to ensure that more capable RTGs are available to support future NASA missions to some of harshest, darkest, and dustiest destinations in the solar system and beyond. NASA plans to develop Next Generation RTGs through a multi-phase effort, building upon the reestablishment of the GPHS-RTG (General Purpose Heat Source-RTG) and providing a path for significant performance upgrades. The original GPHS-RTG qualification unit (Mod 0) should be refurbished and ready for fueling as early as 2024. The first new production unit (Mod 1), with capability akin to the heritage-design units, is planned by 2028. Infusion of advanced thermoelectric converter technology to make upgraded flight units (Mod 2), with greater performance than any previous RTG, would be available for possible flight missions by the early 2030's

PLANNED STEADY STATE IRRADIATION OF CHARACTERIZED INSTRUMENTS FOR NUCLEAR THERMAL ROCKETS USING IN-PILE EXPERIMENT APPARATUS (34972)

Presenting Author: Dan C. Floyd, University of Tennessee (**dfloyd7@vols.utk.edu)**

The development of nuclear rocket technology is critical for the further exploration of extraterrestrial bodies. Nuclear rockets are capable of providing various advantages over current chemical rockets. However, the harsh environment provides a number of challenges regarding instrument performance. Temperature extremes, radiation (reactor and space), and the inability to conduct traditional maintenance activities can lead to a severe degradation in instrument performance. To better understand the effects of radiation on instrumentation, an irradiation campaign has been designed to test a set of instruments provided by a collaborator in the aerospace industry. Details concerning pre-irradiation performance are provided for a future comparison to the irradiated performance. Additionally, the design of the irradiation test is described in detail.

DESIGN OF A LOW ENRICHMENT URANIUM NUCLEAR REACTOR TO POWER A FUTURE MARTIAN COLONY - HEAT REJECTION (35998)

Presenting Author: Conner Glatt, Colorado School of Mines (**cglatt@mines.edu)**

This paper explores the design characteristics of the heat rejection system for a Martian surface reactor sized to produce 2 MWe of electric power for at least ten years. The heat rejection analysis explores the effects of Martian weather on waste heat rejection and how control systems might be used to maintain the desired levels of power dissipation. The resulting adaptive radiator system maintains constant power dissipation by balancing radiative and convective heat transfer through variations in the rejection temperature and the radiator panel geometry. The worst-case hot environment (mid-day during the Martian summer with no wind) dictates the minimum system size, with 3744 m2 of radiator panel area necessary to reject 4.9 MWth of power through radiation and natural atmospheric convection. Preventing heat escape during the worst-case cold conditions *with a fixed effective radiator area requires the implementation of variable rejection temperatures, radiative view factors, and convective angles-of-attack.*

DESIGN OF NERVA-DERIVED HALEU REACTOR ("EMU") FOR NUCLEAR THERMAL PROPULSION (35295)

Presenting Author: Avery Grieve, University of Michigan (agrieve@umich.edu)

During the CSNR 2020 summer program a Nuclear Thermal Propulsion reactor based on NERVA (Nuclear Engines for Rocket Vehicle Applications) designs was investigated. Use of HALEU (High Assay Low Enriched Uranium) fuel in a zirconium carbide matrix mitigates the NERVA issue of fuel vaporization. A larger number of flow tubes than used in NERVA designs are composed of refractory metal alloys to improve heat transfer. The reactor was characterised in both Serpent and MCNP in the interest of dividing labour and playing to each code's strengths.

SPACE NUCLEAR PROPULSION FUEL AND MODERATOR DEVELOPMENT PLAN CONCEPTUAL TESTING REFERENCE DESIGN (34986)

Presenting Author: Jeremy Gustafson, BWX Technologies (jlgustafson@bwxt.com)

As future National Aeronautics and Space Administration (NASA) missions aim for destinations farther out into the solar system, Space Nuclear Propulsion (SNP), and in particular Nuclear Thermal Propulsion (NTP), is the only feasible near-term technology able to provide specific impulses of 900 seconds or greater and thrust in the range of tens of thousands of pounds. To maximize the success of the SNP program as a whole, a Fuel and Moderator Development Plan (FMDP) was created to mature mission critical technology, such as the reactor fuel form and moderator material. This paper details the conceptual testing reference design that provides the basis for the FMDP for future design and testing activities to meet NASA's goals.

MICROSPHERE PLUTONIUM-238 OXIDE FUEL TO REVOLUTIONIZE NEW RADIOISOTOPE POWER SYSTEMS AND HEAT SOURCES FOR PLANETARY EXPLORATION (35943)

Presenting Author: Jeffrey A. Katalenich, Pacific Northwest National Laboratory (jeffrey.katalenich@pnnl.gov)

Microsphere $^{238}PuO_2$ fuels have potential to provide performance and safety enhancements for future radioisotope heat and power systems (RPS) as well as enable more flexible and compact RPS designs. Improvements in RPS specific power and more flexible geometries were recently investigated by JPL and PNNL as part of a study on cryobot devices for exploring Ocean Worlds. Missions to penetrate ice and explore oceans, such as on Europa, will require RPS with high specific power within the vehicle to provide both heat and power. Such missions will be mass-constrained, and the energy required to penetrate the ice is highly dependent on cryobot size. Therefore, compact RPS geometries are needed to maximize heat and power while minimizing ^{238}Pu inventory. Microsphere-based heat sources are an attractive way to obtain flexible geometries and high volumetric power loadings because they can fill a region of any size and shape provided fuel temperatures are kept below a threshold and launch/re-entry safety are not compromised. The sol-gel technique to produce $^{238}PuO_2$ microsphere particles for heat sources has the benefit of preventing dust generation, as opposed to the current $^{238}PuO_2$ powder/pellet processing method, reducing hazards in the fuel fabrication line. Microspheres can also be individually coated to enhance thermal conductivity, and/or reduce the likelihood of $^{238}PuO_2$ fuel dispersal in an accident. Although PNNL has produced $^{238}PuO_2$ microspheres using the sol-gel method, the application of coatings and their integrity over time has yet to be investigated. Continued R&D could demonstrate the feasibility of advanced, microsphere- based heat sources and provide baseline data for planning future missions requiring new RPS with different heat source configurations.

DEVELOPMENT OF KEY TECHNOLOGIES FOR KOREAN SPACE HEAT PIPE REACTOR (35955)

Presenting Author: Chan Soo Kim, Korea Atomic Energy Research Institute (kcs1230@kaeri.re.kr)

The sustainable energy supply is important to carry out the various mission in space environment. The development of the fission power system for space, independent on the distance and direction of sun, is necessary for the surface power and the deep space exploration. Heat pipes can simplify the reactor design and remove the pump, piping and others. The objectives of the Korean space heat pipe reactor development program are the code development for space heat pipe reactor and the experimental evaluation of the thermal performance of the alkali metal heat pipe, which is manufactured by Korean company. This paper summarizes the research progress for Korean space heat pipe reactor technologies.

INTRODUCTION TO A HUMAN MARS CAMPAIGN UTILIZING NUCLEAR THERMAL PROPULSION (34944)

Presenting Author: Timothy Kokan, Aerojet Rocketdyne (timothy.kokan@rocket.com)

Nuclear thermal propulsion (NTP) has been extensively researched as a potential main propulsion option for human Mars missions. NTP's combination of high thrust and high fuel efficiency makes it an ideal main propulsion candidate for these types of missions, providing architectural benefits including smaller transportation system masses, reduced trip times, increased abort capabilities, and the potential for transportation infrastructure reuse.

Since 2016, Aerojet Rocketdyne (AR) has been work ing with NASA and members of industry as part of the NASA Space Technology Mission Directorate. The initial goal of this project was to determine the feasibility and affordability of a low enriched uranium (LEU)-based NTP engine with solid cost and schedule confidence. Having shown feasibility and affordability, the current project focus is on maturing NTP fuel and reactor technology.

As part of this activity, AR has examined potential NTP vehicle configurations to support both short-stay and long-stay crewed Mars missions and potential vehicle synergy to support both mission types.

This paper presents an overview of an envisioned human Mars exploration campaign consisting of uncrewed demonstration flights, crewed short-stay missions, and crewed long-stay missions preparing for the eventual permanent human presence on the surface of Mars.

DEVELOPING PRODUCTION LIFE CYCLE (PLC) LEVELS BASED ON PRODUCTION FACTORS AND THEIR APPLICATION IN DETERMINING THE PRODUCTION READINESS OF A HERITAGE RTG COMPONENT (SiGe UNICOUPLES) (34971)

Presenting Author: Daniel Kramer, University of Dayton (daniel.kramer@udri.udayton.edu)

The development of a process that takes into account the Production Life Cycle (PLC) of a component as a function of time is constructed. PLCs can be utilized to estimate the current production readiness status of a component that is no longer in production, and for which there is a need to estimate the activities required to achieve a production re-start. Re-starting a production capability can be complex, especially if a significant amount of time has elapse since the cessation of a production activity.

In an effort to better identify the status of heritage SiGe unicouple production, a set of Production Factors were developed and utilized to estimate its PLC level. PLC values range from 1 to 9 as actual production readiness increases, while also taking into account the time since the last production unit or campaign. Since PLC values are developed at a particular time, they are a "snapshot" of the production readiness of a component at that date, which also needs to be specified. The first- order analysis shows that the current PLC for the production of heritage SiGe unicouples is PLC 2-4/June- 2020, dependent on the current availability of heritage manufacturing articles from the 1990s.

DECODING MISSION DESIGN PROBLEM FOR NTP SYSTEMS FOR OUTER PLANET ROBOTIC MISSIONS (35952)

*Presenting Author: Saroj Kumar, University of Alabama (**saroj.kumar@uah.edu**)*

This paper discusses the current challenges of exploration of outer planets and proposes a Nuclear Thermal Propulsion (NTP) system for future deep space exploration missions. The mission design problem with respect to NTP system is presented where it is proposed that NTP powered missions need to integrate the requirements and constraints of mission objective, spacecraft design, NTP system design and launch vehicle limits into a self-consistent model. The paper presents a conceptual mission design to Jupiter based on the mission modeling techniques in the paper.

AVOIDING HEU IN SPACE REACTORS: AN EMERGING CONSENSUS (35922)

Presenting Author: Alan J. Kuperman, University of Texas (**ak@NPPP.org**)

Several years ago, it was assumed that prospective U.S. space power reactors would utilize fuel of highly enriched uranium (HEU) – despite such uranium being nuclear weapons-usable and therefore disfavored for civilian applications under longstanding U.S. and international nonproliferation policy. More recently, however, a U.S. government consensus has emerged opposing HEU use in space reactors, and instead advocating fuel of low-enriched uranium (LEU), which is not suitable for nuclear weapons under International Atomic Energy Agency guidelines. This paper first documents the emergence

of the consensus against HEU space reactors and then recommends that the American Nuclear Society promote research and development of LEU-fueled space reactors, which may be the only politically plausible pathway for the United States to achieve nuclear power in space.

MISSION CONCEPT CONSIDERATIONS FOR OCEAN WORLD EXPLORATION USING RPS INSIDE A PRESSURE VESSEL (34982)

Presenting Author: Young H. Lee, Jet Propulsion Laboratory (**young.h.lee@jpl.nasa.gov**)

The National Aeronautics and Space Administration (NASA) has identified six ocean worlds according to the NASA Roadmap to Ocean Worlds, namely: Earth, Europa, Ganymede, Callisto, Enceladus, and Titan. In addition to this set, there are a number of identified potential worlds (e.g., Triton, Ceres, Pluto, Ariel, Miranda)[1]. Accessing into and through the ice shells of ocean worlds will enable compelling science set out in the Decadal Survey[2], including the search for evidence of extinct or extant life.

This paper describes the Ocean Worlds Concept of Operations Study that was conducted by the RPS Mission Analysis Team and A-Team at the Jet Propulsion Laboratory (JPL) for the Radioisotope Power Systems (RPS) Program. The main objective of this study was to investigate a concept of operations of the RPS within a PV over the end-to-end life of a mission. Most past mission concept studies have focused on the novel mission stages within the ice or within the ocean, while this study was focused on identifying considerations needed for developing the RPS within a PV (pressure vessel), examining each mission phase from an end-to-end mission operations perspective.

MANUFACTURING DEVELOPMENT OF CHARGEABLE ATOMIC BATTERIES, AN AFFORDABLE ALTERNATIVE TO PLUTONIUM-BASED RADIOISOTOPE HEATER UNITS AND THERMOELECTRIC GENERATORS (35974)

Presenting Author: Andrew Lesh, Stanford University (**aclesh@stanford.edu**)

Plutonium-fueled radioisotope heater units and thermoelectric generators have enabled a variety of space missions where use of solar power alone is infeasible. While their excellent performance justifies their expense for government projects, the logistical and legal complexity of plutonium use makes them commercially unavailable. Ultra Safe Nuclear Corporation — Technologies (USNC-Tech) is developing an alternative device called a Chargeable Atomic Battery (CAB). CABs contain a nonradioactive precursor isotope that becomes a desired radioisotope via neutron capture in a fission reactor. This means that CAB units are only radioactive after neutronic charging and can be assembled in conventional facilities from relatively inexpensive materials. Prototype uncharged CAB units have been successfully manufactured and indicate the viability of this cost-effective, proliferation-safe radioisotope power source for both space and terrestrial applications.

PRELIMINARY SYSTEM FRAMEWORK FOR THE STARTUP ANALYSIS OF A LOW ENRICHED NUCLEAR THERMAL PROPULSION ENGINE (35683)

Presenting Author: Vigneshwar Manickam, Georgia Institute of Technology (**vigneshwar.manickam@gatech.edu**)

This paper presents a preliminary computational framework for start-up sequence analysis and design of nuclear thermal propulsion (NTP) low enriched uranium (LEU). The computational framework provides a modular package for the integrated transient modeling of key engine components. Additionally, this paper introduces the control of core reactivity and chamber pressure in a modern LEU NTP system based on previous work that was investigated for the control of NERVA engines.

NUCLEAR POWER CONCEPTS FOR HIGH-POWER ELECTRIC PROPULSION MISSIONS TO MARS (35913)

Presenting Author: Lee Mason, NASA Headquarters (**lee.s.mason@nasa.gov**)

Under the Mars Transportation Assessment Study, NASA and DOE are performing analyses and generating concepts for crewed Nuclear Electric Propulsion (NEP) missions to Mars. This paper presents the results of trade studies and concept development for the nuclear electric power system, consisting of the fission reactor, radiation shielding, power conversion, heat rejection and power management & distribution (PMAD). The nuclear power team completed trade studies to evaluate different reactor and power conversion technologies and developed preliminary concepts for the crew shielding, waste heat

radiators, and PMAD. The initial results suggest that a modified terrestrial microreactor combined with supercritical CO_2 Brayton conversion could be used to perform the crew and cargo missions with satisfactory performance and modest risk.

NUCLEAR THERMAL PROPULSION IMMEDIATE XENON RESTART THRESHOLD FOR SHORT BURN DURATIONS (35476)

Presenting Author: Mario Mendoza, USNC-Tech (**m.mendoza@usnc-tech.com**)

For nuclear thermal propulsion systems, the concentration of xenon in the core produced during operations reduces the reactivity in the system and can prevent the reactor from restarting for subsequent burns if not enough time has elapsed to allow for the xenon to decay. Since the amount of xenon produced is dependent on power and time of operation in this application, different burn durations require different lengths of minimum wait-time. By analyzing the maximum xenon negative reactivity insertion after different burn durations, an immediate restart threshold was developed for immediate reactor restarts for extraneous situations not included in mission plans. An NTP burn less than the immediate restart threshold (42.19 min in this case) can afford an immediate second cycle without dropping its k_{eff} below 1 after the second burn. For any burn duration longer than the immediate restart threshold, the same required wait-time between burns will produce sustainable cycles.

DUAL MODERATOR SPACE REACTOR CORES (35994)

Presenting Author: Jesus A. Mendoza, Colorado School of Mines (**jmendoza1@mines.edu**)

Space reactors fueled with Low Enrichment Uranium will most likely require moderators to reduce the size and mass of the reactor. This paper considers combinations of beryllium, yttrium hydride, and zirconium hydride as moderators for a 250 kWe fission power reactor. A dual moderated system can include a more thermally favorable material with less effective moderating capabilities near the fuel and a less thermally favorable, but more effective moderator away from the fuel. This arrangement reduces the impact of the less desirable qualities of both materials. The zirconium hydride cases resulted in the highest infinite multiplication factors (above 1.30 in each case). Zirconium hydride is only viable up to 900 K. Yttrium hydride has an upper operating limit of 1173 K. As a sole moderator, yttrium hydride produced an infinite multiplication factor of 1.24715; but, adding beryllium around the coolant channels increased the infinite multiplication factor to 1.24853. This result, along with beryllium's superior thermal conductivity, indicates that a mixed moderator configuration may be more ideal for a high temperature reactor.

A COOL MODEL TO ANALYZE HEAT DEPOSITION ON MTV PROPELLANT TANKS (35987)

Presenting Author: Nicholas A. Morris, University of Alabama (**nam0021@uah.edu**)

Improved methods for storing liquid hydrogen in larger quantities and over longer periods of time in space are becoming progressively more critical as sights are once again set on Mars. Current storage methods involve the venting of vaporized hydrogen to space, with the consequence that significant amounts of hydrogen are wasted. Extra hydrogen must be stored to account for this loss resulting in unnecessary mass penalties. Eliminating this waste can reduce overall mission mass, extend mission range, and perhaps most importantly lower mission trip times and costs. This paper discusses the methods used to analyze the heat deposition on the Mars Transfer Vehicles' propellant tanks through its mission flight path and gives insight into how this analysis can be used in the selection of the appropriate thermal control methods given mission requirements.

CHARGEABLE ATOMIC BATTERIES - COMMERCIAL RADIOISOTOPE POWER SYSTEMS FOR SPACE AND TERRESTRIAL MISSIONS (35975)

Presenting Author: Christopher Morrison, USNC-Tech (**c.morrison@usnc-tech.com**)

Atomic batteries possess one-million times the energy density of state-of-the-art chemical batteries and fossil fuels. For locations that do not possess access to the sun or other energy sources, atomic batteries are enabling. Relevant use cases include small satellites operating far from the sun, electronics on the moon attempting to survive the lunar night, underwater vehicles to explore the depths of the ocean, and low-power heat in remote regions such as Canada and northern Europe and Asia. USNC-Tech is maturing a patented atomic battery concept and is actively engaging commercial companies, regulatory agencies, and production partners.

IN-SITU ALTERNATIVE PROPELLANTS FOR NUCLEAR THERMAL PROPULSION (34948)

Presenting Author: Dennis Nikitaev, University of Alabama (**dn0038@uah.edu**)

Nuclear Thermal Propulsion (NTP) produces heat by nuclear fission allowing any fluid to function as a propellant if it does not degrade the reactor materials. Liquid hydrogen is commonly considered due to its low molecular weight yielding a high specific impulse (Isp) of up to 900 seconds. However, its density is 7% that of water and increases the dry mass of the vehicle to store it. There are two alternative propellants, water, and ammonia, that are abundant resources in the Solar System, and both are much denser than liquid hydrogen and do not require post processing, such as electrolysis, to be used directly.

At the temperatures found inside the NTP reactor, water will oxidize most materials. Recent work on silicon carbide coatings of water reactors has shown that during reactor accidents, this coating will protect the fuel up to 100-200 hours at temperatures up to 2273 K. Therefore, if a silicon carbide coating is used, then it will allow the engine to operate between 100 to 200 hours, much longer than there is uranium in a low-enriched uranium reactor to support engine operation. Ammonia, on the other hand, is not expected to cause any significant reactor degradation due to its slow kinetics.

NTP expander cycle engine models of 25,000 lbf thrust class were constructed in Simulink which yielded a Isp of 336 seconds for water and 388 seconds for ammonia. Although this Isp is lower than the most efficient chemical engines, since pure water and ammonia are used directly and are stored as such, a propellant tank volume decrease of up to 75% for water and 69% for ammonia are possible. This will decrease the number of launches, given that the tanks are not fully fueled at time of launch and Lunar resources are used to fill the tanks completely.

NUCLEAR SPACE SYSTEM ANALYSIS AND MODELLING (NSSAM): A SOFTWARE TOOL TO EFFICIENTLY ANALYZE THE DESIGN SPACE OF SPACE REACTOR SYSTEMS (35980)

Presenting Author: Kelsa Palomares, Analytical Mechanics Associates (**kelsa.b.palomares@ama-inc.com**)

Space reactors have the potential to play a key role in future NASA exploration activities due to their capability to enable sustainable power and advanced propulsion systems. To enable assessment of the space reactor design space, the nuclear space system analysis and modelling (NSSAM) software was developed by Analytical Mechanics Associates. NSSAM leverages a scalable and extensible software architecture which automates reactor analysis to perform coupled engine- reactor and reactor physics-thermal hydraulics calculations. This allows space reactor systems to be evaluated by a wider number of users with a consistent analysis approach to compare designs. NSSAM has been developed with multiple use cases to tailor the analysis to the level of detail desired by the user and computing resources. This summary overviews the NSSAM architecture and development approach, current capabilities (including design variants and use cases) and analysis approach for reactor and system component models.

MODERATOR CONSIDERATIONS FOR SPACE NUCLEAR POWER AND PROPULSION SYSTEMS (35982)

Presenting Author: Kelsa Palomares, Analytical Mechanics Associates (**kelsa.b.palomares@ama-inc.com**)

Nuclear reactors have the potential to provide high energy density to enable sustainable surface power and advanced propulsion methods needed for human exploration activities at the moon and mars. Current mission planning is surveying different reactor types for space power and propulsion application. Of these reactor types, the use of a moderator within the reactor can enable reduced enrichment, reduce overall fuel loadings, and minimize the critical size of the reactor compared to unmoderated reference systems. This proceeding summarizes some moderator materials identified for space reactor applications: zirconium hydride, yttrium hydride, beryllium, and beryllium oxide, and the unique design considerations inherent to surface power and nuclear thermal propulsion reactor designs. It was found that there are four key considerations during the moderator selection and design process: nuclear properties, thermophysical & mechanical properties, manufacture & readiness, and environmental compatibility. Surface power reactors can benefit from moderators which minimize overall system mass and are capable of surviving high temperature irradiation environments for years with little degradation. Nuclear thermal propulsion reactors can benefit from moderators which are capable of retaining structural integrity under multiple burns while being exposed to a wide temperature range ($40 < T < 500+$ K). Moderator materials which exhibit good stability under irradiation and high temperature operation, minimize fuel pitch, and are high readiness are desirable for near term implementation.

INCREASING CERMET FUEL THERMAL MARGIN WITH THORIA FOR NUCLEAR THERMAL PROPULSION (34949)

Presenting Author: Gyutae Park, Massachusetts Institute of Technology (**park_g@mit.edu**)

The addition of thoria to urania was investigated as means to increase the fuel melting temperature of a Low- Enriched Uranium (LEU) Nuclear Thermal Propulsion (NTP) reactor core. Space Capable Cryogenic Thermal Engine (SCCTE) model[1, 6] was reproduced and tested to investigate the use of thorium dioxide (ThO_2)-uranium dioxide (UO_2)-tungsten (W) cermet to achieve higher fuel melting point, operating temperature, and specific impulse (Isp) for human Mars missions. A critical NTP model with additional fuel thermal margin was achieved with adjustments in the axial fuel composition and the tie tube geometry to minimize the fuel enrichment penalty.

SPARK PLASMA SYNTHESIS OF SiGe MATERIALS AND PERFORMANCE OF UNICOUPLES (35977)

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We will discuss the developments on Spark Plasma Sintered (SPS) synthesis of SiGe materials, their characterization and performance of unicouple devices made from these materials. These are relevant to Next Gen GPHS-RTG systems. SPS SiGe materials were characterized by ZEM3 for electrical resistivity and Seebeck coefficient from 300K to ~1100K. The 300K data for the $Si_{78}Ge_{22}$ N-type and $Si_{78}Ge_{22}$ P-type SPS materials are close to the legacy/heritage materials acceptance criteria. The initial ZT values estimated for N-type $Si_{78}Ge_{22}$ material made by SPS appear significantly better than legacy SiGe materials, which is consistent with several previously published work. A significant risk to the fabrication of heritage GPHS-RTG SiGe couples is the ability to carry out diffusion bonding between various layers – (i) between SiMo and $Si_{78}Ge_{22}$ and (ii) between $Si_{78}Ge_{22}$ and $Si_{63}Ge_{37}$ layers. We have investigated SPS as a potential method to show in-situ diffusion bonding between $Si_{78}Ge_{22}$ and $Si_{63}Ge_{37}$ layers; essentially, the two- layer stack is prepared in-situ, thus avoiding lower-yield diffusion bonding steps in the heritage process. In order to validate the SPS SiGe materials, we built 15 mm-tall SiGe unicouples and tested them upto T_{hot}~985°C and T_{cold}~100°C. We estimate an efficiency of ~9% in these SiGe couples. The V_{oc} and power output from these SiGe unicouples appear good as a function of T_{heater} and we obtained a peak power ~425 mW. These results are of likely value to the Next Gen project tasked with SiGe unicouple production for building a GPHS-RTG system.

SIMULATION OF AN INDUCTIVELY HEATED MULTI-CHANNEL NUCLEAR THERMAL ROCKET MODEL (35931)

Presenting Author: Micah Pratt, University of Southern California (**Micahpra@usc.edu**)

Nuclear thermal rocket propulsion offers an alternative to traditional liquid rockets, yielding similar amounts of thrust combined with two to three times the efficiency. The Hyperion-I project was designed to model solid core nuclear thermal propulsion using induction heating methods to simulate and experimentally validate this model. Here, a coupled electromagnetic and computational fluid dynamic model was created for a 7-channeled test article using ANSYS Maxwell and ANSYS Fluent and was subjected to experimental conditions. Nitrogen gas was flowed through each channel at a 0.25 g/s mass flow rate with an inlet temperature of 288.16 K. The total ohmic loss in the test article from induction heating was 24.72 W, of which 1.87 W was lost to the environment due to convection. The average outlet gas temperature was 307±1 K, yielding a temperature increase of 19±1 K across the article. Future hardware testing will experimentally validate these temperature measurements and will include testing of a full-scale core.

HELICON INJECTED INERTIAL PLASMA ELECTROSTATIC ROCKET (35898)

Presenting Author: Rohan Puri, University of Illinois (**rohanp5@illinois.edu**)

Helicon Injected Inertial Plasma Electrostatic Rocket (HIIPER) is an electric propulsion system being developed at the University of Illinois Urbana-Champaign. It is considered as a steppingstone towards a nuclear fusion propulsion system. This study summarizes the various performance parameters of the device along with ongoing research and future scope of work. Preliminary computational results on plasma dependence on helicon tube dimensions are also presented and discussed. The paper lays the groundwork for possible future upgrades of the experimental setup.

DEVELOPMENT OF MULTI-PURPOSE DYNAMIC NUCLEAR THERMAL ROCKET SYSTEM MODELS (35969)

Presenting Author: Jordan Rader, Oak Ridge National Laboratory (**raderjd@ornl.gov**)

A Modelica-based dynamic system model of a nuclear thermal rocket engine has been created as part of a multi- agency effort to develop space nuclear propulsion technology. There is a need to provide the model to other team members in the fields of engine-vehicle integration and instrumentation and control in a form that is usable by computer codes suited for those purposes. To fulfill this need, the most recent version of the dynamic system model was augmented to support model export using the functional mock-up interface. This work describes the necessary changes to the model to update to the latest engine configuration and describes the model export process. The exported model has been shown to satisfactorily reproduce the baseline results and to run faster than real time.

MODELING OF NTP ENGINE START-UP, SHUTDOWN, AND COOLDOWN AND THEIR IMPACT ON DV (35318)

Presenting Author: Christopher B. Reynolds, Aerojet Rocketdyne (**christopher.reynolds@rocket.com**)

For the past 5 years, nuclear thermal propulsion (NTP) has been evaluated as a potential main propulsion option for crewed missions to Mars. The combination of high thrust and high efficiency (high Isp) make NTP ideally suited for these missions, where transfer times can be in excess of 300 days and vehicle masses can reach several hundred metric tons.

With increases in fidelity to engine and trajectory modeling, a desire to couple the NTP engine start- up/shutdown and cooldown transients with current finite- burn trajectory modeling arose. With engine start-up and shutdown duration on the order of 30 seconds each, and engine cooldown taking place over several hours post- shutdown, enough propellant is expended to provide useful impulse and impact several aspects of the end-to- end trajectory and vehicle sizing.

This paper details current NTP engine start- up/shutdown and cooldown modeling, and the impacts of this impulse on vehicle sizing and end-to-end trajectory modeling.

MITIGATION OF ^{208}TL GAMMA DOSE FROM ^{236}PU DECAY CHAIN VIA CHEMICAL REMOVAL OF ^{232}U (34912)

Presenting Author: Joshua Rhodes, University of Tennessee (**jrhode19@vols.utk.edu**)

Many spacecraft use radioisotope thermal electric generators containing ^{238}Pu to provide power to spacecraft systems and scientific instruments. Originally a byproduct of plutonium for weapons, new domestic production sources are being investigated. The High Flux Isotope Reactor is already producing some ^{238}Pu, but more is needed to meet NASA requirements. The Advanced Test Reactor is being considered. However, ^{236}Pu is produced as a contaminant, which has daughter isotopes that produce high-energy gammas. The SCALE 6.2 ORIGEN module was used to simulate mitigation of the hazards of ^{236}Pu through radioactive decay and chemical processing after aging.

ONLINE MONITORING OF RADIOCHEMICAL PROCESSING STREAMS FOR THE PLUTONIUM-238 SUPPLY PROGRAM (34942)

Presenting Author: Luke Sadergaski, Oak Ridge National Laboratory (**sadergaskilr@ornl.gov**)

Online monitoring with spectrophotometry is being developed to improve the timeliness of analytical measurements for the Plutonium-238 Supply Program at Oak Ridge National Laboratory. A commercially available online monitoring software was used to calculate and view process data in real time to help identify process deviations and optimize system performance. Monitoring detailed process data will improve processing efficiency and help technicians make decisions during hot-cell operations.

SAFETY DESIGN CONSIDERATIONS FOR NUCLEAR REACTOR POWERED SPACECRAFT (35985)

Presenting Author: Robert Schleicher, General Atomics Electromagnetic Systems (**bob.schleicher@ga.com**)

This paper examines how safety considerations may affect the design of nuclear reactor powered propulsion systems, be it either nuclear thermal propulsion (NTP) reactor or nuclear electric propulsion (NEP). From this assessment, it is clear that *safety considerations derive from the full range of development and deployment stages beginning with ground testing and extending to space operation. Each stage can impose design requirements that will affect the overall propulsion system design. It is also recognized that different government organizations may have safety authority for the different deployment stages. For example, the Department of Energy (DOE) would have authority during ground testing at one of its national labs, whereas the Department of Transportation (DOT) has the authority to approve the launch of a vehicle containing a nuclear system. At present, there is not a cohesive set of safety design requirements for space reactors such as exists for terrestrial reactors. Due to the strategic importance and cost of these systems, articulating and consolidating a consistent set of guidelines and requirements is a necessary step for U.S. space nuclear propulsion development. The paper attempts to address each stage of propulsion reactor deployment and suggest design approaches that can practically be implemented to achieve an acceptable standard of safety.*

PROGRESS ON DECAY HEAT MODELING AND MITIGATION IN NTP SYSTEMS (35988)

Presenting Author: Aaron Selby, USNC-Tech (**a.selby@usnc-tech.com**)

Decay heat solutions are essential for maximizing the performance of NTP systems, reducing the amount of required cooldown hydrogen, and guaranteeing system safety. USNC-Tech's solution to NTP decay heat removal and utilization is high-temperature moderator elements with a moderator capable of operation at 1,000K. USNC- Tech is currently designing, building, and testing prototypic high-temperature tie tubes. These high- temperature moderator elements reduce the required cooldown hydrogen by over 50% and enable the co-power generation and RCS/OMS capabilities, enhancing the versatility of NTP for future space mission.

MIT REACTOR IRRADIATION CAPABILITIES FOR SPACE NUCLEAR TECHNOLOGY DEPLOYMENT (34959)

Presenting Author: Koroush Shirvan, Massachusetts Institute of Technology (**kshirvan@mit.edu**)

MITR is a 6 MWth facility on Massachusetts Institute of Technology campus. With peak neutron fluxes of up to $6x10^{13}$ n/cm^2-s (thermal) and $1.2x10^{14}$ n/cm^2-s (fast), MITR provides a unique irradiation capability to support space nuclear technology deployment. Recent experience with handling fissionable materials (up to 100 grams of U235 equivalent) and hydrogen gas along with operating at high temperatures (up to 1600^{o}C) readily enables supporting of current nuclear space missions. Such unique irradiation capability with wide operating envelope provides an ideal platform for emerging fuel technology down selection. Particularly, with advent of advanced manufacturing and progress in material science, the design space for potential high performing materials for space application has considerably widened and requires support from a prototypic irradiation test bed. In the near future, over cubic meter of irradiation space will be available to perform testing on full size components such as fuel blocks, I&C kits, control drums for direct prototypic demonstration. This summary outlines the specific capabilities and recent progress with respect to supporting fission technologies for propulsion and surface power in space.

CORE LOADING PATTERN OPTIMIZATION OF A TIE-TUBE NUCLEAR THERMAL PROPULSION REACTOR USING A SIMULATED ANNEALING ALGORITHM FOR NODAL DIFFUSION SOLVERS (35915)

Presenting Author: Corey Smith, Georgia Institute of Technology (**corey.d.smith@ama-inc.com**)

Since the early 1950s, the key to deep space travel has hinged upon the use of high-temperature nuclear thermal or electric propulsion engines (NTP/NEP). Many design variants have been created by different government agencies, research laboratories, and technical universities, initiated by the Rover/NERVA (RN) program from the United States during the 1950s and 60s. Current and future NTP research designs require adequate moderation due to new restrictions on highly enriched uranium (HEU), posing several additional design challenges for potential mission operation. Both moderation and the use of high-assay low enriched uranium (19.75% w/o U-235) significantly increase core size and intraelemental power peaking which directly affects safety and performance metrics. To optimize key engine performance metrics, such as output specific impulse (Isp), thrust, and thrust to weight ratio, the core loading pattern should prioritize the minimization of the radial power peaking to increase the average element outlet coolant temperature. To perform this analysis, an iterative simulated annealing algorithm is used to couple material cross-section results from a Monte Carlo (MC) model with a computationally efficient nodal diffusion solver. This sequence can run thousands of different core configurations in the same amount of time required to run a single high-fidelity MC simulation.

THE CASE FOR A 50+ YEAR RADIOISOTOPE POWER SUPPLY (36029)

Presenting Author: Clayton Smith, Johns Hopkins University Applied Physics Laboratory (**clay.smith@jhuapl.edu**)

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) is leading the NASA funded Interstellar Probe study to explore the "Very Local" interstellar medium. To perform this exploration the mission will be required to last at least 50 years in regions of space where solar power is no longer practical. Additionally, several new studies for the National Academies' Planetary Science and Astrobiology Decadal Survey are planning missions lasting 20-35 years. The Decadal Survey is used to build consensus on priority of national science goals. These proposed missions are inconsistent with the NASA's current flight lifetime requirement of 14 years. Paramount to these proposed long-duration missions are questions about the longevity of such a mission. Evidence exists that space- borne Radioisotope Power Systems can indeed last a long time. LES-9, Voyager I, and Voyager II are over 40 years old, LES-8, Pioneer 10, and Pioneer 11 lasted 28, 30, and 22 years, respectively, and New Horizons is still active 15 years after launch. None of these missions was terminated because of an RTG failure.

This paper examines the historical record by way of statistical analyses, illustrates the theoretical performance through a long -duration mission, and discusses how reliability engineering and testing methods can be brought to bear to increase confidence in delivering sufficient power at end of mission.

DESIGN OF A LOW ENRICHMENT URANIUM NUCLEAR REACTOR TO POWER A FUTURE MARTIAN COLONY - THERMAL HYDRAULICS (35997)

Presenting Author: Jacob Tellez, Colorado School of Mines (**jtellez@mines.edu**)

This work discusses the single channel analysis of hexagonal and cylindrical reactor configurations for use in a 2 MW_e Martian reactor targeting a 10-year operating lifetime with currently available materials and low enrichment uranium fuel. Each configuration uses a Mo- Re alloy cladding in combination with a closed CO_2 Brayton cycle. Fuels consist of uranium metal-hydrides employing either zirconium or yttrium as the metal for the hydride moderator. System efficiencies are estimated near 22% and 25% for the UZrH and UYH configurations, respectively. Average core mass fluxes are near 6700 kg/m^{2}s (46 kg/s) and 4000 kg/m^{2}s (20 kg/s) for the UZrH and UYH configurations, respectively. Peaking factors for the central fuel elements require flow rates to be increased by as much as a factor of two when compared with the average fuel element. The flow rates in the central channels result in significant pressure drops in the zirconium hydride moderated cores, primarily due to the temperature limit set to limit potential hydrogen migration out of the hot regions in the moderator.

ALTERNATIVES FOR ELECTRICAL POWER PRODUCTION FROM A NUCLEAR THERMAL PROPULSION ENGINE (35917)

Presenting Author: Emily Wood, University of Alabama (**egw0015@uah.edu**)

This paper discusses the concept of a Minimally Intrusive Power generation System (MIPS) for use with a Nuclear Thermal Propulsion (NTP) engine for a crewed Mars Transfer Vehicle (MTV). In order to keep the fuel elements in the nuclear reactor above their ductile-to-brittle transition temperature (DBTT), the reactor will not be turned off after each burn, but instead will idle in a low power mode. The goal of the MIPS is to remove enough of the idle heat so that the reactor core will not be damaged, and convert this thermal energy into an adequate amount of electricity to power the vehicle, without compromising the reactor design. Three alternatives will be considered; thermoelectric generators, a closed-loop Brayton cycle, and a Stirling cycle. This paper describes the candidate systems and the design requirements of the MIPS, then goes on to outline how the systems were modeled and what attributes will be considered when deciding which system is best for this intended use.

OVERVIEW OF RECENT PU-238 PRODUCTION ACTIVITIES AT IDAHO NATIONAL LABORATORY (35945)

*Presenting Author: Andrew Zillmer, Idaho National Laboratory (**Andrew.zillmer@inl.gov**)*

The Plutonium Fuel Services (PFS) program at Idaho National Laboratory (INL) is active in the qualification of irradiation targets containing Np-237 for irradiation in the Advanced Test Reactor (ATR) to produce Pu-238 for future NASA missions. INL qualified and loaded 7 targets in ATR's South Flux Trap (SFT) for cycle 169A, which occurred in Spring 2021. This program was reinitiated after two baseline production targets in three positions validated significant production of Pu-238 [ref.1]. The validation model was followed by the PFS-1 experimental test in the ATRC (Critical) facility [ref.2]. This paper outlines the progress and status of the PFS program. The qualification effort, safety analysis, hardware status, and future activities for qualification of an updated target design for use in the ATR will be discussed.

A SURVEY OF HIGH-TEMPERATURE MODERATORS FOR SPACE NUCLEAR REACTOR APPLICATIONS (35995)

Presenting Author: Jaden Zymbaluk, Colorado School of Mines (**jzymbaluk@mines.edu**)

This paper surveys the existing literature on high- temperature solid moderators and provides derived nuclear and physical property data for beryllium, beryllium oxide, graphite, lithium hydride, yttrium hydride, and zirconium hydride. While zirconium hydride has been used as a moderator in previous space nuclear reactors, the higher disassociation temperature of yttrium hydride, combined with its higher thermal conductivity, make yttrium hydride a strong candidate for use in future Low Enrichment Uranium (LEU)-fueled space nuclear reactors

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EXPLORING LUNAR SEISMIC HAZARDS FOR FUTURE BASE CAMP NUCLEAR INSTALLATIONS (35966)

Presenting Author: Michelle Bensi, University of Maryland
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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.

DEVELOPMENT OF THE MATERIAL PROPERTY HANDBOOK FOR SPACE NUCLEAR APPLICATIONS (36539)

Presenting Author: Jessica Bowers, NASA Glenn Research Center (**jessica.j.bowers@nasa.gov**)

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.

THE PROMISE AND CHALLENGE OF WIRELESS POWER TRANSFER FOR FISSION SURFACE POWER (35643)

Presenting Author: Ethan Chaleff, USNC-Tech (**e.chaleff@usnc-tech.com**)

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.

MONOAMIDES LIGANDS FOR PLUTONIUM-238 PRODUCTION - PROCESS IMPROVEMENT FROM PHOSPHORUS-FREE EXTRACTANTS (36051)

Presenting Author: Lætitia H. Delmau, Oak Ridge National Laboratory (delmaulh@ornl.gov)

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.

AN ALFVENIC RECONNECTING PLASMOID THRUSTER (35441)

Presenting Author: Fatima Ebrahimi, Princeton University (ebrahimi@pppl.gov)

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 Alfvenic 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 Delta-v, including the solar system beyond the Moon and Mars. Because the Alfvenic 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.

NASA'S APPROACH TO NUCLEAR NATIONAL ENVIRONMENTAL POLICY ACT COMPLIANCE (35942)

Presenting Author: Bethany Eppig, NASA Glenn Research Center (bethany.m.g.eppig@nasa.gov)

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.

EFFECT OF TIME AND TEMPERATURE ON HELIUM FLOW RATE THROUGH SINTERED PLATINUM POWDER FRITS (35951)

Presenting Author: Brian Fiske, Oak Ridge National Laboratory (friskeb@ornl.gov)

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).

FABRICATION OF MO30W BASED CERMETS FOR NUCLEAR THERMAL PROPULSION USING SPARK PLASMA SINTERING (35957)

Presenting Author: Neal Gaffin, University of Tennessee (**ngaffin@vols.utk.edu**)

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.

SELECTION OF ALTERNATIVE FIBER TO REPLACE NARC-RAYON FOR THE PRODUCTION OF CBCF (35950)

Presenting Author: Nidia C Gallego, Oak Ridge National Laboratory (**gallegonc@ornl.gov**)

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.

ENABLING AND ENHANCING: EFFECTIVE STAKEHOLDER COMMUNICATION ABOUT RADIOISOTOPE POWER SYSTEMS (35494)

Presenting Author: Douglas Isbell, NASA Jet Propulsion Laboratory (**douglas.m.isbell@jpl.nasa.gov**)

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.

LIMITS ON FUSION PROPULSION FOR EXOPLANET EXPLORATION (35993)

Presenting Author: Gerald Jackson (**gpj@beamalpha.com**)

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.

OPERATIONAL CONSIDERATIONS FOR FISSION REACTORS UTILIZED ON LUNAR IN-SITU RESOURCE UTILIZATION MISSIONS (35187)

Presenting Author: Andrew Klein (**kleina55@yahoo.com**)

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.

OPERATIONAL CONSIDERATIONS FOR FISSION REACTORS UTILIZED ON NUCLEAR THERMAL PROPULSION MISSIONS TO MARS (35188)

Presenting Author: Andrew Klein (**kleina55@yahoo.com**)

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.

BETAVOLTAIC POWER SYSTEM FOR PLANETARY EXPLORATION (36030)

Presenting Author: Marc Litz, Army Research Laboratory (**Marc.s.litz.civ@mail.mil**)

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, AlGaN 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.

^{7}LI ALL SOLID-STATE BATTERIES FOR DEEP SPACE APPLICATIONS (35642)

Presenting Author: Rebecca D. McAuliffe, Oak Ridge National Laboratory (**mcaulifferd@ornl.gov**)

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 ^{7}Li. We have made deposition targets of $^{7}LiCoO_2$ and $^{7}Li_3PO_4$ to make thin film batteries using ^{7}Lipon as a solid electrolyte. These batteries will be tested along with batteries fabricated using naturally abundant Li using Americium-Beryllium sources to understand how ^{7}Li all solid-state batteries perform during irradiation.

PROGRESS IN THERMOELECTRIC MODULE DEVELOPMENT FOR EUROPEAN SPACE NUCLEAR POWER SYSTEMS (35906)

Presenting Author: Ramy Mesalam, University of Leicester (**rm558@le.ac.uk**)

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.

EVALUATION OF REGENERATIVE COOLING CHANNELS FOR NUCLEAR THERMAL PROPULSION (35925)

Presenting Author: Keaton Melendez, Ohio State University (**melendez.65@osu.edu**)

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 H_2 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.

RPS MISSION DATABASE (35929)

Presenting Author: Knut I. Oxnevad, Jet Propulsion Laboratory (**knut.i.oxnevad.dr@jpl.nasa.gov**)

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.

REINFORCEMENT LEARNING IN SIMULATED REALITIES FOR AUTONOMOUS TASKS IN HOSTILE ENVIRONMENTS (34963)

Presenting Author: Mark C. Patterson, Southern Research (**mpatterson@southernresearch.org**)

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.

PYROLYTIC GRAPHITE - AN ENABLING MATERIAL FOR RADIOISOTOPE SPACE POWER SYSTEMS (35972)

Presenting Author: Glenn Romanoski, Oak Ridge National Laboratory (**romanoskigr@ornl.gov**)

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.

DESIGN BASIS FOR NUCLEAR THERMAL PROPULSION TESTING USING A HOT HYDROGEN TEST LOOP (35944)

Presenting Author: William Searight, Penn State University (**wts36@psu.edu**)

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 experimentally[1]. 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.*

SAFEGUARDS AND PROLIFERATION PROTECTIONS (SAPPS): A WAY TO PROTECT AND DEFEND U.S. HEU-FUELED SPACE POWER & PROPULSION REACTORS (35989)

Presenting Author: Joseph A. Sholtis, Jr., Sholtis Engineering (**Sholtis@aol.com**)

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.

AEROGEL PRODUCTION BY CRITICAL POINT DRYING FOR RTG THERMOELECTRIC MODULES AND OTHER APPLICATIONS (35959)

Presenting Author: Ying Song, Teledyne (**Ying.Song@Teledyne.com**)

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.

COMPARING EXPERIMENTALLY VALIDATED COMPUTATIONAL THERMAL RADIATION SOLUTION METHODS AS IT PERTAINS TO NUCLEAR THERMAL PROPULSION (34973)

Presenting Author: Tyler R. Steiner, University of Tennessee (**tsteine1@vols.utk.edu**)

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.

THERMAL CONDUCTIVITY MEASUREMENTS OF NEPTUNIUM-ALUMINUM CERMET PELLETS WITH VARIOUS NEPTUNIUM LOADINGS (36050)

Presenting Author: Gretchen K. Toney, Oak Ridge National Laboratory (**toneygk@ornl.gov**)

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 NpO_2-Al cermet target used in the Plutonium-238 Supply Program contains 20 vol% NpO_2, 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 ^oC). At this loading of NpO_2, ~400 targets per year are required to produce enough ^{238}Pu 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 ^{238}Pu. The first parameter to consider when increasing the concentration of NpO_2 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 NpO_2 in the target, special pellets dedicated for thermal conductivity measurements were manufactured via the current production pellet preparation process with up to 35 vol% NpO_2 loading. The thermal conductivity of the higher NpO_2 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% NpO_2 aligned with previously measured data. Promising thermal conductivity values were obtained for 25, 30, and 35 vol% NpO_2. 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.

DEVICE PERFORMANCE AND CHARACTERISTICS OF SiGe AND SiMo MATERIALS SYNTHESIZED BY SPARK PLASMA SINTERING AT MULTIPLE LABORATORIES (35960)

Presenting Author: Rama Venkatasubramanian, Johns Hopkins University Applied Physics Laboratory (**rama.venkatasubramanian@jhuapl.edu**)

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 lifetime9v6a-cleidmasotnion 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 future0outer-planetary missions.

UPDATE ON HIGH STRAIN RATE TENSILE TESTS OF PT-RH ALLOYS FOR EUROPEAN RADIOISOTOPE POWER SYSTEM CLADS: PT-20%RH AND PT-10%RH (35904)

Presenting Author: Emily Jane Watkinson, University of Leicester (**ejw38@le.ac.uk**)

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 ~2000* s^{-1} *and temperatures of up to 500 °C have been investigated.*

EMPIRICAL ANALYSIS AND EXTRAPOLATION OF MMRTG F1 PERFORMANCE ON CURIOSITY: AN UPDATE (35914)

Presenting Author: Christofer E. Whiting, University of Dayton (**chris.whiting@udri.udayton.edu**)

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.*

AUTONOMOUS OPERATION CAPABILITIES FOR SPACE REACTORS (35639)

Presenting Author: Richard T. Wood, University of Tennessee (**rwood11@utk.edu**)

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.

PARAMETRIC EVALUATION OF ALTERNATIVE NUCLEAR PROPULSION CORES USING CURVED FUEL PLATES (35932)

Presenting Author: Abdalla Abou-Jaoude, Idaho National Laboratory (**abdalla.aboujaoude@inl.gov**)

Nuclear Thermal Propulsion (NTP) holds the potential of reducing travel times for deep space missions (e.g. to Mars). Previous reactor core designs considered by the Rover/NERVA program relied on highly enriched uranium (HEU) fuel contained within a hexagonal graphite matrix. An alternative layout is investigated in this paper. It consists of a circular assembly containing concentric curved plates of UN fuel. These fuel assemblies are placed within a beryllium block and reflector. Preliminary results indicate that many variations of this design are viable, with high power to mass ratio and outlet temperatures.

EUROPEAN RADIOISOTOPE POWER SYSTEMS PROGRAMME: RECENT UPDATES (35937)

Presenting Author: Richard M. Ambrosi, University of Leicester (**rma8@leicester.ac.uk**)

Radioisotope power systems have transformed our ability to explore the solar system for almost seven decades. Most missions have utilized ^{238}Pu as the radioisotope of choice to generate electrical power and to produce heat for the operation and thermal management of space craft systems. In Europe, for the past decade, ^{241}Am has been selected for radioisotope power system (RPS) research programs. This paper provides an update of how the European RPS technology solutions, in the form of radioisotope heater units (RHU) and radioisotope thermoelectric generators (RTG), are developing and evolving by providing a snapshot of some of the most recent results from the program.

A CONCEPT STUDY ON ADVANCED RADIOISOTOPE SOLID SOLUTIONS AND MIXED OXIDE FUEL FORMS FOR FUTURE SPACE NUCLEAR POWER SYSTEMS (35938)

Presenting Author: Richard M. Ambrosi, University of Leicester (**rma8@leicester.ac.uk**)

Radioisotope power systems have transformed our ability to explore the solar system. Radioisotope power systems (RPS) have been in existence for almost seven decades. Most missions have utilized ^{238}Pu as the radioisotope of choice to generate electrical power and to produce heat for the operation and thermal management of spacecraft systems. In Europe, for the past decade, ^{241}Am has been selected for radioisotope power system research programs. This paper hypothesizes that the inclusion of small quantities of relatively short-lived radioisotopes such as ^{232}U and ^{244}Cm, particularly when dealing with long-lived radioisotope ^{241}Am, could have implications for future RPS designs. This paper focuses on the thermal output implications and impact on system level design. The authors recognize that the selection of any new or modified radioisotope heat source material will require extensive research on fuel form stability, the radiological impact, cost of production, containment and launch safety considerations.

POLYMER IRRADIATION TESTING FOR NTP SYSTEMS (35976)

Presenting Author: Jarvis Caffrey, NASA Marshall Space Flight Center (**jarvis.a.caffrey@nasa.gov**)

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 106 and 108 rad, while neutron/gamma samples targeted 1016-1017 n/cm2 (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.

FISSION REACTOR INADVERTENT REENTRY (34964)

Presenting Author: Allen Camp, Quaking Aspen Pl NE (**acamp32@comcast.net**)

NASA's Nuclear Power and Propulsion Technical Discipline Team has directed an effort to consider possible improvements to the launch approval process as it relates to fission reactors, including issues related to reentry risk. This paper includes a discussion of the issues associated with different types of inadvertent reentry, the possible consequences of those events, a review of previous work in the area, security and nonproliferation issues, and options for safety requirements that might be considered, including mission implications.

HEAT PIPE DEVELOPMENT FOR SPACE FISSION DEMONSTRATION MISSIONS (35958)

Presenting Author: Max Chaiken, NASA Glenn Research Center (**max.f.chaiken@nasa.gov**)

NASA is currently formulating a flight mission that will demonstrate a 10 kWe nuclear electric fission power system for use on the lunar surface, with extensibility to Mars. While preliminary mission concepts leverage the successful Kilopower Reactor Using Stirling Technology ground prototype demonstration of a 1 kWe reactor, there are significant engineering challenges associated with adapting that prototype reactor for flight. One of these challenges is to modify the high temperature sodium heat pipes for use in space operation. Ongoing technical work at the NASA Glenn Research Center seeks to address several key areas of heat pipe development, focusing on fluid return under reduced or microgravity conditions and improved interfaces for both the reactor and the power conversion ends of the heat pipe.

CONSIDERATIONS FOR IMPLEMENTING PRESIDENTIAL MEMORANDUM-20 GUIDELINES FOR NUCLEAR SAFETY LAUNCH AUTHORIZATION FOR FUTURE CIVIL SPACE MISSIONS (34981)

Presenting Author: Yale Chang, The Johns Hopkins University Applied Physics Laboratory (**Yale.Chang@jhuapl.edu**)

National Security Presidential Memorandum-20 (NSPM-20) (Launch of Spacecraft Containing Space Nuclear Systems) dated 20 August 2019 provides updated guidelines for launch authorization for three categories of proposed launches of spacecraft with space nuclear systems: Federal Government civil space including NASA, Federal Government defense and intelligence, and commercial. These space nuclear systems provide power, heat, and/or propulsion to the spacecraft.
NSPM-20 states: "For United States launches of space nuclear systems, the Federal Government must ensure a rigorous, risk informed safety analysis and launch authorization process", primarily by examining the probabilities of potential launch and reentry accidents and their consequences. At the same time, for previous NASA missions, the launch approval process "has taken an average of six years and costs over $40 million". In an effort to streamline the process, and improve cost and schedule, NSPM-20 provides specific guidelines including the following: (1) "to the extent possible, safety analyses and reviews should incorporate previous mission and review experience" [e.g., Environmental Impact Statements (EISs), Records of Decision (RODs), Safety Analysis Reports (SARs), and Safety Evaluation Reports (SERs)], (2) "demonstrate that the mission is within the safety basis envelope established in the system-specific SAR, in which case it is not necessary to repeat the analysis supporting the system-specific SAR," and (3) "authorization for launches of spacecraft containing space nuclear systems shall follow a three-tiered process based on the characteristics of the system, the level of potential hazard, and national security considerations" (i.e., use risk-adjusted metrics for required level of effort and launch authorization authority).
A future example interplanetary mission (EIM) that plans to use a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is covered by NSPM-20, and is used here as a proxy to illustrate potential considerations for implementing NSPM-20 guidelines. Assume that this EIM plans to use one or two Earth Gravity Assist (EGA) maneuvers in its mission trajectory and that it will use launch vehicle (LV) stages with solid propellant. Its LV will definitely have a flight termination system (FTS).

This paper investigates each of these three NSPM-20 guidelines for three accident categories associated with the EIM: (1) EGA (aka Earth flyby or Earth swing-by) reentry, (2) solid propellant fires, and (3) FTS functions and probabilities. This paper also identifies the components needed to implement each guideline in a rigorous fashion, then assesses whether the necessary components (e.g., analyses, reports, tests, reviews, risk communications, previous launch approvals) currently exist or would need to be produced or modified.

Although these NSPM-20 guidelines could be logical and appropriate approaches for evaluating the risk associated with a system-of-systems (i.e., launch of nuclear systems) that has reached steady-state, the current state of affairs for the EIM is likely still in the "start-up transient" phase. For example, past EISs and SARs for each successive mission were constantly updated with new test data, new technology, new knowledge, and new understanding, such that previous risk results could change. Additionally, past SARs proactively considered review comments and findings from past SERs. Therefore, one potential future side effect of the proposed cost improvement approach is the stagnation of technological progress in nuclear safety analyses.

Because there are no cases of launch authorization of commercial launches of nuclear systems, and no previous unclassified detailed guidelines for launch authorization of defense or intelligence launches of nuclear systems, this paper refers to relevant NASA missions.

SUNPOWER ROBUST STIRLING CONVERTOR (SRSC) PHASE II OVERVIEW (36541)

Presenting Author: Josh Collins, AMETEK (Josh.Collins@ametek.com)

In July 2018, after successful completion of Phase I, NASA GRC awarded the Sunpower and Aerojet Rocketdyne team Phase II of a development contract under NASA's ROSES 2016 Announcement of Opportunity. The contract is in support of the Radioisotope Power Systems (RPS) office's goal of developing a robust, dynamic convertor that will enable potential future 200W – 500W RPS generators and flight missions. Sunpower's convertor– the Sunpower Robust Stirling Convertor (SRSC) – implements improvements in robustness over the heritage ASC-E3 design that were identified in the Phase I design. New project requirements for potential RPS missions have been added including high reject temperature operation, tolerance of unloaded operation, constant acceleration vibration environment, and high efficiency across a wide range of operating conditions while maintaining requirements for long life (20yrs). Based on a modular design to provide flexibility of output power and redundancy, the SRSC will enable a range of generators from 100W to 500W. This paper will focus on the accomplishments of the SRSC Phase II project including concept generator design and convertor fabrication, testing, and performance.

OPTIMIZATION OF PLUTONIUM-238 PRODUCTION IN THE ADVANCED TEST REACTOR (35948)

Presenting Author: Emory Colvin, Oregon State University (colvinem@oregonstate.edu)

Plutonium production for use in Radioisotope Thermoelectric Generators (RTGs) is necessary to augment a dwindling stockpile of available fuel. Plutonium-238 (^{238}Pu), the isotope of choice for this application, was initially a by-product of the weapons program and is currently in production directly at the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). With a national production goal of 1.5 kg $^{238}PuO_2$ per year, additional production capacity is needed. The Advanced Test Reactor (ATR) at Idaho National Laboratory (INL) is an attractive facility due to its high flux. This paper continues previous work exploring the suitability of several irradiation positions in the ATR for ^{238}Pu production.

INTERFACE AND SUBSURFACE CERAMIC BEHAVIOR IN MOLYBDENUM CERMETS FOR NUCLEAR THERMAL PROPULSION (35046)

Presenting Author: Taylor Duffin, University of Tennessee (tduffin2@vols.utk.edu)

Nuclear thermal propulsion has both high thrust and high specific impulse and is a leading technology for a crewed Mars mission. Molybdenum cermets are an alternative to tungsten cermets that can reduce core mass and add ductility. The Mo matrix appears robust in a MoYSZ cermet after testing in hydrogen at 2500 K with thermal cycling. The subsurface Mo-YSZ interface also appears strong despite indications of debonding at the surface. Striations that appear parallel on the surface in the YSZ fuel surrogate extend below the surface.

USING N,N-DIHEXYLHEXANAMIDE FOR PLUTONIUM-238 PURIFICATION (35956)

Presenting Author: Jarrod Gogolski, Colorado School of Mines (mjensen@mines.edu)

To meet the demand for heat sources to efficiently power radioisotope generators, plutonium-238 is being synthesized from neptunium-237. The two elements are then purified using tri-butyl phosphate (TBP). The quest for cleaner alternatives to TBP

suggests an alternate group of extractants, the N,N-dialkylamides. While there are many compounds within this group, this study focuses on N,N-dihexylhexanamide, which shows promise for a selective separation of ^{237}Np and ^{238}Pu.

STIRLING CONVERTOR EXTENDED TESTING IN SUPPORT OF DYNAMIC RPS MATURATION (35940)

Presenting Author: Daniel Goodell, NASA Glenn Research Center (**nicholas.a.schifer@nasa.gov**)

The Thermal Energy Conversion branch at the NASA Glenn Research Center (GRC) has been developing freepiston Stirling conversion technology for space electrical power for decades. Free-piston Stirling conversion technology is attractive for Radioisotope Power Systems (RPS) because it offers thermal-to-electric conversion efficiency of greater than 20 percent at the system level, which is three to four times greater than state-of-the-art thermoelectric conversion and greater end-of-life performance. Previous Stirling RPS development efforts include two flight projects; the 110 W Stirling Radioisotope Generator (SRG110) project and the Advanced Stirling Radioisotope Generator (ASRG) project. The reformulated Dynamic Radioisotope Power Systems (DRPS) project seeks to mature dynamic power conversion technology to flight readiness. Convertors currently operating at GRC represent two manufacturers and their unique convertor designs, each the result of the two flight projects. Under the SRG110 project from 2001 to 2006, the Infinia Corporation, now known as American Superconductor (AMSC), produced 16 Technology Demonstration Convertors (TDC) which utilize flexure bearings to enable wear-free operation. Under the ASRG project from 2007-2013, Sunpower Incorporated developed and delivered numerous prototypes and engineering models, which utilized gas bearings to enable wear-free operation. Continued extended operation of these highly valued assets at NASA GRC demonstrates long-life designs for future potential science and exploration missions.

ANTIMATTER-BASED PROPULSION FOR EXOPLANET EXPLORATION (35990)

Presenting Author: Gerald Jackson (**gjackson2@hbartech.com**)

Antimatter-based propulsion and onboard electrical power generation technologies are uniquely well suited for unmanned spacecraft sent to explore exoplanets and transmit back scientific observations. Congressional guidance calls for an interstellar coasting velocity of 10% of the speed of light (0.1c). In order to achieve such spacecraft velocities exhaust velocities commensurate with particle energies of at least 1 MeV/nucleon are required. The design of a propulsion system capable of such particle energies is presented. Early demonstration experiments are proposed.

ANTIMATTER-BASED SPACECRAFT POWER GENERATION (35991)

Presenting Author: Gerald Jackson (**gjackson2@hbartech.com**)

Antimatter-based propulsion and onboard electrical power generation technologies are uniquely well suited for unmanned spacecraft sent to explore exoplanets and transmit back scientific observations. For example, a mission to the habitable planet Proxima b will require 100 kW for data communication back to Earth, AI-level computing, and a LIDAR system capable of sensing Oort Cloud objects from both our solar system and the Centauri AB binary system. This paper describes a generator technology capable of on-demand electrical power generation within a mass budget of 1 kg. Early demonstration experiments are proposed.

NEUTRONIC ANALYSIS OF THE SUBMERSION-SUBCRITICAL SAFE SPACE (S4) REACTOR USING REDUCED ENRICHMENT URANIUM FUEL (35949)

Presenting Author: Takanori Kajihara, Texas A&M University (**kajihara@tamu.edu**)

There is a resurgent interest in using space reactors for various space missions. This work models the S^4 (submersion-subcritical safe space) reactor for deploying LEU fuel using Serpent 2. The S^4 reactor is a fast spectrum gas-cooled reactor that ensures subcriticality in case of accident scenarios where the reactor gets submerged in seawater. Increased pressure to curb highly enriched uranium fuel (HEU) in reactor designs has heightened interest in low enriched uranium (LEU). To accomplish this, the S4 reactor was scaled to multiple sizes: one at twice the diameter and three times the length, another at twice the diameter and length. For the original reactor size, 82 % enrichment possessed a k_{eff} of 1.017 after seven years of operation. For the S^4 reactor scaled to 2X the diameter and 3X the length, initial k_{eff} only attained 0.81 in the case of 20 % enrichment fuel. A 34 % ^{235}U concentration was estimated to be the lowest enrichment that allowed for criticality after seven years at a more feasible 2X scaling of this reactor design.

SHIELDING ANALYSIS FOR A MODERATED LOW-ENRICHED URANIUM FUELED KILOPOWER REACTOR (35992)

Presenting Author: Jeffrey King, Colorado School of Mines (**kingjc@mines.edu**)

A Low Enriched Uranium (LEU)-fueled space reactor could avoid the security and proliferation concerns inherent with Highly Enriched Uranium (HEU)-fueled space nuclear reactors. Recent LEU-fueled space reactor designs include a moderator to reduce the size and mass of the reactor core. This paper considers shadow shield options for an unmoderated HEU-fueled space reactor and a moderated LEU-fueled space reactor. Both reactors are kilowatt-class reactors, producing 15 kWth of thermal power over a 5-year operational lifetime. Based on the shielding required to meet established dose limits (a neutron fluence of less than 10^{14} n/cm^2 (>1 MeV equivalent in silicon) and a gamma ray dose of less the 1 Mrad in silicon), the moderated LEU-fueled space reactor will require a thicker shadow shield than the unmoderated HEU-fueled space reactor. The thinner reflector of the moderated LEU fueled reactor results in more neutrons reaching the shadow shield at higher energies compared to the unmoderated HEU-fueled reactor. The presence of a significant reflector in most space reactor designs means that the core spectrum is relatively unimportant in terms of shadow shield design, as the reflector thickness has a much stronger impact on the neutrons and gamma rays reaching the shadow shield.

OPERATIONAL CONSIDERATIONS FOR SPACE FISSION POWER AND PROPULSION PLATFORMS (35182)

Presenting Author: Andrew Klein, Oregon State University (**andrew.klein@oregonstate.edu**)

As consideration of launching reactors into space moves ahead, it is important to consider the issues related to the operation of various types of space nuclear power and propulsion reactors. This paper discusses some of these considerations, including possible human and equipment radiation exposures that might occur during different types of missions and the operational stages within those missions, managing the approach to and working around space reactors, maintaining reactors for long-duration operations, controlling reactors and monitoring their availability and health, evaluating possible reactor accident scenarios, planning for planetary protection due to their operation and post operation decommissioning and disposal.

PRELIMINARY TESTING OF COMMERCIALLY AVAILABLE SILICON GERMANIUM BASED THERMOELECTRIC MODULES (35079)

Presenting Author: Daniel Kramer, University of Dayton Research Institute (**daniel.kramer@udri.udayton.edu**)

Since the launch of Transit 4A in 1961 with the first space radioisotope thermoelectric generator (RTG), various thermoelectric materials have been employed in several generations of U.S. RTGs for converting the decay heat of plutonium-238 into electrical power. Silicon germanium (SiGe) based materials have been successfully utilized in Multi-Hundred Watt (MHW) and General Purpose Heat Source (GPHS) RTGs since the 1970s. SiGe thermoelectrics have a relatively high thermal to electrical conversion efficiency, and recently a manufacturer in Europe has initiated fabrication of SiGe modules for commercial waste heat recovery applications. UDRI obtained several of the SiGe modules and performed preliminary testing to characterize the performance of the modules. Experiments employed a dual cone calorimeter, and a high-temperature furnace. This research has helped to determine various operating parameters of the modules as a function of cold side (~10 - 40°C) and hot side temperatures up to 1025°C.

A FACILE POLYMERIC TEMPLATING ROUTE TOWARDS FABRICATING RTG AND RHU VENT HOLE FILTERS (35426)

Presenting Author: Ramy Mesalam, University of Leicester (**rm467@le.ac.uk**)

Filtered vent holes are typically included in radioisotope fuel clads to accommodate radiogenic outgassing and potential oxygen release. Historically, pressed and sintered metal powder in the form of a porous disc (frit) has been employed as a particulate filter to prevent contamination. However, their small size and thinness mean they can be non-trivial to manufacture with high reproducibility. Not to mention, variability in the characteristics of the starting powder will likely have a critical influence on the final properties of the frit. This paper describes a powder-free method for fabricating porous platinum discs that can potentially be integrated into radioisotope fuel clads. A European clad design incorporating these platinum discs is illustrated. Initial permeability testing of this design concept is reported and compared to a pressed and sintered metal powder frit design.

SIMULATION AND EXPERIMENTAL VALIDATION OF AN INDUCTIVELY HEATED SOLID-CORE NUCLEAR THERMAL ROCKET MODEL (35983)

Presenting Author: Micah Pratt, The Advanced Spacecraft Propulsion and Energy Laboratory (**Micahpra@usc.edu**)

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.*

MODERN TECHNIQUES FOR VISUALIZING RADIATION DATA IN NUCLEAR SPACE SCENARIOS (35394)

Presenting Author: Michael Smith, Oak Ridge National Laboratory (**smithmb@ornl.gov**)

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.

NUCLEAR THERMAL PROPULSION SUBSCALE EXPERIMENTAL TESTBED USING THE OHIO STATE UNIVERSITY RESEARCH REACTOR (35156)

Presenting Author: Tyler Steiner, University of Tennessee (**tsteine1@vols.utk.edu**)

Nuclear thermal propulsion (NTP) has demonstrated a technology readiness level of 5 during the work performed in the 1950s-1970s under the Rover program. This level of capability was achieved through the design, construction, and use of 22 experimental rocket reactors. These experiments served as testbeds for designs, materials, and instrumentation at prototypical NTP conditions. It is of the opinion of the author that there are three primary challenges pertaining to the NTP environment: temperature, neutron and gamma fluence, and hydrogen (propellant) flow. To continue the investigation into NTP system materials, components and fuels, a modern experimental testbed has been designed and implemented. Using the In-Pile Experiment Set Apparatus, developed by Oak Ridge National Laboratory, in conjunction with the Ohio State University Research Reactor, candidate subscale fuel samples have been tested under two of the three NTP prototypical environmental factors: temperature and fluence. The experiment is presented here.

ADVANCEMENTS IN LOW-TEMPERATURE, MID-TEMPERATURE AND HIGH-TEMPERATURE HEAT-TO-ELECTRIC CONVERSION DEVICES (35899)

Presenting Author: Rama Venkatasubramanian, The Johns Hopkins University Applied Physics Laboratory (**rama.venkatasubramanian@jhuapl.edu**)

Current single-stage heat-to-electric energy converters are at best 6 to 8% efficient. In order to develop a paradigm-changing 20 to 25% efficient converters, based on a 3-stage cascade design that utilizes optimum thermoelectric materials for each temperature range rather than a single material covering the full temperature range, it is important to develop advanced low-temperature, mid-temperature and hightemperature heat-to-electric conversion devices. In this paper, we discuss the development of heat-to-electric conversion devices using nano-engineered thin-film Bi_2Te_3-based devices for the low-temperature (~ 250oC), nano-engineered bulk PbTe-based devices for midtemperature (~500oC) and high-performance half

Heusler (HH) based devices for high-temperature (~800oC). We believe these developments will allow us to develop >20% cascade heat-to-electric converters which will lead to efficient RTGs and novel mission capabilities.

BIPOLAR COUPLE ASSEMBLED MODULE (BCAM) DESIGN FOR SCALABLE AND RUGGED ARCHITECTURE FOR TEG APPLICATIONS (35901)

Presenting Author: Rama Venkatasubramanian, The Johns Hopkins University Applied Physics Laboratory (**rama.venkatasubramanian@jhuapl.edu**)

While considerable research in thermoelectric materials, particularly in enhancing the figure of merit (ZT), is progressing in the US and in other countries, the focus in transitioning the ZT of the materials to p-n couple efficiency (in cooling or power generation) has been limited. The research and success in the scalability of device performance from p-n couples to modules is even more limited. In contrast, most of the DARPA funded R&D at JHU-APL has emphasized both materials research for ZT advancement and translating the materials progress to module results. We will describe our unique approach to this endeavor with our Bipolar Couple Assembled Module (BCAM) technology and describe the advantages of the BCAM architecture, based on thermo-mechanical modeling in stress reduction. This has enabled us to build and test scalable modules in a broad spectrum of materials from thin-film to bulk materials and also achieve robust data under extreme conditions of test. We believe the BCAM architecture is essential to scale-up and ruggedization and could lead to successful RTG designs in the future. The relevancy of the BCAM modeling to SiGe modules for RTG missions are discussed in some detail.

AMERICIUM-BASED OXIDE AND PT-RH ALLOYS COMPATIBILITY/INTERACTION TESTS IN THE CONTEXT OF EUROPEAN SPACE RADIOISOTOPE POWER SYSTEMS (35415)

Presenting Author: Emily Watkinson, University of Leicester (**ejw38@le.ac.uk**)

The European Space Agency is funding the development of European radioisotope power systems (RPSs) for space, namely, radioisotope heater units (RHUs), radioisotope thermoelectric generators (RTGs) and Stirling generators. The University of Leicester is leading the design and manufacture of the RHU, and of the heat source that will be common to the RTG and Stirling generator. All RPSs will incorporate Pt-Rh cladded americium based oxide fuel.
In this study, we present an interaction/compatibility test between an americium based oxide disc, namely, an Am-U oxide, and Pt-20%Rh and Pt-30%Rh alloy discs. The number of samples available was extremely limited, i.e., only a single 'fuel' disc was available. This had a direct influence on the procedure required for the test. We summarise the procedure for this study that is underway and the many challenges involved when working with a limited number of samples. Scanning electron microscopy coupled with energy dispersive spectroscopy is used to analyse the discs' surfaces. Initial results are presented. Temperatures relevant to RHU and RTG standard operation are targeted as well as extreme high temperatures. Tests are conducted in argon and air.

EMPIRICAL ANALYSIS OF THE MMRTG QUALIFICATION UNIT OPERATED AT A LOW THERMAL INVENTORY (35907)

Presenting Author: Christopher Whiting, University of Dayton (**chris.whiting@udri.udayton.edu**)

Performance predictions for the MMRTG were recently reported for the first flight unit and the Engineering Unit. Both units were produced and operated/tested within specifications. In an attempt to study the effect of a mid-life, deep space cruise on the MMRTG, the Qualification Unit (QU) was placed on life test with a below-specification thermal inventory of 1904 Wth. Analysis indicates that loading an MMRTG with a lower thermal inventory may result in less power at the beginning-of-life, but more power at the end-of-designlife (EODL). The lower thermal inventory in the QU produces a lower operating temperature, which appears to cause a significant reduction in the degradation rate of the thermoelectric couples. Preliminary calculations indicate that a thermal inventory of 1904 Wth could result in a 9 We power boost at EODL (i.e. 84 We), which is a 12% improvement over F1/EU predictions. Preliminary degradation analysis suggests that a 1904 Wth unit will begin to produce more power than a 2027 Wth unit approximately 4 years after fueling. This suggests that missions with a primary power requirement more than 4 years after fueling would benefit from a lower thermal inventory. In addition, using a lower thermal inventory has significant benefits for 238Pu stockpile management, and may allow for additional MMRTGs to be fueled from our current reserves. Conclusions and hypotheses presented here should be considered preliminary because the QU data set is very small, and there are some uncertainties regarding how early life QU data will translate into later life performance. More QU testing at a thermal inventory of 1904 Wth is needed to prove that the preliminary conclusions presented here are valid.

CONVERTOR DEVELOPMENT FOR DYNAMIC RADIOISOTOPE POWER SYSTEMS (35896)

Presenting Author: Scott Wilson, NASA Glenn Research Center (Scott.D.Wilson@nasa.gov)

Dynamic power conversion technologies are being developed for future space science and exploration missions by NASA's Radioisotope Power Systems (RPS) Program, in collaboration with the U.S. Department of Energy (DOE). The Dynamic Radioisotope Power Systems (DRPS) Project is working to mature dynamic power convertors and controllers for infusion into potential future flight generators. Maturation of power conversion technologies is being executed by the DRPS Project and the Thermal Energy Conversion Branch, located at NASA's Glenn Research Center (GRC), and includes convertor technology development contracts and in-house controller development. Three convertor technology development contractor teams are tasked to design and fabricate prototypes, and complete performance testing before the units are delivered to GRC for independent assessment. All contractors have completed convertor designs and are fabricating convertors to enable performance testing, while one has demonstrated initial performance of their design. The contractors also have provided generator conceptual designs, which utilize their respective convertor technologies being developed.