# NETS - 2017

## Nuclear and Emerging Technologies for Space

*ANS Aerospace Nuclear Science and Technology Division*

*Full proceedings on jump drive/memory stick*



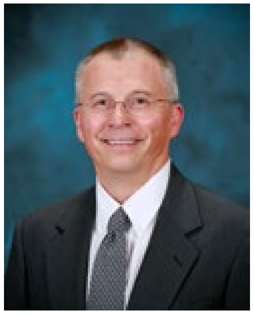
## About the Meeting

In February 2017, The Aerospace Nuclear Science and Technology Division (ANSTD) of the American Nuclear Society (ANS) will hold the 2017 Nuclear and Emerging Technologies for Space (NETS 2017) topical meeting at the Orlando Airport Marriott Lakeside hotel in Orlando, FL. NETS 2017 is the premier conference for landed and in-space applications in 2017.

With authors from universities, national laboratories, NASA facilities and industry, NETS 2017 will provide an excellent communication network and forum for information exchange.

## Topic Areas

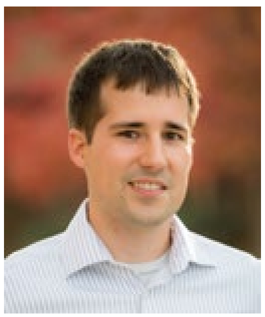
NASA is currently considering capabilities for robotic and crewed missions to the Moon, Mars, and beyond. Strategies that implement advanced power and propulsion technologies, as well as radiation protection, will be important to accomplishing these missions in the future. NETS serves as a major communications network and forum for professionals and students working in the area of space nuclear research and management personnel from international government, industry, academia, and national laboratory systems. To this end, the NETS 2017 meeting will address topics ranging from overviews of current programs to methods of meeting the challenges of future endeavors.



**David DePoali, PhD**
*General Chair*
*Oak Ridge National Laboratory*

**Robert Wham, PhD**
*Honorary Chair*
*Oak Ridge National Laboratory*

**Sedat Goluoglu, PhD**
*Finance Chair*
*University of Florida*



**Jeff Katalenich, PhD**
*Technical Co-Chair*
*Pacific Northwest National Laboratory*

**Jorge Navarro, PhD**
*Technical Co-Chair*
*Idaho National Laboratory*

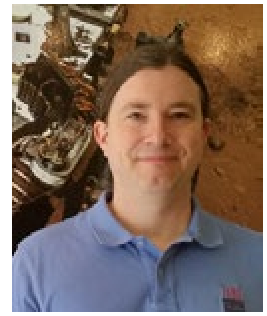
**Patrick Moo**
*Logistics Co-Chair/*
*Website Chair*
*University of Florida*

**Katherin Goluoglu**
*Logistics Co-Chair*
*Nuclear Safety Associates*





**John Bess, PhD**
*Track I Chair*
*Idaho National Laboratory*



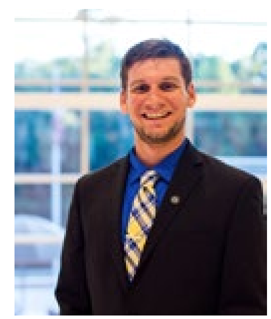
**Christofer Whiting, PhD**
*Track II Chair*
*University of Daytona Research Institute*

**Stephen Johnson, PhD**
*Track III Chair*
*Idaho National Laboratory*

**Margaret Marshall**
*Publications Co-Chair*
*Idaho National Laboratory*

**Nathan Jerred**
*Publications Co-Chair*
Center for Space Nuclear Research, USRA

**Delisa Rogers**
*Sponsorship Chair*
Center for Space Nuclear Research, USRA



**Zander Mausloff**
*Student Program Chair*
University of Florida

## Track I: Energy Conversion and Power Systems

**Technical Chair: John Bess,** Idaho National Laboratory

| | |
|---|---|
| Jeffrey King | Colorado School of Mines |
| Mike Houts | NASA Marshall Space Flight Center |
| Tim Tinsley | National Nuclear Laboratory |
| Keith Stephenson | European Space Agency |
| Pat McClure | Los Alamos National Laboratory |
| Lee Mason | NASA Glenn Research Center |
| Mark Sarsfield | National Nuclear Laboratory |
| John Scott | NASA Johnson Space Center |

## Track II: Fuels and Material

**Technical Chair: Christofer Whiting,** University of Dayton Research Institute

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|---|---|
| Robert Hickman | NASA Marshall Space Flight Center |
| Sabah Bux | Jet Propulsion Laboratory/California Institute of Technology |
| Jackie Lopez-Barlow | Los Alamos National Laboratory |
| Rob O'Brien | Idaho National Laboratory |
| Emily Jane Watkinson | University of Leicester |

## Track III: Missions and Infrastructure

**Technical Chair: Stephen Johnson,** Idaho National Laboratory

| | |
|---|---|
| Young Lee | Jet Propulsion Laboratory/California Insitiute of Technology |
| Richard Ambrosi | University of Leicester |
| Dave Woerner | Jet Propulsion Laboratory/California Institute of Technology |
| Dirks Cairns-Gallimore | Department of Energy NE |
| Tom Sutliff | NASA - Glenn Research Center |
| Kelly Lively | Idaho National Laboratory |





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Additional information about Aerojet Rocketdyne and GenCorp can be obtained by visiting the companies' websites at www.Rocket.com and www.GenCorp.com.

The UK's National Nuclear Laboratory (NNL) offers a unrivaled breadth of technical products and services to our customers across the whole nuclear industry. Covering the complete nuclear fuel cycle from fuel manufacture and power generation, through reprocessing, waste treatment and disposal including defense, new nuclear builds and Homeland Security. NNL provides these services supported by academia and other national laboratories. NNL's facilities are second to none. The Central Laboratory at Sellafield is the most modern nuclear research facility in the world. The Windscale Laboratory provides Post-Irradiation Examination (PIE) and other services critical to plant life extension. At Workington, NNL operates a non-radioactive test rig facility and at Preston NNL operates a uranium active chemistry laboratory. NNL also has staff at the Risley, Stonehouse and Harwell sites providing Head Office functions, graphite technology, radiation chemistry and modeling/simulation.

## Monday February 27, 2017

| | | |
|---|---|---|
| 7:00am - 8:15am | Registration | Registration Desk |
| 8:15am - 10:00am | **Plenary Session I** | Amelia/Sanibel Ballroom |
| | **Welcome and Announcements:**<br>**David DePaoli**<br>**Introduction: Robert Wham**<br>• Tracey Bishop, US Department of Energy<br>• Ralph McNutt, Johns Hopkins University/Applied Physics Laboratory | |
| 10:00am - 10:20am | Break | Amelia/Sanibel Ballroom |
| 10:20am - 12:20pm | **Technical Sessions** | Captiva A, B, and C |
| 12:30pm - 1:30pm | Lunch | On your own |
| 1:30pm - 3:10pm | **Panel I:**<br>**Beyond the Decadal Study:**<br>**Horizons for Nuclear-Powered Space Exploration**<br>• Mike Houts, NASA Marshall Space Flight Center<br>• Ralph McNutt, Johns Hopkins University/Applied Physics Laboratory<br>• Dave Woerner, Jet Propulsion Laboratory/California Institute of Technology<br>• Lee Mason, NASA Glenn Research Center<br>Moderators:<br>Jeff Katalenich, Pacific Northwest National Laboratory<br>Jorge Navarro, Idaho National Laboratory | Amelia/Sanibel Ballroom |
| 3:10pm - 3:30pm | Break | |
| 3:30pm - 5:30pm | Technical Sessions | Captiva A, B, and C |
| 7:00pm - 9:00pm | **Opening Reception**<br>Keynote Speaker: Tim Tinsley,<br>National Nuclear Laboratory | Capri Ballroom |



## Tuesday February 28, 2017

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|---|---|---|
| 7:00am - 8:00am | Registration | Registration Desk |
| 8:00am - 8:50am | **Plenary Session II** | Amelia/Sanibel Ballroom |
| | **Welcome: David DePaoli**<br>**Announcements: Robert Wham**<br>• Charles Whetsel, Jet Propulsion Laboratory/California Institute of Technology | |
| 8:50am - 9:00am | Break | Amelia/Sanibel Ballroom |
| 9:00am - 10:20pm | **Technical Sessions** | Captiva A, B, and C |
| 10:20am - 10:40am | Break | |
| 10:40am - 12:00pm | **Technical Sessions** | Captiva A, B, and C |
| 12:00pm - 1:30pm | Lunch | On your own |
| 1:30pm - 3:10pm | **Panel II:**<br>**Future Applications of Small Spacecraft for Exploration Missions**<br>• Brad King, Michigan Technological University<br>• Andrew Klesh, Jet Proplusion Laboratory/California Institute of Technology<br>• Terry Hendricks, Jet Propulsion Laboratory/California Institute of Technology<br>Moderators:<br>Jeff Katalenich, Pacific Northwest National Laboratory<br>Jorge Navarro, Idaho National Laboratory | Amelia/Sanibel Ballroom |
| 3:10pm - 3:30pm | Break | |
| 3:30pm - 5:30pm | **Technical Sessions** | Captiva A, B, and C |

| Wednesday March 1,2017 | | |
|---|---|---|
| 7:00am - 8:00am | **Registration** | Registration Desk |
| 8:00am - 8:50am | **Plenary Session III** | Amelia/Sanibel Ballroom |
| | **Welcome: David DePaoli**<br>**Announcements: Robert Wham**<br>• Keith Stephenson, European Space Agency | |
| 8:50am - 9:00pm | Break | Amelia/Sanibel Ballroom |
| 9:00am - 10:20pm | **Technical Sessions** | Captiva A, B, and C |
| 10:20am - 10:40am | **Break** | Amelia/Sanibel Ballroom |
| 10:40am - 12:00pm | **Technical Sessions** | Captiva A, B, and C |
| 12:00pm - 1:30pm | Lunch | On your own |
| 1:30pm - 3:10pm | **Panel III:**<br>**Radioisotope Power System Challenges**<br>• Robert Wham, Oak Ridge National Laboratory<br>• Stephen Johnson, Idaho National Laboratory<br>• Jackie Lopez-Barlow, Los Alamos National Laboratory<br>• Jean-Pierre Fleurial, Jet Propulsion Laboratory/California Institute of Technology<br>Moderators:<br>Jeff Katalenich, Pacific Northwest National Laboratory<br>Jorge Navarro, Idaho National Laboratory | Amelia/Sanibel Ballroom |
| 3:10pm - 3:30pm | Break | |
| 3:30pm - 5:00pm | **Technical Sessions** | Captiva A, B, and C |
| 7:00pm - 9:00pm | **Closing Banquet**<br>**Introduction: Russ Joyner,**<br>Aerojet Rocketdyne<br>**Keynote Speaker: Chuck Tatro,**<br>NASA Kennedy Space Center | Capri Ballroom |





| Thursday March 2, 2017 - Tour of NASA Kennedy Space Center | |
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| 7:30am - 8:00am | Load bus at Marriott |
| 8:00am - 8:50am | Travel from Marriott to KSC Visitors Center (car or shuttle provided) |
| 9:00am - 9:20am | Depart from KSC Visitor Complex for drive to CCAFS (KSC tour bus) |
| 9:20am - 9:35pm | CCAFS, Mercury 7 Memorial-CCAFS |
| 9:45am - 10:30am | Drive Beach Road passing Delta-IV, SpaceX, Atlas-V, and Complex 39A launch pads to LC-39Ara/VAB |
| 10:45am - 11:30am | Vehicle Assembly Building - ground level Xfter Aisle walk through |
| 11:40am - 12:30am | Banana Creek Apollo/Saturn V viewing |
| 12:40am - 1:00pm | Return to KSC Visitor Center |
| 1:00pm -2:50pm | Visitors explore Rocket Garden, shuttle Atlantis, Heroes & Legends exhibit, etc. |
| 3:00pm - 3:30pm | Load bus at KSC Visitors Center |
| 3:30pm - 4:30pm | Travel from KSC Visitors Center to Marriott (car or shuttle provided) |

## Monday February 27, 2017

**Track I: Energy Conversion and Power Systems**
Next Generation Energy Conversion in Space

captiva A

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| 10:20 am | 20181 | **The NASA Radioisotope Power Systems Program — An Overview and Plans for the Future,** *J. Hamley (NASA Glenn Research Center), P. McCallum (NASA Glenn Research Center), C. Sandifer II (NASA Glenn Research Center), T. Sutliff (NASA Glenn Research Center), J. Zakrajsek (NASA Glenn Research Center)* |
| 10:40 am | 20187 | **Radioisotope Thermoelectric Generators and Heater Units for the European Space Nuclear Power Programme,** *R. Ambrosi (University of Leicester), H. Williams (University of Leicester), E. J. Watkinson (University of Leicester), A. Barco (University of Leicester), R. Mesalam (University of Leicester), M. Reece (Queen Mary University of London), K. Chen (Queen Mary University of London), K. Simpson (European Thermodynamics Ltd.), M. Robbins (European Thermodynamics Ltd.), R. Tuley (European Thermodynamics Ltd), C. Burgess (Airbus Defence and Space), M-C. Perkinson (Airbus Defence and Space), A. Walton (Airbus Defence and Space), C. Stroud (Lockheed Martin UK), A. Godfrey (Lockheed Martin UK), S. Gibson (Lockheed Martin UK), K. Stephenson (European Space Agency), T. Crawford (University of Leicester), C. Bicknell (University of Leicester), J. Sykes (University of Leicester), M. Sarsfield (National Nuclear Laboratory), T. Tinsley (National Nuclear Laboratory)* |
| 11:00 am | 20194 | **10We Radioisotope Thermophotovoltaic (RTPV) Power Source Demonstration,** *J. Khatry (Center for Space Nuclear Research, University of Idaho), J. Nieminen (Center for Space Nuclear Research, University of Southern California), J. Smith (Center for Space Nuclear Research, University of Tennessee), K. Slotten (Center for Space Nuclear Research, Embry-Riddle Aeronautical University)* |
| 11:20 am | 21147 | **Turbo-Brayton Power Converter for Spaceflight Applications,** *J. Breedlove (Creare LLC), T. Conboy (Creare LLC), M. Zagarola (Creare LLC)* |





## Monday February 27, 2017

**Track III: Missions and Infrastructure**
Nuclear-Enabled Space Science and Mission Concepts

Captiva C

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| 10:20 am | 19763 | **A New Manned Space Flight Mission for NASA,** *P. Fisher (Ruffner Associates, LTD.)* |
| 10:40 am | 20177 | **Optimal Nuclear Thermal Propulsion Thrust Level for Human Mars Exploration,** *C. Joyner II (Aerojet Rocketdyne), T. Kokan (Aerojet Rocketdyne), D. Levack (Aerojet Rocketdyne), J. Crowley (Aerojet Rocketdyne), F. Widman (Aerojet Rocketdyne)* |
| 11:00 am | 20510 | **Feasibility Study for a Pluto Orbiter Mission,** *J. Elliott (Jet Propulsion Laboratory/California Institute of Technology), N. Arora (Jet Propulsion Laboratory/California Institute of Technology)* |
| 11:20 am | 20540 | **RPS-Enabled Micro/CubeSat Mission Opportunities Supporting Planetary Science Objectives,** *R. Cataldo (NASA Glenn Research Center)* |
| 11:40 am | 20543 | **Radioisotope Power Systems for Outer Planet SmallSats - Enceladus Express Mission Concept,** *B. Bairstow (Jet Propulsion Laboratory/California Institute of Technology), Y. Lee (Jet Propulsion Laboratory/California Institute of Technology), J. Riedel (Jet Propulsion Laboratory/California Institute of Technology), T. Spilker (Jet Propulsion Laboratory/California Institute of Technology), S. Oleson (NASA Glenn Research Center)* |
| 12:00 pm | 20544 | **Alternate Tactical Power Generation for Small Spacecraft,** *D. Meier (Pacific Northwest National Laboratory), J. Katalenich (Pacific Northwest National Laboratory)* |

**Monday February 27, 2017**

**Track II: Fuel and Materials**
Uranium Fuels for Spaceflight Application

Captiva B

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| 10:40 am | 21281 | **Multiscale NTP Fuel Element Materials Simulation,** *R. Hickman (NASA Marshall Space Flight Center), M. Barnes (NASA Marshall Space Flight Center), M. Tonks (Pennsylvania State University)* |
| 11:00 am | 20547 | **Survey of Fuel System Options for Low Enriched Uranium (LEU) Nuclear Thermal Propulsion Systems,** *K. Benensky (University of Tennessee), P. Venneri (Korea Advanced Institute of Science & Technology), M. Eades (The Ohio State University)* |
| 11:20 am | 20164 | **Nuclear Rocket CERMET Fuel Fabrication using Tungsten Powder Coating and Spark Plasma Sintering,** *M. Barnes (NASA Marshall Space Flight Center), D. Tucker (NASA Marshall Space Flight Center), L. Hone (Center for Space Nuclear Research), S. Cook (Center for Space Nuclear Research)* |
| 11:40 am | 20573 | **Testing of NERVA-derived Composite Surrogate Fuel Element in NTREES,** *L. Qualls (Oak Ridge National Laboratory)* |



NETS 2017 Program Details

**Monday February 27, 2017**

**Track I: Energy Conversion and Power Systems**
Nuclear Thermal Propulsion

Captiva A

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| 3:30 pm | 20482 | **Simulation Model and Control System Requirements for the Nuclear Thermal Propulsion System, (***A. Hasse University of Tennessee),M. Smith (University of Tennessee), B. Pershke (University of Tennessee), N. Gilliam (University of Tennessee), A. Adams (University of Tennessee), L. Qualls (Oak Ridge National Laboratory), L. Miller (University of Tennessee)* |
| 3:50 pm | 20588 | **Enhanced Control Drums for NTP Submersion Criticality Safety,** *P. Venneri (Korea Advanced Institute of Science & Technology), M. Eades (The Ohio State University), Y. Kim (Korea Advanced Institute of Science & Technology)* |
| 4:10 pm | 21141 | **Conceptual Design of Light-Weight Small Core With Fast Spectrum for Nuclear Propulsion Rocket,** *Y. Sato (Tokyo City University), H. Takezawa (Tokyo City University), N. Takaki (Tokyo City University)* |
| 4:30 pm | 20048 | **Nuclear and Thermal Hydraulic Design for a Low-Enriched Nuclear Thermal Rocket,** *S. Cope (North Carolina State University), J. Cambareri (North Carolina State University), N. Sorrell (North Carolina State University), J. Doster (North Carolina State University)* |
| 4:50 pm | 20585 | **Initial Investigation of In-Element Power Peaking in LEU Cermet NTP Fuel Elements,** *M. Eades (Ultra Safe Nuclear Corporation), P. Venneri (Ultra Safe Nuclear Corporation)* |

**Monday February 27, 2017**

**Track II: Fuels and Materials**
Novel Thermoelectric Materials Development

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| 3:30 pm | 20550 | **High Temperature Oxide Thermoelectric Materials for RTGs,** *D. Tucker (NASA Marshall Space Flight Center), A. O'Connor (Purdue University), C. Hill (NASA Marshall Space Flight Center), C. Romnes (University of New Mexico)* | Captiva B |
| 3:50 pm | 20505 | **Graphene Superlattice Heterostructures Based Thermoelement for Radioisotope Thermoelectric Generator,** *K. Mishra (Homi Bhabha National Institute), J. Diwan (Homi Bhabha National Institute), C. Kaushik (Homi Bhabha National Institute), B. Dikshit (Homi Bhabha National Institute), A. Kumar (Homi Bhabha National Institute)* | Captiva B |
| 4:10 pm | 20542 | **Development of Earth Abundant Complex Zintl Phases: Alternates to Skutterudites,** *S. Bux (Jet Propulsion Laboratory/California Institute of Technology), S. Ohno (Northwestern University), S. Chankian (Jet Propulsion Laboratory/California Institute of Technology), K. Lee (Jet Propulsion Laboratory/California Institute of Technology), M. Wood (Northwestern University), Y. Hu (University of California), H. Musunuri (Jet Propulsion Laboratory/California Institute of Technology), U. Aydemir (Northwestern University), D. Uhl (Jet Propulsion Laboratory/California Institute of Technology), B. Li (Jet Propulsion Laboratory/California Institute of Technology), J. Snyder (Northwestern University), S. Kauzlarich (University of California), J.-P. Fleurial (Jet Propulsion Laboratory/California Institute of Technology)* | Captiva B |
| 4:30 pm | 20419 | **Segmented Thermoelectric Devices for a High-Performance Modular System Concept Upgrade to the GPHS-RTG,** *J-P. Fleurial (Jet Propulsion Laboratory), S. Firdosy (Jet Propulsion Laboratory/California Institute of Technology), B. Lin (Jet Propulsion Laboratory/California Institute of Technology), K. Smith (Jet Propulsion Laboratory/California Institute of Technology), O. Villalpando (Jet Propulsion Laboratory/California Institute of Technology), G. Nakatsukasa (Jet Propulsion Laboratory/California Institute of Technology), J. Ni (Jet Propulsion Laboratory/California Institute of Technology), K. Star (Jet Propulsion Laboratory/California Institute of Technology), F. Drymiotis (Jet Propulsion Laboratory/California Institute of Technology), V. Ravi (Jet Propulsion Laboratory, California State Polytechnic University)* | Captiva B |





**Monday February 27, 2017**

**Track II: Fuels and Materials**
Novel Thermoelectric Materials Development

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| 4:50 pm | 20463 | **Improved Composite Assisted Funneling of Electrons in Nickel Composited La3-xTe4 via Particle Size Reduction,** *D. Cheikh (University of California Los Angeles), S. Bux (Jet Propulsion Laboratory/California Institute of Technology), J. Ma (Teledyne Energy Systems Inc.), P. Allmen (Jet Propulsion Laboratory/California Institute of Technology), T. Vo (Jet Propulsion Laboratory/California Institute of Technology), J-P. Fleurial (Jet Propulsion Laboratory/California Institute of Technology), B. Dunn (University of California Los Angeles)* | Captiva B |

**Monday February 27, 2017**

**Track III: Misisons and Infrastructure**
Nuclear-Enabled Space Science and Mission Concepts

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|---|---|---|---|
| 3:30 pm | 20591 | **ELMOE: Europa Lander, Melter, and Oceanic Explorer,** *L. Beveridge (Idaho State University), W. MacCalla (Embry-Riddle Aeronautical University), H. Moore (Texas A&M University), R. Raju (University of Michigan), J. Scherr (Texas A&M University)* | Captiva C |
| 3:50 pm | 21106 | **An RTG-Powered New Frontiers Titan Lander Concept,** *R. Lorenz (Johns Hopkins University Applied Physics Laboratory)* | Captiva C |

**Monday February 27, 2017**

**Track III: Misisons and Infrastructure**
Project and Mission Architectures

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| 4:10 pm | 20118 | **Development and Utilization of Space Fission Power and Propulsion Systems,** *M. Houts (NASA MSFC), S. Mitchell (NASA MSFC), K. Aschenbrenner (NASA MSFC), A. Kelley (NASA MSFC)* | Captiva C |
| 4:30 pm | 20484 | **Updated Mars Mission Architectures Featuring Nuclear Thermal Propulsion,** *M. Rodriguez (Jacobs ESSSA Group), T. Percy (Jacobs ESSSA Group)* | Captiva C |
| 4:50 pm | 20599 | **A Cost-Analysis of LEU-NTP for Crewed Mars Missions,** *S. Rawlins (Korea Advanced Institute of Science and Technology), P. Venneri (Korea Advanced Institute of Science and Technology), Y. Kim (Korea Institute of Advanced Technology)* | Captiva C |

NETS 2017 Program Details

**Tuesday February 28, 2017**

**Track I: Energy Conversion and Power Systems**
Shielding and Nuclear Electric Propulsion

Captiva A

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| 9:00 am | 20458 | **Criticality Safety Design and Analysis of the Heat-Pipe Nuclear Reactor,** *W. Sanbig (Chinese Academy of Engineering Physics), X. Qilin (Chinese Academy of Engineering Physics), G. Simao,(Chinese Academy of Engineering Physics), H. Chaohui (Xian Jiaotang University)* |
| 9:20 am | 20574 | **Autonomy for Space Reactor Power Systems,** *D. Sikorski (University of Tennessee), R. Wood (University of Tennessee)* |
| 9:40 am | 20537 | **Optimization of Radiation Shielding for Space Nuclear Propulsion,** *J. Caffrey (Oregon State University)* |
| 10:00 am | 20186 | **Study of Small CANDLE Burnup Reactor for Space Nuclear Power,** *J. Nishiyama (Tokyo Institute of Technology), T. Obara (Tokyo Institute of Technology)* |

**Tuesday February 28, 2017**

**Track III: Missions and Infrastructure**
Flight Systems Mission Performance

Captiva C

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|---|---|---|
| 9:00 am | 20149 | **Enhanced Lifetime Performance Predictions in Radioisotope Thermoelectric Generators (RTGs) Using Integrated SINDA/ DEGRA Modeling Tool,** *T. Hendricks (Jet Propulsion Laboratory/California Institute of Technology), E. Wood (Jet Propulsion Laboratory/California Institute of Technology), D. Hanks (Jet Propulsion Laboratory/California Institute of Technology)* |
| 9:20 am | 20183 | **Cassini Power Subsystem,** *J. Grandidier (Jet Propulsion Laboratory), J. Gilbert (Jet Propulsion Laboratory), G. Carr (Jet Propulsion Laboratory)* |
| 9:40 am | 20575 | **TERRA Project: a Brazilian View for Nuclear Energy Application to Space Exploration,** *L. Guimaraes (Institute for Advanced Studies - IEAv, UNIP), G. Ribeiro (Institute for Advanced Studies - IEAv, UNIP), J. Nascimento (Retired from Institute for Advanced Studies - IEAv, UNIP), E. Araujo (Institute for Advanced Studies - IEAv, UNIP), F. Filho (Institute for Advanced Studies - IEAv, UNIP), A. Dias (Institute for Advanced Studies - IEAv, UNIP), V. Laite (Intitute for Advanced Energy Studies - IEAv, UNIP)* |



**Tuesday February 28, 2017**

**Track II: Fuels and Materials**
Heat Source Fuel Properties and Development

Captiva B

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|---|---|---|
| 9:00 am | 20106 | **The Preparation of 241Am Oxide Pellets Under Oxidizing and Reducing Atmospheres,** *J. Colle (European Commission, Joint Research Centre), D. Freis (European Commission, Joint Research Centre), P. Lajarge (European Commission, Joint Research Centre), D. Manara (European Commission, Joint Research Centre), M. Naji (European Commission, Joint Research Centre), M. Sarsfield (National Nuclear Laboratory), J. Somers (European Commission, Joint Research Centre), K. Stephenson (European Space Agency), T. Tinsley (National Nuclear Laboratory), J. Vigier (European Commission, Joint Research Centre)* |
| 9:20 am | 20203 | **Particle Size and Characterization of Fuel for 238PuO2 Heat Source Fabrication,** *R. Mulford (Los Alamos National Laboratory)* |
| 9:40 am | 20191 | **X-ray Diffraction Studies on Surrogates for Americium Oxides for European Radioisotope Power Systems,** *E.J. Watkinson (University of Leicester), R. Ambrosi (University of Leicester), D. Chateigner (Normandie Université), H. Williams (University of Leicester), C. Haidon (University of Leicester), G. Hansford (University of Leicester), D. Weston (University of Leicester), M. Sarsfield (National Nuclear Laboratory), M. Reece (Queen Mary University of London), D. Kramer (University of Dayton Research Institute), K. Stephenson (European Space Agency)* |
| 10:00 am | 20196 | **Fuel Behavior in Aging 238PuO2 Heat Sources,** *R. Mulford (Los Alamos National Laboratory)* |

## Tuesday February 28, 2017

**Track I: Energy Conversion and Power Systems**
Stirling Development and Testing

Captiva A

| | | |
|---|---|---|
| 10:40 am | 20569 | **Dynamic Power Convertor Development for Radioisotope Power Systems at NASA Glenn Research Center,** *S. Oriti (NASA Glenn Research Center)* |
| 11:00 am | 20195 | **A Risk-Informed Life Testing Framework for Uncertainty Characterization and Life Estimation,** *O. Ndu (Johns Hopkins University, University of Maryland), C. Smith (Johns Hopkins University)* |

## Tuesday February 28, 2017

**Track II: Fuels and Materials**
Reactor Support

Captiva B

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|---|---|---|
| 10:40 am | 21137 | **Status Update of the Department of Energy's Transient Test Program and its Capabilities for Space Power and Propulsion Reactor Fuels Testing,** *R. O'Brien (Idaho National Laboratory), D. Wachs (Idaho National Laboratory)* |
| 11:00 am | 21145 | **Preliminary Conceptual Neutronic, Thermal and Mechanical Design for 238Pu Advanced Test Reactor (ATR) Targets,** *J. Navarro (Idaho National Laboratory), C. Biebel (Idaho National Laboratory), P. Murray (Idaho National Laboratory), B. Hawkes (Idaho National Laboratory), C. Dwight (Idaho National Laboratory)* |
| 11:20 pm | 20595 | **Description of a Novel Target for the Production of Pu238 in Commercial Nuclear Reactors,** *B. Reid (Pacific Northwest National Laboratory), A. Prichard (Pacific Northwest National Laboratory), R. Gates (Pacific Northwest National Laboratory)* |
| 11:40 pm | 21148 | **Using CANDU Reactors for Pu-238 Production for Space Exploration,** *G. Elliott (Canadian Nuclear Partners), C. Lorencez (Ontario Power Generation)* |





## Tuesday February 28, 2017

**Track III: Missions and Infrastructure**
Space Nuclear Policy and Regulation

Captiva C

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|---|---|---|
| 10:40 am | 20059 | **Safety Analysis for the Kilowatt Reactor Using Stirling Technology (KRUSTY) Test,** *P. McClure (Los Alamos National Laboratory), L. Restrepo (Nuclear Solutions US), R. Miller (Nuclear Solutions US), J. Strelow (Los Alamos National Laboratory)* |
| 11:00 am | 20100 | **The Aerospace Nuclear Science & Technology Division of the American Nuclear Society,** *J. Bess (Idaho National Laboratory), J. King (Colorado School of Mines), W. Saylor (United States Air Force Academy), M. Briggs (NASA Glenn Research Center)* |
| 11:20 am | 20160 | **A Nuclear Engineering Board Game for Education and Outreach,** *K. Schillo (University of Alabama in Huntsville), A. Kumar (Center for Space Nuclear Research)* |

## Tuesday February 28, 2017

**Track III: Missions and Infrastructure**
Space Power Programs

Captiva C

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|---|---|---|
| 3:30 pm | 20099 | **The Paucity Problem: Where Have All the Space Reactor Experiments Gone?,** *J. Bess (Idaho National Laboratory), M. Marshall (Idaho National Laboratory)* |
| 3:50 pm | 20152 | **A 40kWe Nuclear Reactor Power System Concept for Mars Base,** *G. Hun (China Institute of Atomic Energy), C. Yao (China Institute of Atomic Energy), J. Xie (China Institute of Atomic Energy), C. Xu (China Institute of Nuclear Information and Economy)* |
| 4:10 pm | 20213 | **The Pulsed Fission-Fusion (PuFF) Propulsion System – Overall Concept and Mission Analysis,** *R. Adams (NASA Marshall Space Flight Center),J. Cassibry (University of Alabama), R. Cortez (University of Alabama), G. Goughty (NASA Marshall Space Flight Center), B. Taylor (NASA Marshall Space Flight Center), A. DeCicco (University of Maryland)* |

**Tuesday February 28, 2017**

**Track I: Energy Conversion and Power Systems**
Thermoelectric Development and Testing

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| 3:30 pm | 21154 | **Manufacturability and Performance of Skutterudite Thermoelectric Couples for the eMMRTG,** *T. Holgate (Teledyne Energy Systems), J. Ma (Teledyne Energy Systems), Y. Song (Teledyne Energy Systems), R. Bennet (Teledyne Energy Systems), S. Keyser (Teledyne Energy Systems), T. Caillat (Jet Propulsion Laboratory)* | Captiva A |
| 3:50 pm | 20139 | **Impedance Spectroscopy of Neutron Irradiated Bi2Te3 Based Thermoelectric Modules for RTG Environments,** *R. Mesalam (University of Leicester), H. Williams (University of Leicester) R. Ambrosi (University of Leicester), D. Kramer (University of Dayton Research Institute), C. Barklay (University of Dayton Research Institute), J. García-Cañadas (Universitat Jaume I), K. Stephenson (European Space Agency)* | Captiva A |
| 4:10 pm | 20526 | **Skutterudite-Based Thermoelectric Technology for Integration into a Proposed eMMRTG: An Update,** *T. Caillat (Jet Propulsion Laboratory/ California Institute of Technology), I. Chi (Jet Propulsion Laboratory), S. Firdosy (Jet Propulsion Laboratory/California Institute of Tec/California Institute of Technologyhnology), C. Huang (Jet Propulsion Laboratory/ California Institute of Technology), K. Smith (Jet Propulsion Laboratory/California Institute of Technology), K. Yu (Jet Propulsion Laboratory/ California Institute of Technology), J. Ni (Jet Propulsion Laboratory/ California Institute of Technology), J. Paik (Jet Propulsion Laboratory/ California Institute of Technology), P. Gogna (Jet Propulsion Laboratory/California Institute of Technology), S. Pinkowski (Jet Propulsion Laboratory/California Institute of Technology), J.-P. Fleurial (Jet Propulsion Laboratory/California Institute of Technology), R. Bennett (Teledyne Energy Systems Inc.), S. Keyser (Teledyne Energy Systems Inc.), J. Ma (Teledyne Energy Systems Inc.), T. Colgate (Teledyne Energy Systems Inc.)* | Captiva A |





**Tuesday February 28, 2017**

**Track I: Energy Conversion and Power Systems**
Thermoelectric Development and Testing

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| 4:30 pm | 20533 | **Advanced Integrated Thermal-Thermoelectric Modeling for the eMMRTG,** *J. VanderVeer (Teledyne Energy Systems Inc.), T. Hammel (Teledyne Energy Systems Inc.)* | Captiva A |
| 4:50 pm | 20551 | **Advanced Skutterudite-Based Unicouples for a Proposed Enhanced Multi-Mission Radioisotope Thermoelectric Generator,** *I. Chi (Jet Propulsion Laboratory/California Institute of Technology), K. Smith (Jet Propulsion Laboratory/California Institute of Technology), S. Firdosy (Jet Propulsion Laboratory/California Institute of Technology), K. Yu (Jet Propulsion Laboratory/California Institute of Technology), B. Phan (Jet Propulsion Laboratory/California Institute of Technology), J. Paik (Jet Propulsion Laboratory/California Institute of Technology), P. Gogna (Jet Propulsion Laboratory/California Institute of Technology), C. Huang (Jet Propulsion Laboratory/California Institute of Technology), S. Sujittosakul (Jet Propulsion Laboratory/California Institute of Technology), B. Li (Jet Propulsion Laboratory/California Institute of Technology), J. Blosiu (Jet Propulsion Laboratory/California Institute of Technology), T. Hendricks (Jet Propulsion Laboratory/California Institute of Technology), J.-P. Fleurial (Jet Propulsion Laboratory/California Institute of Technology), T. Caillat (Jet Propulsion Laboratory/California Institute of Technology)* | Captiva A |
| 5:10 pm | 20596 | **Qualification Limit Testing of the MMRTG for Mars 2020,** *C. Barklay (University of Dayton Research Institute), B. Tolson (UES, Inc.), C-W. Sjöblom (University of Dayton Research Institute)* | Captiva A |

**Tuesday February 28, 2017**

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| | | **Track II: Fuels and Materials**<br>RTG Fuel Production |
| 3:30 pm | 19821 | **Development of a European Isotope of Choice for Radioisotope Power Systems,** *T. Tinsley (National Nuclear Laboratory), M. Sarsfield (National Nuclear Laboratory), K. Stephenson (European Space Agency)* |
| 3:50 pm | 20176 | **Analysis of Operating Strategies Using Alternative Target Designs for $^{238}$Pu Production,** *T. Thomas (University of Tennessee), R. Sawhney (University of Tennessee), S. Sherman (Oak Ridge National Laboratory)* |
| 4:10 pm | 19882 | **Development of Chemical Processes for Production of Pu-238 from Irradiated Neptunium Targets,** *D. DePaoli (Oak Ridge National Laboratory), D. Benker (Oak Ridge National Laboratory), L. Delmau (Oak Ridge National Laboratory), E. Collins (Oak Ridge National Laboratory), R. Wham (Oak Ridge National Laboratory)* |
| 4:30 pm | 20592 | **Separation and Purification of Np-237 and Pu-238 from a Simulated Irradiated Target,** *J. Katalenich (Pacific Northwest National Laboratory), S. Sinkov (Pacific Northwest National Laboratory)* |
| 4:50 pm | 20105 | **An Alternative Solvent Extraction Flowsheet for Separating 238Pu from 237Np,** *M. Carrott (National Nuclear Laboratory), C. Maher (National Nuclear Laboratory), C. Mason (National Nuclear Laboratory), M. Sarsfield (National Nuclear Laboratory), R. Taylor (National Nuclear Laboratory), T. Tinsley (National Nuclear Laboratory), D. Woodhead (National Nuclear Laboratory), D. Whittaker (National Nuclear Laboratory)* |
| 5:10 pm | 20594 | **Production of PuO2 and Np02 Microspheres,** *J. Katalenich (Pacific Northwest National Laboratory), S. Sinkov (Pacific Northwest National Laboratory), C. Padilla-Cintron (Pacific Northwest National Laboratory)* |

Captiva B





**Tuesday February 28, 2017**

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| | | **Track III: Missions and Infrastructure**<br>Spacecraft Design Concepts |
| 4:30 pm | 20157 | **Overview of Rayleigh-Taylor Instability and the Impact on Target Design for a Pulsed Fusion / Fission Propulsion System,** *B. Taylor (Marshall Space Flight Center), J. Cassibry (University of Alabama in Huntsville), R. Adams (Marshall Space Flight Center)* |
| 4:50 pm | 20169 | **Investigating the Effects Shielding and Astronaut Position Have on Effective Dose Outside the Lower Earth Orbit,** *D. Bond (Virginia Commonwealth University), S. Bilbao y León (Virginia Commonwealth University), R. Singleterry Jr. (NASA Langley Research Center)* |
| 5:10 pm | 20972 | **DEMOCRITOS: Nuclear Electric Propulsion to EUROPA and MARS,** *T. Tinsley (National Nuclear Laboratory), W. Bauer (DLR Institute of Space Systems),M. Hillebrandt (DLR Institute of Composite Structures and Adaptive Systems), M. Richter (DLR Institute of Composite Structures and Adaptive Systems), A. Gomez (DLR Institute of Space Systems), S. Jahnke (DLR Institute of Space Systems, D. Digirolamo (DLR Institute of Space Systems), F. Jansen (DLR Institute of Space Systems), S. Ferraris (Thales Alenia Space), M. Tosi (Thales Alenia Space), A. Koroteev (Keldych Research Centre), A. Semenkin (Keldych Research Centre), A. Soloduckhin (Keldych Research Centre), F. Masson (Centre National d'Etudes Spatiales), J-M. Ruault (Centre National d-E'tudes Spatiales), S. Oriol (Centre National d'Etudes Spatiales), J-C. Worms (European Science Foundation), E. Detsis (European Science Foundation), F. Lassoudière (Airbus Safran Launchers), R. Granjon (Safran Electronics & Defense), Hodgson (National Nuclear Laboratory), L. Geuimarães (Instituto de Estudos Avançados)* |

Captiva C

## Wednesday March 1, 2017

**Track I: Energy Conversion and Power Systems**
Thermal Management

Captiva A

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| 9:00 am | 20224 | **Thermal-control Consideration and Preliminary Analysis of a Heat Pipe Cooled Space Reactor Power System,** *M. Ma (China Academy of Engineering Physics), Q. Xie (China Academy of Engineering Physics), W. Liang (China Academy of Engineering Physics), S. Wang (China Academy of Engineering Physics), X. Fan (China Academy of Engineering Physics)* |
| 9:20 am | 20583 | **Preliminary Overview of Decay Heat Issues in NTP Systems,** *M. Eades (Ultra Safe Nuclear Corporation), P. Venneri (Ultra Safe Nuclear Corporation)* |
| 9:40 am | 21152 | **Titanium Water Heat Pipes for Kilopower System,** *D. Beard (Advanced Cooling Technologies), W. Anderson (Advanced Cooling Technologies), C. Tarau (Advanced Cooling Technologies), B. Schwartz (Advanced Cooling Technologies), K-L. Lee (Advanced Cooling Technologies)* |
| 10:00 am | 21153 | **High Temperature Heat Pipes for Space Fission Power,** *D. Beard (Advanced Cooling Technologies), C. Tarau (Advanced Cooling Technologies), W. Anderson (Advanced Cooling Technologies)* |

## Wednesday March 1, 2017

**Track II: Fuels and Materials**
Materials Properties and Testing for Nuclear Systems

Captiva B

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| 9:00 am | 20188 | **Aeroshell Re-entry Modelling and Testing for European Radioisotope Thermoelectric Generators and Radioisotope Heater Units,** *R. Ambrosi (University of Leicester), D. Kramer (University of Dayton Research Institute), C. Barklay (University of Dayton Research Institute), C. Stroud (Lockheed Martin UK), A. Godfrey (Lockheed Martin UK), H. Williams (University of Leicester), J. Merrifield (Fluid Gravity Engineering Ltd.), K. Stephenson (European Space Agency)* |
| 9:20 am | 20582 | **An Investigation of Material and Processing Variables Affecting Density and Thermal Properties of Carbon Bonded Carbon Fiber Insulation,** *G. Romanoski (Oak Ridge National Laboratory), K. Lach (University of Dayton), N. Gallego (Oak Ridge National Laboratory), C. Contescu (Oak Ridge National Laboratory), A. Clark (Oak Ridge National Laboratory), G. Ulrich (Oak Ridge National Laboratory)* |





## Wednesday March 1, 2017

**Track II: Fuels and Materials**
Materials Properties and Testing for Nuclear Systems

Captiva B

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| 9:40 am | 21150 | **Advanced Insulation Material for eMMRTG Flight Module,** *Y. Song (Teledyne Energy Systems, Inc.), R. Bennet (Teledyne Energy Systems, Inc), T. Holgate (Teledyne Energy Systems, Inc.), T. Hammel (Teledyne Energy Systems, Inc.) S. Keyser (Teledyne Energy Systems, Inc.), J-A. Paik (Jet Propulsion Laboratory/California Institute of Technology), S. Jones (Jet Propulsion Laboratory/California Institute of Technology), T. Caillat (Jet Propulsion Laboratory/California Institute of Technology)* |
| 10:00 am | 20512 | **Zirconium – Rates of Reaction for a Common Getter Material,** *C. Whiting (University of Dayton Research Institute), C. Barklay (University of Dayton Research Institute), D. Woerner (Jet Propulsion Laboratory/California Institute of Technology)y)* |

## Wednesday March 1, 2017

**Track III: Missions and Infrastructure**
Infrastructure and Capabilities

Captiva C

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| 9:00 am | 21181 | **Alternate Siting for Nuclear Thermal Propulsion Ground Testing,** *A. Meidinger (National Security Technologies, LLC), C. Martin (National Security Technologies, LLC)* |
| 9:20 am | 20536 | **Robust Exploration and Commercial Missions to the Moon Using NTR / LANTR Propulsion and Lunar-Derived Propellants,** *S. Borowski (NASA Glenn Research Center), L. Burke (NASA Glenn Research Center), S. Ryan (NASA Glenn Research Center), D. McCurdy (Vantage Partners, LLC at Glenn Research Center), J. Fittje (Vantage Partners, LLC at Glenn Research Center), C. Joyner (Aerojet Rocketdyne)* |
| 9:40 am | 20050 | **Vaporous Hydrogen Peroxide Sterilization Capability at the Idaho National Laboratory for Radioisotope Power Systems and Components,** *S. Davis (Idaho National Laboratory), K. Wahlquist (Idaho National Laboratory)* |
| 10:00 am | 20182 | **Idaho National Laboratory Radioisotope Power Systems Nuclear Operations: Readiness Assessment Supporting a Nuclear-Enabled NASA Mission,** *K. Lively (Idaho National Laboratory), D. Kirkham (Idaho National Laboratory)* |

## Wednesday March 1, 2017

**Track I: Energy Conversion and Power Systems**
Component Development and Testing

Captiva A

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| 10:40 | 21151 | **Status of the Kilowatt Reactor Using Stirling TechnologY (KRUSTY),** *M. Briggs (NASA Glenn Research Center), M. Gibson (NASA Glenn Research Center)* |
| 11:00 am | 20189 | **Architecture, Structural and Thermal Analysis of an 241Am Fueled Radioisotope Heater Unit,** *A. Barco (University of Leicester), H. Williams (University of Leicester), R. Ambrosi (University of Leicester), J. Sykes (University of Leicester), T. Crawford (University of Leicester), M. Sarsfield (National Nuclear Laboratory), K. Stephenson (European Space Agency)* |
| 11:20 am | 20190 | **Architecture Structural and Thermal Analysis of an 241Am Fueled RTG Heat Source,** *A. Barco (University of Leicester), H. Williams (University of Leicester), R. Ambrosi (University of Leicester), J. Sykes (University of Leicester), T. Crawford (University of Leicester), K. Stephenson (European Space Agency)* |
| 11:40 am | 21155 | **Comparative Studies for the MHD Modeling of Annular Linear Induction Pumps for Space Applications,** *J. Nieminen (MAIDANA RESEACH, University of Southern California), C. Maidana (MAIDANA RESEARCH, Idaho State University)* |

## Wednesday March 1, 2017

**Track III: Missions and Infrastructure**
Infrastructure and Capabilities

Captiva C

| | | |
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| 10:40 am | 20565 | **Light Weight Radioisotope Heater Unit Dimensional Inspection Qualification Process for the Radioisotope Power Systems Program at Oak Ridge National Laboratory,** *K. Veach (Oak Ridge National Laboratory)* |
| 11:00 am | 21149 | **Plutonium-238: An Option to Improve RPS Throughput and Availability,** *B. Shipp (Technical Solutions Management), B. Reid (Pacific Northwest National Laboratory), C. Thornhill (Pacific Northwest National Laboratory)* |
| 11:20 am | 20530 | **Effects of Laser Marking Versus Mechanical Scribing on DOP-26 Iridium Alloy Material,** *B. Friske (Oak Ridge National Laboratory), R. Waked, G. Ulrich (Oak Ridge National Laboratory), C. Carmichael Jr. (Oak Ridge National Laboratory)* |





## Wednesday March 1, 2017

**Track II: Fuels and Materials**
Materials Properties and Testing for Nuclear Systems

Captiva B

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| 10:40 am | 20174 | **Hot Hydrogen Testing of Silicon Carbide for Nuclear Thermal Propulsion Applications,** *K. Benensky (University of Tennessee), M. Barnes (NASA Marshall Space Flight Center), D. Trent (NASA Marshall Space Flight Center), R. Hickman (NASA Marshall Space Flight Center), K. Terrani (Oak Ridge National Laboratory), M. Houts (NASA Marshall Space Flight Center), S. Zinkle (University of Tennessee, Oak Ridge National Laboratory)* |
| 11:00 am | 20141 | **Enhanced Mechanical Properties in n-type Bi2Te3 Prepared by FAST-Deformation Processing,** *R. Mesalam (University of Leicester), H. Williams (University of Leicester), R. Ambrosi (University of Leicester), K. Chen (Queen Mary University of London), M. Reece (Queen Mary University of London), K. Stephenson (European Space Agency)* |
| 11:20 am | 20264 | **Neutron Irradiation Experiments on Various RPS Materials such as Bi2Te3 Based Thermoelectric Modules,** *D. Kramer (University of Dayton), C. Barklay (University of Dayton), R. Ambrosi (University of Leicester), S. White (The Ohio State University), K. Herminghuysen (The Ohio State University), A. Kauffman (The Ohio State University)* |

## Wednesday March 1, 2017

**Track I: Energy Conversion and Power Systems**
Advanced Concepts

Captiva A

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| 3:30 am | 20184 | **Three Dimensional Modeling of Pulsed Fission Fusion (PUFF) Targets for Advanced Propulsion,** *J. Cassibry (University of Alabama), R. Adams (NASA Marshall Space Flight Center), R. Cortez (University of Alabama)* |
| 3:50 am | 20214 | **Propulsion Through Direct Conversion of Fusion Energy,** *J. Slough (University of Washington), A. Pancotti (MSNW LLC), A. Shimazu (University of Washington)* |
| 4:10 am | 20159 | **Progress on Fusion Modeling and the Charger-1 Pulsed Power Facility at UAH,** *Ross J. Cortez (University of Alabama in Huntsville), J. Cassibry (University of Alabama in Huntsville), R. Adams (Marshall Space Flight Center), G. Doughty (Marshall Space Flight Center), B. Taylor (Marshall Space Flight Center), A. DeCicco (University of Maryland)* |
| 4:30 am | 20201 | **Investigation of Pu-238 Heat Source Modifications to Increase Power Output Through (a,n) Reaction Induced Fission,** *A. Cusick (Los Alamos National Laboratory), G. McMath (Los Alamos National Laboratory)* |

**Tracey Bishop**
*Deputy Assistant Sectretary for Nuclear Infrastructure Program*

*US Department of Energy*

As the Deputy Assistant Secretary for Nuclear Infrastructure Programs, Ms. Tracey Bishop is responsible for the management of the Office of Nuclear Energy's infrastructure programs, including NE's field operations at the Nuclear Energy Oak Ridge Site Office supporting the lease administration of uranium enrichment capabilities at Oak Ridge Reservation and the Portsmouth Gaseous Diffusion Plant.

In this capacity, Ms. Bishop is responsible for a large portfolio of infrastructure programs, spanning facility management, capital asset planning and construction, safeguards and security, emergency planning, and nuclear materials management. These programs and capabilities enable critical nuclear energy research and development activities by providing and maintaining safe, secure, and compliant facilities for multiple customers within and external to the Department of Energy. She is also responsible for delivering compact, safe radioisotope power systems, heater units, and related technologies to support the National Aeronautics and Space Administration and other agencies in space exploration and national security missions.

Ms. Bishop has over 25 years of experience in facility management and environmental, safety and health oversight experience with DOE. Before joining the Office of Nuclear Energy in 2008, Ms. Bishop served as the Acting Director of the Office of Facilities Operations, Office of Defense Programs, National Nuclear Security Administration.



Featured Speakers

**Tracey Bishop**
*Deputy Assistant Sectretary for Nuclear Infrastructure Program*

*US Department of Energy*

In this capacity, Ms. Bishop managed a multi-site facility operations program that supported the Stockpile Stewardship Program and other national security missions at Kansas City Plant, Pantex Plant, Savannah River Tritium Facilities, Y-12 National Security Complex, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Sandia National Laboratories, and Nevada National Security Site.

Ms. Bishop holds a Bachelor of Nuclear Engineering degree from the Georgia Institute of Technology and a Master of Business Administration degree from the University of Maryland. Ms. Bishop is certified as a Project Management Professional with the Project Management Institute

**Ralph McNutt, PhD**
*Chief Scientist*

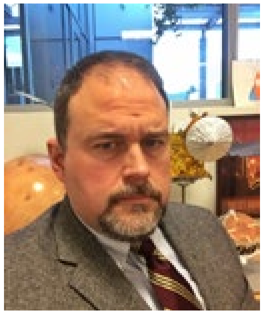
*Johns Hopkins University/Applied Physics Laboratory*

Dr. McNutt is the chief scientist in the Space Department at the Johns Hopkins University Applied Physics Laboratory, which he joined in 1992. As project scientist for the MESSENGER mission, he serves as the principal investigator's "right-hand man" in making sure that the spacecraft, mission design and experiment plan answer all six of the major science questions the project will investigate at the innermost planet. He will participate in analysis of Mercury's surface composition using data from MESSENGER's X-Ray Spectrometer and Gamma-Ray and Neutron Spectrometer instruments.

Dr. McNutt is also a co-investigator on NASA's New Horizons (Pluto-Kuiper Belt) mission, a team member of the Cassini Ion Neutral Mass Spectrometer investigation and a science team member of two Voyager investigations. He has been involved in a range of space physics research projects and mission studies, including studies of the magnetospheres of the outer planets, the interaction of the solar wind with the interstellar medium, solar neutrinos, and solar probe and interstellar probe missions for the future.



Featured Speakers



**Charles Whetsel**

*Program Formulation & Advanced Studies*

*Jet Propulsion Laboratory/California Institute of Technology*

Charles Whetsel currently works in NASA's Mars Exploration Program as the manager of the Program Formulation & Advanced Studies at JPL, in Pasadena, where he has worked for over 25 years. During this time he has held several Mars-related positions such as the Chief Engineer of the overall Mars Program (2001-2004) and the Chief Engineer for the Mars Curiosity Rover from (2004 – 2008). He has also served as the manager of Spacecraft Systems Engineering at JPL from 1999-2001. Whetsel holds degrees in Aerospace Engineering from MIT and Stanford and in Planetary Science from MIT. He resides in South Pasadena with his wife Anne and their 4 children.

**Tim Tinsley**
*Spent Fuel Management Business Lead*

*National Nuclear Laboratory*

Tim is a Chartered Engineer and a Fellow of the Institute of Chemical Engineers. He has over 25 years international experience managing projects in the Nuclear Industry, having worked in a number of roles at Sellafield in the UK and with BNFL Inc in the USA supporting the Waste Treatment Project at Hanford.

He currently holds the role of Spent Fuel Management Technology Business Leader at the National Nuclear Laboratory. He has accountability for the delivery of domestic and international projects. His technical and team accountability covers work in relation to used or spent fuel management, including fuel storage, open / closed fuel cycles, and special nuclear materials management. In addition he manages the NNL's portfolio of work related to space, including power and propulsion.



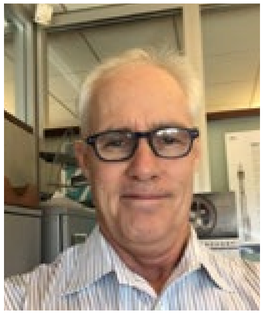


**Keith Stephenson, PhD**

*European Space Agency*

Keith Stephenson is a nuclear power system engineer in the European Space Agency (ESA), and is based at ESA's technology centre "ESTEC" at Noordwijk in the Netherlands. He is managing and coordinating various projects that are aimed towards the development of a European capability for radioisotope power systems.

Before joining ESA in 2007, Keith worked for twelve years on the Sellafield nuclear site. After beginning his career in the field of active-neutron radiometrics, he moved to the mixed-oxide (MOX) fuel business, working on performance characterisation of mixed-oxide (MOX) reactor fuel and process engineering in a MOX fuel manufacturing plant.



**Charles (Chuck) Tatro**
*Launch Site Integration Branch Chief*

*NASA*
*Kennedy Space Center*

Chuck is the Launch Site Integration Branch Chief in the Launch Services Program (LSP) at Kennedy Space Center. (KSC). His oversees personnel, facilities, and spacecraft launch processing activities at Kennedy Space Center and Vandenberg Air Force Base (VAFB.)

Before becoming a Branch Chief, he served as LSP Mission Manager for the following missions: James Webb Space Telescope (JWST), MAVEN, LRO-LCROSS, GRACE-Follow-On, InSight, and Mars 2020.

He has also served as Launch Site Integration Manager (LSIM) for Mars'98 Orbiter and Lander, Stardust, Kodiak Star, Spitzer (SIRTF), Pluto-New Horizons, and assisted in launch site planning and processing for the Deep Impact and Dawn missions.

Before coming to the unmanned rocket world, he was Lead Engineer for space shuttle orbiter thermal protection systems and Space Shuttle Orbiter Endeavour.

Chuck began his NASA career at Glenn (Lewis) Research Center in Cleveland Ohio (1986) and prior to joining NASA, worked at the Los Alamos National Laboratory and the US Navy Pacific Missile Test Center.

He has a B.S degree from the University of California, San Diego (UCSD), and M.S. Degrees from the University of Arizona – Nuclear Engineering (Tucson, AZ) and the University of Central Florida - Engineering Management (UCF).





ACT

Advanced Cooling Technologies, Inc. (ACT) is a premier thermal management solutions company. We serve customers in diverse markets including Aerospace, Electronics, HVAC and Energy Recovery, Let Thermal Management and Temperature Calibration and Control. Our highly engineered products include Heat Pipes, Heat Exchangers and Cold Plates. Our diverse R&D and Technical Services programs range from developing thermal protection materials for space reentry vehicles to investigating nanoscale heat transfer in next generation electronic devices to designing high temperature heat recovery systems for industrial processes. Innovation, Teamwork, and Customer Care are our core values that drive the continuous growth of our company.

NATIONAL NUCLEAR LABORATORY

The UK's National Nuclear Laboratory (NNL) offers a unrivaled breadth of technical products and services to our customers across the whole nuclear industry. Covering the complete nuclear fuel cycle from fuel manufacture and power generation, through reprocessing, waste treatment and disposal including defense, new nuclear build and Homeland Security. NNL provides these services supported by academia and other national laboratories. NNL's facilities are second to none. The Central Laboratory at Sellafield is the most modern nuclear research facility in the world. The Windscale Laboratory provides Post-Irradiation Examination (PIE) and other services critical to plant life extension. At Workington, NNL operates a non-radioactive test rig facility and at Preston NNL operates a uranium active chemistry laboratory. NNL also has staff at the Risley, Stonehouse and Harwell sites providing Head Office functions, graphite technology, radiation chemistry and modeling/simulation.

The National Aeronautics and Space Administration (NASA) Radioisotope Power Systems (RPS) Program, in partnership with the Department of Energy (DOE), is ensuring the United States will remain the world's leader in nuclear power for space exploration enabling scientific discovery for years to come. RPS is investing in both Thermoelectric and Dynamic Power conversion technologies, making critical advances in technology maturation and power systems development, such as a potential enhanced Multi-Mission Radioisotope Thermoelectric Generator, to provide a more efficient system to power a spacecraft. Under RPS-funded Production Operations, NASA gains insight into the processes DOE executes, including work that resulted in the first new U.S. production of the Heat Source – plutonium dioxide since the 1980s. This renewed capability is enabling the RPS Program to support future NASA missions such as the upcoming Mars 2020 mission and potential New Frontiers or Discovery opportunities.

Headquartered in Lynchburg, Va., BWX Technologies, Inc. (BWXT) is a leading supplier of nuclear components and fuel to the U.S. government; provides technical, management and site services to support governments in the operation of complex facilities and environmental remediation activities; and supplies precision manufactured components and services for the commercial nuclear power industry. BWXT has approximately 5,600 employees and significant operations in Lynchburg, Va.; Erwin, Tenn.; Mount Vernon, Ind.; Euclid, Ohio; Barberton, Ohio; and Cambridge, Ontario, as well as more than a dozen U.S. Department of Energy sites around the country



Exhibitors

Idaho National Laboratory (INL) serves as the nation's command center for andvanced nuclear energy research, development, demonstration and deployment, and is home to the unparalleled Advanced Test Reactor and allied post-irradiation examination, fuel fabrication and materials testing and development assets. Leveraging these numerous other distinguishing features, the lab and its more than 3,500 scientists, engineers and support personnel build on the potential and promise of the theoretical for the benefit of the real world. INL is one of only 10 multiprogram national laboratories owned by the U.S. Department of Energy. Geographically, INL is the largest lab - its nearly 570,000-acre desert operations site also serves as a national enivironmental research park. As with its sister laboratories, INL performs work in support of DOE's mission - to ensure America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions.

Idaho National Laboratory and the Universities Space Research Association created the Center for Space Nuclear Research (CSNR) in 2005 to foster collaboration with university scientists. CSNR scientists and engineers research and develop advanced space nuclear systems, including power systems, nuclear thermal propulsion, and radioisotopic generators. The CSNR is located at the Center for Advanced Energy Studies (CAES) building on the INL research campus.

Aerojet Rocketdyne is a world-recognized aerospace and defense leader providing propulsion and energetics to the domestic and international space, missile defense and strategic systems, tactical systems and aremaments areas, and transformational energy technology solutions to address the world's energy needs. GenCorp is a diversified company providing innovative solutions to its customers in teh aerospace and defense, energy and real estate markets. Additional information about Aerojet Rocketdyne and GenCorp can be obtained by visiting the companies' websitees at www.Rocket.com and www.GenCorp.com.

**Mike Houts, PhD**
*Nuclear Research Manager*

*NASA Marshall Space Flight Center*

Dr. Houts has a PhD in Nuclear Engineering from the Massachusetts Institute of Technology. He was employed at Los Alamos National Laboratory for 11 years where he served in various positions including Team Leader for Criticality, Reactor, and Radiation Physics and Deputy Group Leader of the 70 person Nuclear Design and Risk Analysis group. Dr. Houts currently serves as Nuclear Research Manager for NASA's Marshall Space Flight Center, where he has been employed for 15 years. He is also the principal investigator for NASA's Nuclear Thermal Propulsion (NTP) project. Recent awards include a NASA Exceptional Engineering Achievement Medal, a NASA Space Flight Awareness Honoree award, a NASA MSFC Director's Commendation Honor Award, and being selected as an Associate Fellow of the American Institute of Aeronautics and Astronautics.



Panel Speakers

**Robert Wham, PhD**
*Technology Integration Manager*

*Oak Ridge National Laboratory*

Robert Wham is a Ph.D. Chemical Engineer whose research focus is radioisotope production and radiochemical separations including recycle of used nuclear fuel. He currently serves as Technical Integration Manager for the Pu-238 Supply Project within the Nuclear Security and Isotope Technology Division.

Previously, he served as Technology Integration manager for the Nuclear Science and Technology Division (NSTD) and was responsible for six groups within NSTD. The groups covered diverse areas such as radiochemical processing, robotics, stable isotope production, radioisotope production, and design of remotely operated equipment.

Prior to that, he managed several radiochemical processing programs at the Radiochemical Engineering Development Center (REDC). His experience in hot cells and radioisotope production comes from working on the production of heavy elements in the Transuranium Element Program, as well as the recovery of plutonium, americium and curium from targets irradiated at the Savannah River Site. Both of these took place at REDC. He was Facility and Program Manager for REDC from 1991 to 1997.

**Jackie Lopez-Barlow,**
*Power Systems Program Manager*

*Los Alamos National Laboratory*

Ms. Jacquelyn Lopez-Barlow is the Power Systems Program Manager and has worked at Los Alamos National Laboratory for 13 years. She began her career with LANL as a student while getting her Bachlors of Science degree in Chemical Engineering at the University of New Mexico. After attaining her degree she began working as a Process Engineer in Actinide Aqueous, Oxide, and Pyrochemical operations. In 2011, she became the Engineering Manager for 238Pu Operations supporting development, production, and surveillance activities. She transitioned to the Program Manager for 238Pu Operations in 2016. She has supported Defense, NASA, and Non-Proliferation programs at LANL.





**Stephen Johnson, PhD**
*Director of the Space Nuclear Power and Isotope Division*

*Idaho National Laboratory*

Dr. Johnson is currently the Director of the Space Nuclear Power and Isotope Technologies Division in the Nuclear Science and Technology Directorate of the Idaho National Laboratory. He has served as the Director of the Technical Integration Office for DOE's Office of Space and Defense Power Systems since 2012. Most recently this program fueled, tested and delivered the MMRTG for NASA's Mars Scientific Laboratory mission to the planet Mars.

Dr. Johnson has over 25 years of experience working with radioactive materials and the analysis of such using either chemical or material science techniques and methods and has extensive knowledge of analytical chemistry spectroscopic methods of analysis and analysis related to characterizing high-level waste for geologic disposal. He holds a B.S. degree with a double major in Mathematics and Chemistry from Lake Superior State University (1984) and a Ph. D. in Physical Chemistry from Iowa State University (1990).

**David Woerner**
*RTG Integration Manager*

*Jet Propulsion Laboratory/California Institute of Technology*

David Woerner has more than 30 years of experience as a systems engineer and manager at NASA's Jet Propulsion Laboratory. This includes being an office manager for the Mars Science Laboratory (MSL) mission that successfully landed on Mars on August 6, 2012. He is currently working as the RTG integration manager for NASA's Radioisotope Power System Program, and he is the Chief Engineer of the Nuclear Space Power Office at JPL.

David has worked on such missions as Galileo (to Jupiter), Cassini (to Saturn), Magellan (to Venus), Mars Pathfinder, and MSL. He was the chief engineer of the avionics for the Mars Pathfinder mission that successfully landed on Mars on July 4, 1996. Shortly after that, in the late 1990s, he managed the X2000 Project that developed the RAD750 space processor that is still regularly flown.

He has won numerous NASA awards, including NASA's Exceptional Service and Exceptional Achievement medals.





**Andrew Kelsh, PhD**
*Chief Engineer*

*Jet Propulsion Laboratory/ California Institute of Technology*

Dr. Andrew Klesh is NASA/JPL's Chief Engineer for the Mars Cube One (MarCO) mission to Mars and serves as Co-PI of the Buoyant Rover for Under-Ice Exploration. He also is PI of the INSPIRE interplanetary CubeSats, a Lecturer at Caltech in EE, and an Adjunct Professor at Arizona State University where he teaches "MacGyver Engineering". Andy's research primarily specializes in robotic exploration in extreme environments, including aerial, surface, and underwater field investigations in the arctic, and NanoSpacecraft (including CubeSat) missions throughout the solar system. Prior to JPL, he served as a Postdoctoral Fellow at JAXA's Space Exploration Center in Sagamihara, Japan, and as Postdoc and Chief Engineer for the Radio Aurora Explorer project. He earned a PhD, MSE and BSE in Aerospace Engineering, MEng in Space Systems, and BSE in Electrical Engineering all from the University of Michigan.

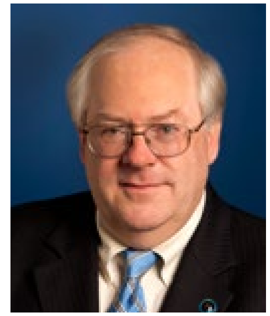
**Lyon (Brad) King, PhD**
*Professor*

*Michigan Technological University*

Dr. Lyon (Brad) King is presently the Ron and Elaine Starr Professor of Space Systems Engineering. Dr. King earned his Ph.D. in Aerospace Engineering from the University of Michigan in 1998. Dr. King is an experimentalist with expertise in spacecraft design, electric space propulsion systems, and plasma physics. From 1998-2000 King was a postdoctoral research associate with David Wineland's Ion Storage Group at the National Institute of Standards and Technology were he worked on laser-cooled cryogenic plasmas. King currently serves on the AIAA Electric Propulsion Technical Committee and was committee Chair from 2009-2011. King is a recipient of the National Science Foundation Faculty Early Career Award (CAREER) and the SAE International Ralph R. Teetor Engineering Educator Award. In 2004, King received the Presidential Early Career Award for Scientists and Engineers in a White House ceremony for DoD-sponsored research related to Hall-effect thrusters. Dr. King is presently an Associate Editor for the AIAA Journal of Propulsion and Power. King has worked on multiple small-satellite architectures for government and industry customers and is currently the PI on three university small-satellite missions.



Panel Speakers



**Ralph McNutt, PhD**
*Chief Scientist*

*Johns Hopkins University/Applied Physics Laboratory*

Dr. McNutt is the chief scientist in the Space Department at the Johns Hopkins University Applied Physics Laboratory, which he joined in 1992. As project scientist for the MESSENGER mission, he serves as the principal investigator's "right-hand man" in making sure that the spacecraft, mission design and experiment plan answer all six of the major science questions the project will investigate at the innermost planet. He will participate in analysis of Mercury's surface composition using data from MESSENGER's X-Ray Spectrometer and Gamma-Ray and Neutron Spectrometer instruments.

Dr. McNutt is also a co-investigator on NASA's New Horizons (Pluto-Kuiper Belt) mission, a team member of the Cassini Ion Neutral Mass Spectrometer investigation and a science team member of two Voyager investigations. He has been involved in a range of space physics research projects and mission studies, including studies of the magnetospheres of the outer planets, the interaction of the solar wind with the interstellar medium, solar neutrinos, and solar probe and interstellar probe missions for the future.

**Terry Hendricks, PhD**
*Technical Group Supervisor, Thermal Energy Conversion Systems Group/MMRTG Pyroshock Project Manager/JPL MATRIX Technical Manager*

*Jet Propulsion Laboratory/California Institute of Technology*

Dr. Hendricks is currently a Technical Group Supervisor, Project Manager, an ASME Fellow, and IEEE Senior Member in the Power and Sensor Systems Section, Autonomous Systems Division at NASA–Jet Propulsion Laboratory (JPL)/California Institute of Technology, Pasadena, CA, responsible for managing NASA-JPL radioisotope power system projects; and designing radioisotope power systems, spacecraft power systems, hybrid solar power systems, thermal management and thermal energy storage systems critical to NASA missions. He was previously Energy Recovery Program Director at Battelle Memorial Institute, Columbus, OH, and a Senior Program Manager at the U.S. Department of Energy (DOE) Pacific Northwest National Laboratory (PNNL) in Richland, WA and Corvallis, OR from 2005-2013, where he managed U.S. DOE and U.S. Army programs in hybrid power system development, automotive and industrial waste energy recovery, military energy recovery and power system development, and advanced nano-scale heat transfer. Dr. Hendricks received his Ph.D. and Master of Science in Engineering from the University of Texas @ Austin and Bachelor of Science (Summa Cum Laude) in Physics from the University of Massachusetts at Lowell. He has over 35 years of professional experience and expertise in thermal & fluid systems, energy recovery, energy conversion and energy storage systems, terrestrial and spacecraft power systems, micro electro-mechanical systems, and project management. His extensive expertise is cited in over 85 reports and journal articles in the Journals of Electronic Materials; Energy; Materials Research; Heat Transfer; Thermophysics and Heat Transfer; and International Heat & Mass Transfer. He is a registered Professional Engineer in the states of California and Texas.





**Jeanne-Pierre Fleurial, PhD**

*Thermoelectric Technology Development Project Manager*

*Jet Propulsion Laboratory/California Technological*

Dr. Jean-Pierre Fleurial is a Senior Research Scientist at the Jet Propulsion Laboratory. He holds a Ph.D. in Materials Science from the National Polytechnic Institute of Lorraine, France, as well as a Professional Engineering Degree from the School of Mines, France. JPL is a Division of the California Institute of Technology under contract to the National Aeronautics and Space Administration. Dr. Fleurial currently manages JPL's Thermal Energy Conversion Research & Advancement Group and he is the Thermoelectric Technology Development Project Manager for the NASA SMD's Radioisotope Power Systems Program.

He is leading and participating in several projects related to advanced materials research and engineering, novel high temperature power generation and cooling devices, sensing and waste heat recovery thermoelectric systems and next generation radioisotope and fission space power systems.

He has achieved international recognition in his field as a leader in the research and development of novel materials and devices for thermoelectric energy conversion, in particular for high temperature power generation applications.

His area of technical expertise is in solid-state energy conversion, especially thermoelectrics but also direct energy conversion based on photovoltaics, thermophotovoltaics, beta- and alpha-voltaics. Dr. Fleurial has also developed system-level designs, models and trade studies and he is familiar with a wide variety of energy conversion and energy storage technologies.

# A New Manned Space Flight Mission for NASA

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**Abstract.** Definition of a manned space flight mission into deep space was initiated by an unsolicited proprietary proposal to NASA Headquarters in February 1973. That and subsequent similar proposals to NASA of 1998, 2004, and 2013 are contained in the Philip C. Fisher Papers of the Niels Bohr Library and Archives of the American Institute of Physics (scheduled to be publicly available one year after the author's death). Part of the contents of the 1998 proposal was published in 1999. By 2013 the five technical variables of 1998 had increased to over ten. An updated version of the effort was published last year when it was stated the proposed effort seemed to be superior to any effort that NASA had publicly advocated. To help "size" the effort two tables from 2016 and additional data are presented here. The purpose of this presentation is to encourage NASA to use the information provided to decide if it is willing to ask the United States Congress to fund the first flight of the mission involving a few specified leading governing nations plus all other interested qualifying governments.

**Keywords:** manned space flight, nuclear reactor**.**





# Development of a European Isotope of Choice for Radioisotope Power Systems

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**Abstract.** Production of $^{238}$Pu requires considerable facilities including a nuclear reactor and reprocessing plants that are very expensive to build and operate. Thus, a more economical alternative is very attractive to the industry, especially in Europe where production facilities for $^{238}$Pu do not currently exist. There are many alternative radioisotopes that exist but few that satisfy the criteria of performance, availability and cost to produce. Any alternative to $^{238}$Pu must exist in a chemical form that is compatible with the materials required to safely encapsulate the heat source at the high temperatures of operation and potential launch failure scenarios. The chemical form must also have suitable thermal properties to ensure maximum energy conversion efficiencies when integrated into radioisotope thermoelectric generators over the required mission durations. In addition, the radiation dose must be low enough for operators during production and not so prohibitive that excessive shielding mass is required on the space craft.

The European Space Agency (ESA) commissioned an assessment of the options for post-launch power generation in future European space missions and has made the decision to pursue the use of $^{241}$Am as an alternative isotope to power future European Radioisotope Thermoelectric Generators (RTG) and Radioisotope Heater Units (RHU). Despite its lower power density of ~ 0.11Wth/g, $^{241}$Am was viewed as a potential alternative to $^{238}$Pu because of its production in the nuclear fuel cycle. What makes $^{241}$Am attractive for the European market is its 100% isotopically pure production from the decay of $^{241}$Pu in separated civil plutonium stockpiles. The UK and France have a policy of reprocessing irradiated nuclear fuel and storing the plutonium product for reuse in U/Pu mixed oxide (MOx) fuel. When irradiated fuel is reprocessed all of the americium formed during irradiation is directed with the fission products to be vitrified in glass as high level waste. The plutonium is separated as a chemically pure $PuO_2$ product containing around 3-11% w/w $^{241}$Pu isotope and placed into storage. During storage, the $^{241}$Pu beta decays to $^{241}$Am with a half-life of 14.4 years.

Within Europe $^{241}$Am is a feasible alternative to $^{238}$Pu that can provide a radiogenic heat source for RTGs and RHU. As a daughter product of $^{241}$Pu decay, $^{241}$Am is present at 1000s kg levels within the UK civil plutonium stockpile. Following the decision to pursue $^{241}$Am as the isotope of choice within Europe, ESA commissioned further studies to define the production flowsheet and requirements.

A chemical separation process is required to extract the $^{241}$Am in a pure form and the process to achieve this has been developed and refined to produce a process capable of delivering the required quantities and purity of $^{241}$Am to meet ESAs requirements. A two-step chemical separation process, Pu/Am followed by Ag/Am separation, was used to process batches of aged $PuO_2$ to generate multi-gram quantities of pure $^{241}$Am as an americium nitrate solution in nitric acid. An oxalate precipitation process was used to generate americium oxalate solid, which was subsequently decomposed into americium dioxide at elevated temperatures. A sample of this oxide was dissolved and analysis of trace metals performed, by resin column separations followed by Inductively Coupled Mass Spectrometry, to establish purity levels. This controlled precipitation and decomposition process was applied to the americium system creating ~3.6g of americium dioxide ready for eventual fabrication into ceramic test pellets.

**Keywords:** Americium, Radioisotope power system, heat source, solvent extraction.

# Development of Chemical Processes for Production of Pu-238 from Irradiated Neptunium Targets

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**Abstract.** Oak Ridge National Laboratory (ORNL) is currently working on the Plutonium-238 (Pu-238) Supply Project to reestablish the capability to produce plutonium dioxide ($PuO_2$) for use in radioisotope power systems for deep-space applications. ORNL is using neptunium-237 oxide ($NpO_2$), currently stored at Idaho National Laboratory, to fabricate targets for irradiation at the High Flux Isotope Reactor and the Advanced Test Reactor. The processing of the irradiated targets will be performed in equipment installed in the hot cells and gloveboxes at ORNL's Radiochemical Engineering Development Center. The product $PuO_2$ will be shipped to Los Alamos National Laboratory for conversion into heat sources for use by the National Aeronautics and Space Administration. The neptunium remaining in the irradiated targets will be recovered and recycled for reuse in the fabrication of additional targets.

This presentation will provide an overview of the status of chemical process development and testing activities at ORNL. Kilogram quantities of $NpO_2$ have been irradiated to generate test materials. Two chemical processing demonstration tests have been conducted to determine the efficiency of process steps and to validate product purity. Chemical process testing includes a two-step target dissolution process to first remove aluminum from the cladding and pellet matrix with caustic, followed by the dissolution of neptunium and plutonium oxides and fission products in nitric acid. The primary separation of the neptunium, plutonium, and fission products is accomplished using solvent extraction with tributyl phosphate in a hydrocarbon diluent using countercurrent mixer-settler contactors. The plutonium product is purified and converted to $PuO_2$ by means of a resin loading/calcination process. The neptunium may be recovered and recycled by purification using either solvent extraction or ion exchange processes and converted to $NpO_2$ for target fabrication by means of the modified direct denitration process.

Results obtained during the first two demonstration tests with irradiated targets will be presented, along with remaining questions to be addressed to increase production over the next few years toward a goal of 1500 g/year of heat-source plutonium oxide containing >85% Pu-238.

**Keywords:** Plutonium-238, production, chemical processing, solvent extraction, ion exchange





# Nuclear and Thermal Hydraulic Design for a Low-Enriched Nuclear Thermal Rocket

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**Abstract.** In efforts to realize the first manned mission to Mars, engineers have been faced with many unique challenges; requiring exceptional thrust from a relatively lightweight engine in order to fulfill time and acquired dose restrictions. This new nuclear thermal rocket (NTR) design seeks to provide a comparable low-enriched uranium (LEU) engine providing vehicle thrust for the orbit-to-orbit transfer.

The core design involves a cylindrical block of nuclear grade graphite from which holes will be drilled to allow fuel elements and moderator components to be added. The core is approximately a square cylinder with an active fuel height of 70 cm and diameter of roughly 80 cm. There are 483 hexagonal fuel elements and 978 moderator elements with designs similar to those from the historic NERVA program. The approximately two moderator elements to one fuel element configuration allows for sufficient moderation reaching a desirable $k_{eff}$ while meeting thermal limits. The radial reflector contains 12 rotating control drums to allow for reactor control, and a top reflector helps to maximize neutron economy. The reflectors are beryllium oxide, selected based on beneficial scattering and absorption cross sections with the control drums containing a crescent moon-shaped section of boron carbide for primary reactivity control.

A thermal hydraulic analysis determined that the integrity of the core was maintained while providing the thrust and specific impulse to meet the DRA 5.0 mission requirements. The LEU fuel elements are ($U_{0.1}$, $Zr_{0.45}$, $Nb_{0.45}$)C and based off the NERVA design, featuring 19 coolant channels surrounded by $ZrH_{1.8}$ moderator elements. A once through coolant system was employed to ensure the integrity of core components while maximizing the coolant exit temperature. The coolant is hydrogen, with a core averaged exit temperature of 1325 K producing a specific impulse of 615 s and the required thrust of 111.2 kN. Previous NERVA studies and the DRA 5.0 mission describe operation of the core at four times for approximately 45 minutes each. The reactor will burn to assist in breaking LEO towards Mars and slowing to enter Mars' orbit upon arrival; similar uses exist for the return trip.
Criticality safety for an NTR addresses possible accident scenarios including failure of a single control drum and core submersion upon launch. Analysis of the failure of the highest worth control drum at nominal core operating temperatures determined that the value for $k_{eff}$ remains at $0.92709 \pm 0.00043$. Consideration of launch failure accidents discovered core submersion in a large body of fresh water to be the most limiting case. Using a design which allows for disassembly of the core, preliminary results demonstrate these smaller pieces remain subcritical for all submersion scenarios. Additional reactivity control measures are incorporated to address the large reactivity changes due to temperature differences between shutdown and operating conditions.

# Vaporous Hydrogen Peroxide Sterilization Capability at the Idaho National Laboratory for Radioisotope Power Systems and Components

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**Abstract.** National Aeronautical Space Administration's (NASA) missions often involve looking for signs of life or the building blocks of life on other planets. NASA and other space agencies have implemented planetary protection protocols to control and monitor the transportation of earth-based organisms to extraterrestrial space bodies. This helps ensure that any discovery of life or building blocks of life, during space missions, do not originate from the spacecraft.

The Idaho National Laboratory (INL) fuels and tests the radioisotope power systems (RPSs) for many of NASA's missions that utilize deep space probes and rovers. During fueling, the RPS is partially disassembled thus exposing the internals to the possibility of contamination by earth-based organisms. Some RPS units, such as the Multi Mission Radioisotope Thermoelectric Generator (MMRTG), produce enough heat from the decay of plutonium-238 that they are internally self-sterilizing. Other RPS units, such as Stirling generators, contain significantly less plutonium-238, and therefore do not produce enough heat to be considered internally self-sterilizing. In addition not all RPS components can withstand NASA's conventional sterilization process, known as dry heat microbial reduction (DHMR), which utilizes heat and time to achieve the desired microbial reduction. INL was directed to utilize the European Space Agency's (ESA) vaporous hydrogen peroxide sterilization parameters as guidance for developing a planetary protection process using vaporous hydrogen peroxide to sterilize RPSs and other components that aren't internally self-sterilizing or can't be sterilized by the DHMR process.

Prior to use on actual space hardware, the efficacy and repeatability of the vaporous hydrogen peroxide microbial reduction process must be demonstrated. With the assistance of a Steris Process Engineer, sterilization cycles were developed and tested on an enclosure, referred to as a glovebox, designated for fueling RPS units requiring vaporous hydrogen peroxide sterilization. The cycle development required the use of both chemical and biological indicators placed throughout the glovebox. The chemical indicators were used to provide a real time "go/no-go" verification of vaporous hydrogen peroxide exposure. The biological indicators, certified with a known spore count, were used to validate the microbial reduction process.

The INL has developed a process, though not yet approved by NASA, for performing the sterilization of RPSs and associated components using vaporous hydrogen peroxide. Testing and validation has been performed to demonstrate that the required magnitude microbial reduction could be accomplished. An overview of the vaporous hydrogen peroxide microbial reduction cycle development, testing, challenges, and results will be presented.

**Keywords:** vaporous hydrogen peroxide, planetary protection, sterilization, microbial reduction.





# Safety Analysis for the Kilowatt Reactor Using Stirling Technology (KRUSTY) Test

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**Abstract.** The Kilowatt Reactor Using Stirling TechnologY (KRUSTY) is a prototypic nuclear-powered test of a 5-kWt KiloPower space reactor. The test is slated to occur in FY17 at the Nevada National Security Site (NNSS) National Criticality Experiments Research Center (NCERC). The test will include a 32 kg Highly Enriched Uranium-Molybdenum alloy core, eight sodium heat pipes for heat removal, two ~125 watt Stirling Engines for power conversion, six Stirling Engine simulators, and a Beryllium Oxide Reflector. The experiment will be enclosed in a vacuum chamber to simulate outer space conditions and the Stirlings will be cooled by nitrogen gas instead of a radiator.

In order to perform the test, the test had to be analyzed for new hazards, new accidents or other conditions that would be outside of the existing safety analysis for the critical experiments. For the KRUSTY experiment this resulted in a Safety Basis Addendum that is specific to this experiment and is one time use only.

The Safety Basis Addendum contained a description of the experiment, a detailed identification of hazards, a hazards analysis and a detailed accident analysis. Several new hazards were identified for the KRUSTY experiment, including sodium in the heat pipes, pyrophoric uranium, nitrogen gas used as a coolant and the increase in excess reactivity over what is currently allowed. Of these hazards, the increase in reactivity was deemed significant enough that further analysis was warranted. Therefore new set of accidents were analyzed that all deal with the addition of reactivity that is beyond the current limit of $0.80. The $0.80 cent limit was set in the original safety analysis to ensure that the critical experiments always operate on delayed neutrons, thus most reactivity insertion accidents that could melt or disrupt the fuel are precluded. The $0.80 also limits the temperature of the fuel, since the fuel expansion from heating introduces a negative temperature feedback that must be overcome by the excess reactivity. Since the KRUSTY experiment is designed to achieve a peak fuel temperature of approximately 800 C, calculations show that $1.70 in excess reactivity is needed to achieve that temperature. Given uncertainties in the materials approximately $2.00 is anticipated to be loaded on the critical experiment machine. The increased excess reactivity gives rise to the potential of accidents that could cause the fuel to melt. These accidents are generalized into three types of accidents and include, 1) a step insertion of reactivity, 2) a reactivity rate of insertion accident, and 3) a melt from an over-loading of reactivity.

This paper focuses on the analysis of the reactivity insertion accidents. The analysis includes the calculation of the potential dose to onsite workers and the public. The analysis also examines the behavior of the system during the transient phase of the accidents. A coupled neutronics and heat transfer model called FRINK, is used to examine both the thermal response of the core while approximating the corresponding reactor power during these accident transients. Finally, the types of controls that can prevent or mitigate the accidents are evaluated. Controls such as the design of the experiment, the design of the critical experiment machine, the use of a neutron source and the actions of the operators either prevent the accident from occurring or greatly diminish its likelihood. The DOE regulator must approve the accident analysis and the controls derived from this analysis before the experiment can be performed..

**Keywords:** Space Nuclear Power, Space Fission Reactor, Heat Pipe Reactor, Nuclear Safety, Safety Analysis

# The Paucity Problem: Where Have All the Space Reactor Experiments Gone?

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**Abstract.** The Handbooks of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and the International Reactor Physics Experiment Evaluation Project (IRPhEP) together contain a plethora of documented and evaluated experiments essential in the validation of nuclear data, neutronics codes, and modeling of various nuclear systems. Unfortunately, only a minute selection of handbook data (twelve evaluations) are of actual experimental facilities and mockups designed specifically for space nuclear research. There is a paucity problem, such that the multitude of space nuclear experimental activities performed in the past several decades have yet to be recovered and made available in such detail that the international community could benefit from these valuable historical research efforts. Those experiments represent extensive investments in infrastructure, expertise, and cost, as well as constitute significantly valuable resources of data supporting past, present, and future research activities. The ICSBEP and IRPhEP were established to identify and verify comprehensive sets of benchmark data; evaluate the data, including quantification of biases and uncertainties; compile the data and calculations in a standardized format; and formally document the effort into a single source of verified benchmark data.

The recovery of space nuclear experiments before they become permanently lost plays a synergistic role with current-day needs and could be of great service to unknown future efforts. Numerous experiments were performed investigating the capability to construct and operate autonomous compact nuclear reactors in harsh, remote locations. Such capabilities are of interest supporting development of small modular reactors for terrestrial applications. Unique materials such as tungsten, tantalum, lithium, and potassium, to name a few, were investigated in some of the space programs. Some of these experiments may represent our best, if not only, experiments available for refinement and integral validation of some nuclear data libraries. Interest in advanced modeling and simulation of multiphysics experiments can benefit from modern space nuclear experimentation, which includes the measurement of thermal, hydraulics, or material effects coupled with the neutronic conditions. Fission product buildup, minor actinide cross sections and decay properties, and radiation shielding aspects for building advanced fast reactors have needs that must be addressed to support both terrestrial and space nuclear applications.

So where have all the space reactor experiments gone? More importantly, what must be done to preserve these components of our nuclear heritage before the usefulness of what remains to be recovered becomes insignificant? Recorded knowledge beyond summary reports and journal articles such as logbooks, memos, and drawings need located and digitized. While the time and cost necessary to completely evaluate all space nuclear experiments is limited, the first key step is to recover and preserve what can be found, making that information publicly available such that we enable our next generation of nuclear scientists and engineers to someday evaluate and apply the information before designing and implementing next generation test facilities and reactors. Otherwise, if we continue to ignore, and effectively support, this paucity problem, our next generation may well take its first steps reinventing heritage space nuclear research.

**Keywords:** Benchmarks, Data, Experiments, Preservation, Validation.





# The Aerospace Nuclear Science & Technology Division of the American Nuclear Society

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**Abstract.** The Aerospace Nuclear Science & Technology Division (ANSTD) of the American Nuclear Society (ANS) was founded in 2008 after evolving from a technical group established in 2000. The ANSTD was created to play an integral role in the nuclear community by promoting the advancement of knowledge in the use of nuclear science and technologies in aerospace applications. Membership in ANSTD grew rapidly to over 500 members and typically maintains between 500 and 600 members annually, representing approximately 5 to 6 % of total ANS membership. Many ANSTD members herald from academia or are students, with the remaining participants representing government, utilities, industry, military, etc. As a smaller division of ANS, there is much room to grow. Opportunities to participate in ANSTD include leadership roles on the Executive Committee, development of ANSI/ANS standards for space nuclear applications, preparation of space nuclear policy statements, and technical presentations and tutorials at ANS conferences and topical meetings. The ANSTD supports the annual topical meeting, Nuclear and Emerging Technologies for Space (NETS), providing a major communications network and forum for professionals and students engaged in space nuclear technology and applications. The NETS conference was organized to replace the historic traditions of the Space Technology and Applications International Forum (STAIF) held annually in Albuquerque, New Mexico. The aim of ANSTD is to continue to provide avenues such as NETS as well as public support for the application of space nuclear technology; interested individuals are encouraged to become actively engaged in current and future ANSTD activities. While many challenges remain to be addressed as a whole for nuclear science and technology, other unique challenges to space nuclear activities also exist. One of the most dominant challenges lies in the exponentially growing necessity to not just preserve data, but the knowledge behind that data, such as background information, know-how, and experience. The path forward will require a concerted effort to identify, prioritize, and address these issues. The ANSTD provides an avenue for focused participation to not just promote space nuclear science and technology, but address the challenges along the way.

**Keywords:** Aerospace, Nuclear, Science, Technology, Division.

# An Alternative Solvent Extraction Flowsheet for Separating $^{238}Pu$ from $^{237}Np$

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**Abstract.** In the UK, a strategy of reprocessing spent nuclear fuel has led to a detailed understanding of solvent extraction technology to separate the uranium and plutonium from highly radioactive fission products using the well-established Plutonium Uranium Redox Extraction (PUREX) process. One of the troublesome elements in PUREX is neptunium, which can be distributed throughout the various products and waste streams because of the complicated oxidation/reduction chemistry. Such behavior requires the use of additional purification cycles to remove neptunium from the uranium and plutonium products; at considerable cost and increased volumes of waste. Over the last two decades the National Nuclear Laboratory has compiled a large body of experimental data to help understand the kinetics and thermodynamics of neptunium species under conditions of relevance to the PUREX process.

This expertise has recently been applied to the issue of separating neptunium from plutonium in the production of $^{238}Pu$ heat source material at the Oak Ridge National Laboratory hotcells. Targets of $^{237}Np$ are irradiated in the High Flux Isotope Reactor to give $^{238}Pu$, unreacted $^{237}Np$ and fission products. Data published by NNL has been utilized in defining a solvent extraction process where all of the neptunium and plutonium is extracted and separated form radioactive fission products. Neptunium is then selectively removed from the solvent to give an aqueous phase product leaving the plutonium, which is stripped separately from the solvent. The neptunium is then purified and recycled into new targets for $^{238}Pu$ production and the plutonium is further purified before fabricating into heat source pellets.

While this process has been demonstrated successfully on real irradiated materials, the amounts of neptunium in the plutonium product can be improved. Also, the stripping reagent for the separation of neptunium adds sodium to the neptunium product, which needs to be removed using ion exchange columns. NNL have proposed an alternative flowsheet that will provide pure products, without any sodium, by taking advantage of the difference in the kinetics of reduction between Pu(IV) and hydroxylamine nitrate (HAN) and Np(VI) and HAN.

This presentation will detail some of the experimental work that has been performed to underpin this flowsheet and detail the chemical modelling results that have been used to guide the flowsheet design. Batch tests have been performed to demonstrate the selective reduction of Np(VI) over Pu(IV) by HAN, with good separation factors over a range of acidities. The flowsheet chemical models will be discussed together with some preliminary results from a flowsheet trial using centrifugal contactors.

**Keywords:** Plutonium, neptunium, solvent extraction, purification.





# The Preparation of $^{241}Am$ Oxide Pellets Under Oxidizing and Reducing Atmospheres

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**Abstract.** Over the last few years there has been an increased interest by the European Space Agency (ESA) to develop radioisotope power systems for space missions and a study was initiated to explore the development of radioisotope powered systems suitable for producing heat and electrical power. A wide range of isotopes were considered and while $^{238}Pu$ was the most attractive from a performance perspective, the most accessible and economically viable isotope in Europe proved to be americium-241 ($^{241}Am$) with a half-life of 432.7 years and a specific thermal power output of 0.1146 $W_{th}/g$.

The radioisotope $^{241}Am$ is a by-product of the civil nuclear energy industry. Over the last few decades France and the UK have provided a service to reprocess spent nuclear fuel from nuclear reactor sites, separating the uranium and plutonium and storing these products as the oxides ready for reuse in new fuel. Some of the plutonium has been stored for many decades and one of the isotopes ($^{241}Pu$), present within the plutonium, has beta decayed to the isotopically pure $^{241}Am$. A programme of work was initiated by ESA in 2009 to develop a process to isolate $^{241}Am$ from plutonium dioxide ($PuO_2$), while separate parallel studies established how the isotope would be incorporated in to power systems. The method for chemical separation is now well developed, with research now focused on the formation of ceramic pellets.

In this paper a description of the thermodynamic properties of americium at high temperatures will be discussed followed by the results of a small programme of pellet pressing and sintering using americium dioxide isolated from aged civil plutonium dioxide. The pellets were pressed and sintered within a hotcell facility using remotely operated manipulators to handle samples safely. The influence of sintering atmosphere on the stoichiometry and density of the resultant pellets will be reported together with powder X-Ray diffraction and Raman spectroscopy results.

**Keywords:** Americium, sintering, thermodynamics, density, crystal phases.

# Development and Utilization of Space Fission Power and Propulsion Systems

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**Abstract.** Space fission power and propulsion systems can enable robust space architectures and the sustained exploration and development of space. However, the benefits of such systems will only be realized if they are affordable and viable to develop and utilize.

Some space fission systems may require the use of highly enriched uranium (HEU) to achieve adequate performance. However, many systems can use low enriched uranium (LEU) with minimal loss of performance. The use of LEU is consistent with current US policy, as stated in a 2012 White House Fact Sheet: "The United States is committed to eliminating the use of HEU in all civilian applications …" The use of LEU also enables significant programmatic flexibility, with the choice of participants and facilities not dictated primarily by the need to work with HEU. An additional (though still significant) benefit from using LEU is the direct savings from eliminating the cost of additional security at facilities not already handling HEU or other Safeguards Category 1 materials.

Rocket engines undergo a rigorous qualification and acceptance process. In addition, rocket engine testing typically requires a wide range of consumables and specific infrastructure. The ability to use an established rocket engine test facility in the development and qualification of nuclear thermal propulsion (NTP) systems could be a significant cost and viability advantage. An exhaust capture system designed to prevent radionuclides from being released into the environment could help enable NTP testing at such a facility.

Significant expertise related to the development and utilization of space fission power and propulsion systems exists within industry and universities. Drawing on that expertise, in addition to expertise available within NASA, DOE, and other government agencies, will be important to affordability and viability.

Fission systems are significantly different from radioisotope systems, and some modifications to the "nuclear" launch approval process may be required. Handling and pre-launch processing of fission systems may also be significantly different from radioisotope systems. Experience from over seven decades of terrestrial fission systems will be beneficial in many areas.

Although certain specifics are different, there is also significant commonality between the development and utilization of fission power systems and the development and utilization of fission propulsion systems. A coordinated approach amongst fission projects is also important.

**Keywords:** space nuclear power propulsion fission testing exhaust capture





# Impedance Spectroscopy of Neutron Irradiated $Bi_2Te_3$ Based Thermoelectric Modules for RTG Environments

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**Abstract.** The performance of the thermoelectric modules following exposure to neutron radiation is of significant interest due to the likely application of radioisotope thermoelectric generators (RTG) in deep space vehicles or planetary landers requiring prolonged periods of operation. In this study, thermoelectric modules with different unicouple aspect ratios (0.15 and 0.2) and microstructure (directionally solidified and polycrystalline) were investigated. Based on the operational conditions expected in a 200 $W_{th}$ americium-241 RTG design, it has been estimated that the thermoelectric devices will receive an integrated flux of ~ $5x10^{13}$ neutrons/cm$^2$. To simulate such an environment, the thermoelectric modules were investigated experimentally via an acute (~2 hour) exposure in a research reactor at The Ohio State University – Nuclear Reactor Lab (OSU-NRL). After irradiation, a gamma spectrometer was employed to determine if any of the elements in the thermoelectric modules activated prior to shipping. To evaluate the thermoelectric properties pre and post irradiation, a characterisation technique utilising impedance spectroscopy (IS) was employed. A systematic shift and broadening of IS spectra were observed for all post irradiated modules. While this corresponded to an overall change in thermoelectric properties, all modules demonstrated more than sufficient radiation hardness. The effect of annealing and the implications for overall system performance will be reported.

**Keywords:** RTG, americium, bismuth telluride, Impedance Spectroscopy

# Enhanced Mechanical Properties in n-type $Bi_2Te_3$ Prepared by FAST-Deformation Processing

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**Abstract.** Initial design studies and a successful laboratory breadboard experimental campaign have demonstrated that $Bi_2Te_3$ based thermoelectric modules are a viable power conversion option for the European Radioisotope Thermoelectric Generator (RTG) development programme. However, Chalcogenides like $Bi_2Te_3$ alloys tend to have inferior mechanical properties compared to most thermoelectric families. Therefore, investigating ways to enhance their mechanical performance while maintaining excellent thermoelectric properties is highly desirable. Bismuth telluride crystals have clear anisotropy with a quasi-2D layered structure composed of a quintuple atomic series in the order of Te1-Bi-Te2-Bi-Te1 along the c-axis. This results in their electrical and thermal conductivities along the c-plane being approximately four and two time higher, respectively, than those along the c-axis. Unidirectional solidified $Bi_2Te_3$-based alloys exploit this by aligning the preferential orientation through coarse single crystals which stack on top of each other to form lamellar microstructures. While this allows for good thermoelectric properties, weak van der Waals bonding between neighboring Te1 layers leads to easy cleavage along the direction normal to the c-axis. By combining microstructural refinement through a field assisted sintering technique (FAST) and subsequent rapid recrystallisation through FAST assisted forging, this study demonstrates how mechanical properties can be enhanced without sacrificing thermoelectric performance. Mechanical properties such as micro and nano-hardness, elastic modulus, characteristic flexural strength, Weibull modulus and single-edge v-notch bending (SEVNB) fracture toughness will be reported.

**Keywords:** RTG, Bismuth Telluride, Mechanical properties





# Enhanced Lifetime Performance Predictions in Radioisotope Thermoelectric Generators (RTGs) Using Integrated SINDA / DEGRA Modeling Tool

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**Abstract.** Current Lifetime Performance Prediction Models (LPPMs) for radioisotope thermoelectric generators (RTGs) are one-dimensional models that do not provide sufficiently accurate temperature predictions and temperature resolution, or three-dimensional models with limited thermoelectric modeling capability to distinguish lifetime power degradation differences throughout a complex multi-couple RTG. The current LPPM, with its one-dimensional temperature capability, limits power degradation rate predictions (which are based on temperature) to only average assessments throughout any RTG. The lack of spatial resolution directly implies that RTG temperature and temperature gradient predictions have uncertainties associated with them because of unquantified internal heat flows; therefore, RTG lifetime power predictions will contain higher uncertainties because of these uncertain temperatures and temperature gradients. For example, Mars Science Laboratory recommendations for uncertainty in future power prediction were +/-6% at the beginning of mission to +/-10% at the end of mission, significantly higher and beyond the 4.8% per year Mars surface degradation observed to date.

This presentation describes a new integrated SINDA/DEGRA analysis model to improve our thermal and power predictive capability in LPPM to provide better RTG internal temperature predictive resolution (higher axial, circumferential, and radial fidelity), in order to better predict power degradation and lifetimes over the entire Mars 2020 mission and future potential mission profiles. This model is a three-dimensional, 459-node thermal/thermoelectric power model with eight circumferential temperature zones, eight axial temperature zones, and six radial temperature zones, which is integrated with the current LPPM modeling algorithms to predict temperatures and power more accurately and precisely. This is a necessary capability for RTG lifetime power predictions because refined knowledge of spatial temperature profiles and gradients within the MMRTG structure allow one to quantify spatially-dependent and distinguishable power degradation rates throughout an RTG system.

The new integrated SINDA / LPPM analysis model has been validated against current LPPM predictions for similar thermal conditions and is being validated against other life prediction models to improve and increase confidence in its predictive capability. This presentation will review our validation approach and the key validation cases across hot- and cold-environments, and validations with current LPPMs at JPL and at industry team members.

**Keywords:** Lifetime performance predictions, radioisotope power, thermal/thermoelectric analysis, SINDA/DEGRA

# A 40kWe Nuclear Reactor Power System Concept for Mars Base

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**Abstract.** With the development of space exploration technologies and urgent demand for resources exploitation, many countries have made their plans to explore the outer planets and deep space in the next few years. Mars is the closest planet to earth in the solar system, and its surface environment is close to the earth. So Mars has been the first choice for human exploration and immigration. In the mid of 2016, China announced the Mars exploration project and planned to launch a Mars probe before 2021. In the foreseeable future (~2040), China will actualize manned Mars exploration and build a manned Mars outpost to prepare for future Mars resources utilization and immigration.

For human missions, power requirements may vary from 10s of kWe to support initial human visits to 100s of kWe for a permanent Mars base, especially if in-situ resource utilization processes are required. In such output power range, a preponderant planetary surface nuclear power is being considered because it can provide constant and enough energy for human life-support systems, recharging rovers, mining for resources, and so on, despite of the rough Mars environment. Alternatives such as solar power systems are limited. Because of the big distance from the Sun and the attenuation through the atmosphere, insolation at the Martian surface is reduced, and the value decreases significantly with dust storms.

A Mars nuclear power system is different from traditional nuclear reactors because of the special application environment. The system should be small, compact, robust and low mass to satisfy the launch requirement. The system should be simple and highly reliable because it is difficult, even impossible to maintain the reactor in the Mars. The system should be safe and easy to operate considering lack of professional operators. The system must be suitable for the Mars environment such as corrosive, carbon-dioxide atmosphere.





# Overview of Rayleigh-Taylor Instability and the Impact on Target Design for a Pulsed Fusion / Fission Propulsion System

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**Abstract.** This document presents an overview of the Rayleigh-Taylor instability for a pulsed z-pinch target. The overview presents information gathered in an ongoing literature review on the subject. Theory and past work is discussed. This instability is of particular interest to the authors due to its importance in the magnetic inertial confinement of fusion and fission fuels in a z-pinch. A related z-pinch based fusion/fission propulsion system is reviewed. The influence of the Rayleigh-Taylor instability upon the design of a z-pinch target is discussed, specifically in how it relates to a pulsed fusion/fission propulsion system. The paper concludes with a discussion of future work in regards to how to address and manage the instability to achieve the density and confinement time required to burn an adequate percentage of the fuel.

**Keywords:** fusion, fission, plasma, instability, z-pinch, advanced propulsion

# Progress on Fusion Modeling and the Charger-1 Pulsed Power Facility at UAH

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**Abstract.** This paper summarizes the current progress in fusion modeling activities and the operational status of the Charger-1 pulsed power facility at the University of Alabama in Huntsville. We review the current efforts in modeling fusion burn processes through incorporation of stopping power routines in a 3-D smoothed particle hydrodynamics code followed by discussion of some burn scenarios of interest. This discussion is followed by a summary of the progress to date on the initial operational capability of the Charger-1 pulsed power facility. We will describe what has been accomplished, what is left to be completed, and the initial tests being performed on the system. Finally, the future direction of research activities at UAH is discussed with a focus on the long-term goal of an operational fusion propulsion system to enable routine trips to and from Mars.

**Keywords:** fusion, z-pinch, advanced propulsion





# A Nuclear Engineering Board Game for Education and Outreach

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**Abstract.** (10 point) Nuclear engineering projects have been faced with much public and political opposition throughout the decades. Much of this opposition can be attributed to widespread misconceptions about nuclear technologies. To combat this, it is important to help inform the general public of the safety inherent in many nuclear reactor concepts, and why nuclear engineering is vital for the future of energy production. A board game is presented that can be used for such educational outreach efforts. The objective of the board game is to collect cards needed to build one of ten different nuclear reactor designs, which include molten salt breeder reactors, pressurized water reactors, and advanced gas-cooled reactors. The cards list different reactor components, such as fuel, coolant, and shielding. Each card also contains many useful facts about nuclear engineering fundamentals that the general public may not know. No engineering experience is required to play this game, and can be played across any age group. This game presents a useful opportunity to spread awareness of how important nuclear engineering is for society.

**Keywords:** Board game, reactor design, education, outreach

# Nuclear Rocket CERMET Fuel Fabrication using Tungsten Powder Coating and Spark Plasma Sintering

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**Abstract.** Nuclear thermal propulsion (NTP) is an enabling technology for crewed Mars missions. Nuclear thermal rockets (NTR) offer performance advantages over traditional chemically propelled spacecraft (liquid engines, solid motors, etc.). Key to the development of an NTR is a robust nuclear fuel material that can perform in the harsh high-temperature hydrogen environment of an NTR. An investigation was conducted to evaluate spark plasma sintering (SPS) as a method to produce tungsten (W) – depleted uranium dioxide ($dUO_2$) ceramic-metal (CERMET) fuel material when employing fuel particles that were coated using tungsten powder coating (WPC). The goal was to produce fuel material that exhibited a uniform distribution of $dUO_2$ fuel particles within the W matrix. SPS is a process that utilizes electric current and pressure to rapidly sinter powder into a dense consolidated material. Advantages of SPS over conventional sintering techniques include decreased sintering times resulting in minimal grain growth, highly densified post-sintered materials, and the ability to produce net-shape or near net-shape parts. Prior to sintering, the $dUO_2$ fuel particles were coated with W using a WPC. WPC uses an organic binder to paste the smaller W powder to the surface of the fuel particles. The investigation focused on the density and microstructure to assess the ability of this fabrication method to uniformly distribute the fuel particles within the W matrix. CERMET fuel wafers were produced from a blend of W-60vol% $dUO_2$ powder that was sintered via SPS. The maximum sintering temperatures were varied from 1600 °C to 1850 °C while applying a 50 MPa axial load. Immersion density measurements were obtained and the microstructure was evaluated using scanning electron microscopy (SEM). Wafers exhibited high density (> 95% of theoretical) and a uniform microstructure (fuel particles uniformly dispersed throughout W matrix). The study shows that WPC improves the microstructure when compared to fuel materials produced with uncoated fuel particles. Future research will focus on a means to transform fuel wafers into prototypic fuel elements for NTR applications.

**Keywords:** Nuclear Thermal Propulsion, Fuel Material, CERMET, Tungsten, $UO_2$, Spark Plasma Sintering.





# Investigating the Effects Shielding and Astronaut Position Have on Effective Dose Outside the Lower Earth Orbit

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**Abstract.** On October 11, 2016, President Obama reaffirmed the United States' goal to have a manned mission to Mars by 2040 [1]. To accomplish this goal, radiation protection must be in place to shield astronauts from the two main sources of space radiation: Galactic Comic Rays (GCR) and Solar Particle Events (SPE). GCRs, which are composed of highly energetic and fully ionized elements, are considered a chronic source of radiation exposure and account for the majority of the background radiation. SPEs, which originate from solar flares and are composed of mostly protons, are spontaneous and vary in magnitude, composition and duration. As a space vehicle travels out of lower earth orbit into deep space, the vehicle is exposed to both high energy radiation sources; therefore, to determine human risk from this exposure, the whole body effect dose equivalent ($H_T$) is evaluated using various human phantoms, which are the computational representation of a human. Shielding composition, vehicle shape and astronaut position have been shown to effect $H_T$ as much as 40% [2], therefore the objectives of this research are to assess and verify how space radiation is modeled and to evaluate its attenuation through shielding material and the human body. The main goal of this work is to show how shielding and position affects $H_T$.

These objectives are accomplished using Los Alamos' MCNP and NASA's OLTARIS codes. MCNP, which stands for Monte Carlo N-Particle Transport Code, and OLTARIS, which stands for On-Line Tool for the Assessment of Radiation in Space, are both versatile transport models with the ability to account for nuclear reactions in shielding materials and biological systems. Each accomplishes these differently, with MCNP being a three dimensional transport model and OLTARIS being one dimensional. Multiple spacecrafts have successfully traveled from Earth to Mars, with one-way travel times ranging from 131 days by the Mariner 7 to 360 days by the Viking 2. For this research the focus mission time is 400 days [3], limiting the one way trip to 200 days. The results for this study will be expressed in the number of days of travel time until the exposure of 150 mSv (based on [4]) $H_T$ is reached. Since vehicle shielding depends on vehicle geometry, shielding material and shielding thickness, each involves a comprehensive evaluation of its effect on particle attenuation and $H_T$. NASA is currently in the process of building and testing a conical shaped spacecraft, named Orion, for their missions outside of lower earth orbit. Vehicle shapes investigated in this study are conical, spherical, right circular cylindrical and a cubical. Shielding materials investigated are aluminum, liquid hydrogen, liquid helium, polyethylene, and water. Composite materials are also evaluated.

This research also investigates the relationship between $H_T$ and astronaut position within these vehicle shapes. Those results are used to position rooms for an astronaut's everyday activity, such as living/lounging areas, work areas, and sleeping quarters.

**Keywords:** Radiation Shielding, Effective Dose, MCNP, OLTARIS, Mars

# Hot Hydrogen Testing of Silicon Carbide for Nuclear Thermal Propulsion Applications

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**Abstract.** Nuclear thermal propulsion (NTP) offers the potential of high specific impulse (850 - 900 s) and high inherent thrust (100 – 2,200 kN). However, a key feasibility issue is to identify robust fuel forms with adequate performance during operation in flowing hydrogen at extreme temperatures exceeding 2200°C. Maturation of new NTP fuel forms compliments the current development path by reducing risk associated with previously developed fuels and offering opportunities for breakthrough technologies that could enable new missions or capabilities. Silicon carbide (SiC) is a high temperature structural material of interest for nuclear and aerospace industry with a pre-existing irradiation property database and industrial-scale manufacturing facilities. In order to evaluate the applicability of SiC for NTP applications, hot hydrogen testing of SiC-based materials is being performed at NASA Marshall Spaceflight Center (MSFC) in the Compact Fuel Element Environmental Test (CFEET) facility. Three grades of SiC samples are undergoing testing: 'Nano-Infiltrated and Transient Eutectic' (NITE) process SiC, chemical vapor deposition (CVD) SiC, and chemical vapor infiltration (CVI) composite SiC-SiC. The samples are evaluated in a hydrogen ($H_2$) environment at temperatures between 2000 – 2500 K to determine maximum operating temperature and mass loss rates for exposure times ranging between 0.5 to 2 hours. The SiC materials were mechanically polished to a mirror finish prior to the $H_2$ exposure, and the corrosion behavior and near-surface microstructure following $H_2$ exposure was quantified using a combination of microbalance measurements, optical characterization, scanning electron microscopy, and transmission electron microscopy. This presentation will overview the results of the experiments and characterization of the material pre- and post-hot hydrogen testing.

**Keywords:** Nuclear Thermal Propulsion, Fuel Material, Hot Hydrogen Testing, Silicon Carbide





# Analysis of Operating Strategies Utilizing Different Target Designs for $^{238}$Pu Production

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**Abstract.** A multi-laboratory team, including Oak Ridge National Laboratory (ORNL), Idaho National Laboratory (INL), and Los Alamos National Laboratory (LANL), is re-establishing domestic production of $^{238}$Pu for use in power supplies for deep space missions. The process being developed includes retrieval of $^{237}$Np feed stock material from storage at INL; transportation of the material to ORNL; pressing and sintering of the material to make pellets; incorporation of the pellets into Al-clad targets; irradiation of targets to produce $^{238}$Pu; chemical processing of the targets to separate the Pu; conversion of Pu to an oxide; and transportation of the oxide to LANL where the Pu will be used to produce radioisotope thermoelectric generators (RTGs). A process optimization study of only the chemical processing section of the process was recently completed. The study used discrete-event simulation to evaluate the effects of operational detractors on the $^{238}$Pu production rate. Although process behaviors were varied in the study, the target design was held constant in all simulation scenarios. The study concluded the full-scale $^{238}$Pu supply process is likely capable of achieving its production goal under some conditions, but additional changes are needed to increase the likelihood of success.

This study examines the effect of changing the target design on the $^{238}$Pu production rate. Two target configurations are considered – an Al-clad target containing 50% greater $^{237}$Np oxide content than the original target, and a zirconium alloy-clad target containing no aluminum. The results of this study indicate use of the Al-clad target with increased $^{237}$Np oxide content should allow the process to achieve its $^{238}$Pu production goal using fewer targets in less time. If the zirconium alloy-clad target is used, then even fewer targets would be needed to reach the production goal, but some process changes would be required to handle the zirconium cladding. Multiple production scenarios are simulated using each target type (original target design, modified Al-clad target design, zirconium alloy-clad target design), and the simulation results for the yearly process output and total time to completion are compared.

**Keywords**: Discrete, simulation, process, neptunium, plutonium

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# Optimal Nuclear Thermal Propulsion Thrust Level for Human Mars Exploration

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**Abstract.** Future human exploration missions to Mars are being studied by NASA and industry. One of the key architecture decisions involves selecting the propulsion used to transport the crew from Earth orbit to Mars. Nuclear Thermal Propulsion (NTP) is a proven technology that provides the performance to enable significant benefits for crewed missions to Mars due to its high specific impulse. The potential benefits to human Mars exploration include: reduction in interplanetary transit time for astronaut safety and health; reduced launch mass for improved affordability; increased payload mass; improved abort options; and widened launch and departure windows for mission flexibility.

Aerojet Rocketdyne (AR) performed an extensive study to assess the optimum NTP engine thrust for a Mars campaign involving crewed missions in 2033, 2039, and 2043. The study assumed a set of ground rules and assumptions consistent with a NASA Evolvable Mars Campaign (EMC) architecture that uses low-thrust Solar Electric Propulsion for efficient delivery of cargo to Mars and high-thrust propulsion to more rapidly transport the crew to Mars. Building on NASA work, AR assessed NTP as the high-thrust propulsion option to transport the crew.

The impacts of NTP vehicle configuration, number of engines, engine out capability, Earth aggregation/departure orbit, payload mass, and transfer time on optimal engine thrust were assessed. Prior NTP mission architecture studies were also assessed to determine the impact of different architecture scenarios on NTP thrust level. In addition, NTP engine development constraints on thrust size were included in the assessment. This paper provides results of the study and provides a recommendation and associated rationale for an optimal NTP engine thrust level.

**Keywords:** Nuclear, Mars, EMC, Thrust, Propulsion.





# The NASA Radioisotope Power Systems Program--An Overview and Plans for the Future

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**Abstract.** The NASA Radioisotope Power Systems (RPS) Program works with the United States Department of Energy (DOE) to ensure the availability of RPS for missions that are significantly enhanced or enabled by their use. The RPS Program funds activities at the DOE that include the production and processing of plutonium 238 fuel and certain activities associated with the analysis of risk pertaining to the launch of nuclear materials. The program also funds work within NASA that centers on the production of electrical power from the heat of decay of the isotopic fuel. This work involves the more traditional static thermoelectric conversion technologies and also dynamic power conversion devices driven via thermodynamic cycles. To ensure that this portfolio is germane to the needs of the science community, the program also conducts systems and mission analyses that engage the science community via Surrogate Mission Teams that consider the environments and requirements for planned missions. Over the past year the program has made significant strides in the development of new thermoelectric chemistries, and the transfer of skutterudite technology to industry. Studies are also underway for a next generation Radioisotope Thermoelectric Generator (RTG) that may prove the need for modular systems to maximize applications based on mission class and target. In the dynamic conversion arena, a procurement was initiated for a potential development of a robust system targeting the 300-500W power regime. This presentation describes these efforts and lays out the plans for the development of these systems, the applicable mission sets, and the resulting demands on the plutonium inventory.

**Keywords:** radioisotope, skutterudite, plutonium 238, thermoelectric

# Idaho National Laboratory Radioisotope Power Systems Nuclear Operations: Readiness Assessments Supporting a Nuclear-enabled NASA Mission

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**Abstract.** The Radioisotope Power Systems (RPS) Program, located at Idaho National Laboratory (INL), is responsible for assembling, testing, and delivering plutonium oxide-fueled RPSs for use in powering missions in remote, harsh environments such as deep space. An informative presentation will be given discussing the readiness assessments involved in performing nuclear operations to support providing these systems to end users for the Department of Energy (DOE). Readiness for start-up is determined through independent assessment against established acceptance criteria to ensure activities can be performed safely and within a well-defined nuclear safety envelope. There is also an RPS Program approval element for product quality requiring additional readiness review before nuclear operations can begin. Typically, the assessments/review criteria requires, at a minimum, review of operating instructions to ensure technical safety requirements are adequately identified, review of training records to ensure personnel are adequately trained to perform the specified work scope, personnel are interviewed to determine adequacy of level of knowledge for work scope, and a high-fidelity performance of the operation to ensure the operating instructions and conduct of operations are adequate to perform the work scope. As each assessment/review is conducted, a formal report delineating any issues in the form of findings, observations, and noteworthy practices will be issued. Before start-up approval is obtained, all issues must be resolved to the satisfaction of the individual teams. Approval for start-up is formally communicated by memorandum from DOE. Programmatic approval is also formally communicated where vested Program representatives in the RPS community (to include DOE Nuclear Energy (DOE NE) and DOE Idaho Operations Office (DOE ID) representatives) ensure personnel, documentation, and materials are in place to perform the activity. RPS assembly and testing operations to support the Mars 2020 Mission, the next planned space mission using a nuclear power system, will require about of year of assessments/reviews before the nuclear operations are performed. From a regulatory perspective, Title 10 of the Code of Federal Regulations (CFR), Part 830[1] governs DOE and its contractors conducting activities that affect, or may affect, the safety of DOE Nuclear Facilities. Further, DOE Order 425.1[2] and 414.1[3] establish requirements to verify readiness for startup or re-start of Hazard Category 1, 2, and 3 nuclear-facility activities and to ensure products and services meet or exceed customer's requirements and expectations, respectively.

**Keywords:** INL, Operations, Assessments, DOE, Quality Assurance, QA





# Cassini Power Subsystem

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**Abstract.** Cassini's power source output has been decaying consistently during the twenty year mission between October 1997 and September 2017. We present the power telemetry data for the entire Cassini mission from launch to the most recent available data of the mission. The spacecraft has been powered by three independent Radioisotope Thermoelectric Generators (RTGs) connected in parallel and was able to generate 882 W at the beginning of the mission shortly after launch. We present here the recorded power data during Cassini's cruise to Saturn and during the Saturn orbiting period. Decrease in power energy output was mainly driven by the heat reduction of the hotside of the RTGs due to radioactive decay of plutonium 238 ($^{238}$Pu), degradation of thermoelectric material performance, and interface degradation.

The power source of the Cassini Power and Pyrotechnic Subsystem (PPS) consists of three RTGs. The RTG is a thermoelectric conversion power generating system composed of a heat source, $^{238}$Pu, and a cool side, that converts thermal energy to electrical energy using the Seebeck effect. During the entire Cassini mission, the power output data has been communicated to earth and recorded through telemetry data. The exponential $^{238}$Pu decay and material/interface degradation caused a 30.5% power degradation over 19 years, which was expected per current lifetime performance prediction models (LPPMs). The comparison of LPPM predictions to actual-power-data was redefined in April 2013 and show good agreement within about 0.3%. This paper will discuss the comparisons and reasons for the small prediction/data deviations. Other external environmental effects due to spacecraft control events can have an impact on the power output of the spacecraft. Environmental temperature variations and different solar exposure can increase the temperature of cool side of the thermoelectric device and therefore decrease the power output. These spacecraft control events will be discussed and correlated to various power variations seen in the Cassini power telemetry data.

**Keywords:** Cassini, Power, RTG.

# Three Dimensional Modeling of Pulsed Fission Fusion (PUFF) Targets for Advanced Propulsion

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**Abstract. .** A three dimensional model of pulsed fission fusion (PUFF) hybrid targets is presented. The purpose of this work is to explore some effects of initial conditions (temperature and density of fusion fuel, thickness of fissile material, and thickness of each layer) on the overall reaction rate and energy gain obtained from the coupled fission and fusion reactions for targets of ~1 cm scale length and yields of $10^6$ to $10^9$ J per pulse. The hydrodynamics and equations of state are modeled with a smooth particle hydrodynamic (SPH) code. Reaction rates are based on local SPH particle properties. A neutron diffusion model is used to determine the local neutron flux. Single pass ray tracing from a point source accounts for charged particle transport from the fusion products through the surrounding material





# Study on Small CANDLE Burnup Reactor for Space Nuclear Power

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**Abstract.** Historically, plutonium-238 has been proven to be the best radioisotope for the provision of space nuclear power because of its high specific power, enough half-life, low radiation levels, and stable fuel form at high temperature. However, current concerns over the limited supply and difficult treatment of $^{238}$Pu have increased the need to explore alternative isotopes for space nuclear power applications. This study propose a small CANDLE burnup reactor as a heat source to be an alternative of plutonium-238. The CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy producing) burnup strategy was proposed by Sekimoto *et al.*, which does not require a burnup reactivity control instrument such as a control rod, chemical control. For this burn-up strategy, distributions of fuel nuclide densities, neutron flux and power density move with the same constant speed and without any change in their shapes. In this study, we designed a small CANDLE reactor without any dynamic instrument nor coolant. The heat by fission reactions is directly converted to electrical energy by thermoelectric devices. The conceptual design of the small CANDLE reactor core consists of uranium-zirconium hydride fuel included gadolinium-157 as burnable poison and a beryllium reflector. The reactor core provides 20 kWth-1 kWe power for over 20 y. For the burnup calculations, MVP-BURN code was used with JENDL-4.0 nuclear data library. As a results of the optimization, the core structure was UZrH (90% enrich uranium) fuel of 100 cm height and 14 cm in diameter surrounded by a beryllium reflector of thickness 9cm. The total core weight was 224 kg and the specific power was 89 W/kg. In this design, the moving speed of burning region was 0.64 cm/year. This study showed that the CANDLE burnup reactor was feasible for such small reactor core.

**Keywords:** space nuclear reactor, CANDLE burnup, uranium-zirconium hydride, burnable poison.

# Radioisotope Thermoelectric Generators and Heater Units for the European Space Nuclear Power Programme

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**Abstract.** Radioisotope thermoelectric generators (RTG) and heater units (RHU) systems are under development in Europe as part of a European Space Agency (ESA) funded programme. Aimed at enabling or significantly enhancing space science missions, the development programme relies on the cost effective production of americium-241 as the radiogenic heat source and an iterative engineering approach to developing the systems which include isotope containment architectures and in the case of RTG systems bismuth telluride based thermoelectric generators The RHU configuration is based on a 3 W thermal power output has been designed, analysed and electrically heated and mechanical models are in production. The RTG and RHU containment systems rely on the use of the same containment materials: inner platinum-rhodium alloy cladding, insulation layers based on carbon-bonded-carbon-fibre and quasi-isotropic carbon-carbon composite outer aeroshells. The RTG heat source configuration is designed to deliver 200 W of thermal power output while minimising the volume occupied by the fuel. A 5% total system conversion efficiency and a modular scalable design imply that electrical power output can range between 10 W and 50 W given that each RTG system could house up to 5 heat sources. This paper describes the most recent updates in system designs and provides further insight into recent laboratory prototype test campaigns of both RTG and RHU systems.

**Keywords:** space nuclear power, americium, thermoelectric, generator, heater, unit.





# Aeroshell Re-entry Modelling and Testing for European Radioisotope Thermoelectric Generators and Radioisotope Heater Units

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**Abstract.** Radioisotope thermoelectric generators (RTG) and radioisotope heater units (RHU), based on americium-241, are under development in Europe as part of a European Space Agency (ESA) funded programme. The design and architecture for both RTG heat sources and RHUs has been evaluated under re-entry conditions as part of a study to determine how the architecture would cope with launch safety re-entry scenarios considered as part of the ESA project. This modelling exercise has been carried out and the initial results with a focus on the aeroshell structures are highlighted in this paper. A number of quasi-isotropic carbon-carbon composite materials have been selected for the aeroshells for both RTG heat sources and RHUs and the modelling involved determining how re-entry scenarios would affect recession depth, heat fluxes and stresses on these aeroshell structures. In order to determine how a typical aeroshell material would perform under such extreme conditions, an experimental campaign at the Laser Hardened Materials Evaluation Laboratory (LHMEL) at Wright Patterson Air Force Base in Ohio was carried out and the initial results are presented in this paper. The campaign involved both static (or worst case) and rotating (simulating tumbling) experiments. The outputs from the modelling work were used to inform the test campaign.

**Keywords:** americium, radioisotope, thermoelectric, generator, heater, unit, aeroshell, re-entry, testing

# Architecture, Structural and Thermal Analysis of an $^{241}$Am Fueled Radioisotope Heater Unit

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**Abstract.** A 3 W thermal radioisotope heater unit (RHU) prototype fueled with $^{241}$Am has been designed and analysed within the framework of ESA Radioisotope Power System programme. The aim of the system is to provide localised heat to critical spacecraft elements, offering the advantages of long-duration thermal energy input and no moving parts. The RHU general architecture consists of a multi-layer containment approach, which has a platinum-30%rhodium inner containment structure surrounded by insulation layers and outer aeroshell consisting of a carbon-carbon composite. Two configurations with different thickness for the insulation layer (3 mm and 6 mm) have been investigated; this has been partly driven by the manufacturability of the thinner carbon-bonded-carbon-fibre insulation sleeve. The prototype design providing 3 W of thermal power makes this design competitive with existing models on specific power. Finite element structural and thermal analyses have been performed and the results of the thermal and structural analysis are presented. Initial estimates show that the fuel centre-line temperature will reach ~150°C and that the natural frequencies of the RHU are all expected to be higher than 100-150 Hz. These results confirm the theoretical feasibility of the component as initially conceived.

**Keywords:** radioisotope, heater unit, americium, space nuclear power, thermal, mechanical, analysis





# Architecture, Structural and Thermal Analysis of an $^{241}$Am Fueled RTG Heat Source

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**Abstract.** A 10 W electric RTG system design has been developed and studied as part of the ESA radioisotope power system programme. The design is based on an $^{241}$Am fueled heat source and the objective of the ESA programme is to develop a European solution for a safe, continuous and near-constant supply of electrical power to the spacecraft subsystems. The heat source has a 6-side polygonal shape and a distributed 3-fuel clad architecture. The configuration is designed to accommodate six thermoelectric modules. The heat source is designed to deliver 200 W of thermal power, with an expected electrical power output of 10 W. This configuration allows to maximize the specific power of the RTG, since Am-based fuels have a lower power density of Pu-based fuels. The architecture of the heat source has been refined including the addition of insulation layers. Some of the properties of the layers have been measured and are reported. Finite element structural and thermal analyses have been performed and additional thermal analysis carried out by solving a heat balance equation for the outer layer. The results of the structural analysis are presented. The correlation between finite element analysis of the thermal performance and heat balance equation solutions are also presented. In addition, initial estimates of the overall thermal efficiency of the system are provided.

**Keywords:** RTG, space nuclear power system, thermal and structural analysis

# X-ray Diffraction Studies on Surrogates for Americium Oxides for European Radioisotope Power Systems

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**Abstract.** European Radioisotope Power Systems will be fuelled with an americium oxide heat source. This will require integral discs or pellets to be created with reproducible geometry, high relative density and well characterised mechanical properties. With few published investigations on americium oxides, conducting sintering studies with surrogate oxides helps to inform sintering trials with highly radioactive americium oxides by reducing the field of investigation.

Understanding the crystallography of a surrogate oxide prior to and post sintering is essential to understanding the crystallographic changes that may occur during the densification process. Such changes could impact disc/pellet integrity. Americium dioxide ($AmO_{2.00}$) loses oxygen at high temperatures, which can lead to sub-stoichiometric materials of the type $AmO_{2-(x/2)}$ where the americium is present as a mixture $Am^{3+}$ and $Am^{+4}$ ions occupying crystal lattice sites. It is in theory possible to make $CeO_{2-(x/2)}$ solids with similar mixed oxidation sites, however, these solids easily re-oxidise in air. To replicate this arrangement, non-radioactive surrogate materials have been used to simulate the +3 and +4 metal sites. Neodymium, $Nd^{3+}$ and cerium, $Ce^{4+}$ mixed oxides can be made by co-precipitating cerium and neodymium oxalate solids and decomposing them to the oxide $Ce_{1-x}Nd_xO_{2-(x/2)}$. These solids are stable in air and allow the crystal properties to be examined in detail.

Earlier studies outlined the synthesis and characterisation of a cubic (Ia-3) cerium-neodymium oxide, $Ce_{1-x}Nd_xO_{2-(x/2)}$, as a surrogate for certain $AmO_{2-(x/2)}$ species between $AmO_{1.65}$ and $AmO_{1.75}$, and also showed early X-ray diffraction (XRD) analysis results of spark plasma sintered (SPS) $CeO_2$. Quantitative X-ray fluorescence analysis of the Ce Nd oxides suggested they had an x-value with a small discrepancy (0.02) from the initial nominal target ratio of 0.60 dictated by the molar ratio of the Ce and Nd nitrate reagent inputs to the oxalate precipitation process. Initial XRD of the SPS discs indicated consistency with $CeO_2$ yet the grey colours suggested some reduction. Detailed XRD analysis (Rietveld refinement) results of the Ce-Nd oxide has been conducted and data are presented. An x-value for the material has been estimated from the lattice parameter using published Vegard-like laws for $Ce_{1-x}Nd_xO_{2-(x/2)}$ specific solid solutions. The results have been compared with the quantitative X-ray fluorescence results and checked for consistency. The SPS discs Rietveld refinement results are also presented. Lattice parameters have been measured and compared to $CeO_2$ to determine if there is an expansion that would be consistent with small amounts of reduction.

**Keywords:** cerium-neodymium oxide, cerium dioxide, surrogates, X-ray diffraction, americium.





# Performance of a Novel Betavoltaic Material

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**Abstract.** A novel betavoltaic semiconductor material created by Kinetic Energy Australia (KEA) was tested using Sr/Y-90 at the Pacific Northwest National Laboratory. Exposure to the beta radiation from a 2.55 Curie Sr-90 source with fully in-grown Y-90 (5.1 Ci total) produced approximately 2.5 milliW of power for an efficiency of approximately 28%. The generator material and radioisotope source were separated by a thin polymer film for ease of retreival and post-testing examination. The generator was left exposed to the beta radiation for a week, with no observed loss of generating ability. Comparison to other power systems currently in-use suggests this technology can provide significantly higher power at the same or lower weight. The technology could be used to produce a range of generator sizes, from microW to kiloW.

# 10 $W_e$ Radioisotope Thermophotovoltaic (RTPV) Power Source Demonstration

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**Abstract.** Long lasting, non-plutonium energy sources would serve well small underwater vehicles and deep space satellites with modest power requirements. Unlike their thermoelectric counterparts, thermophotovoltaic (TPV) energy conversion systems can easily achieve double-digit conversion efficiency without major advances in materials. The efficiency of a TPV system is largely dictated by the spectral control of the emitted (and absorbed) infrared radiation. Recent advances in selective emitter coatings -both photonic crystals and metamaterials- enable tailoring the emitted spectrum more suitable for conversion to electrical power at the photovoltaic cell than was possible before. Design for 1U CubeSat sized $AmO_2$/tungsten core radioisotope thermophotovoltaic power source producing 10 $W_e$ is presented, along with an electrically heated mockup for performance verification purposes. Radiation shielding analysis didn't reveal any major threat for the personnel or the photovoltaic (PV) cells. However, experimental data for low energy gamma radiation effects on PV cells is scarce. The work was conducted during the Summer Fellow program at the Center for Space Nuclear Research in Idaho.

**Keywords:** Thermophotovoltaic, radioisotope, americium





# A Risk-Informed Life Testing Framework for Uncertainty Characterization and Life Estimation

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**Abstract.** A framework for assessing and comparing the uncertainties associated with risk-driving parameters of any complex system would provide utility in decision-making endeavors. With this in mind, a study was conducted by NASA Glenn Research Center and The Johns Hopkins University Applied Physics Laboratory (APL) recommending the adoption of a risk-informed life-testing process to determine the target, nature, and extent of testing required for the demonstration of reliability of Radioisotope Power Systems. This paper presents the methodology for implementing such a risk-informed decision-making process through the combined use of physics-of-failure models and Bayesian inference techniques.

**Keywords:** Reliability, Uncertainty, Life-testing, Bayesian Inference, Failure modeling.

# Fuel behavior in Aging $^{238}PuO_2$ Heat Sources

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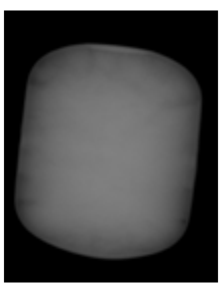
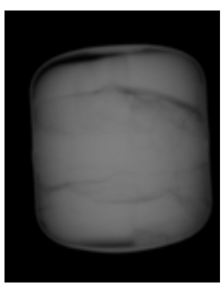
**Abstract.** Slight distension of cladding on unvented plutonium-238 oxide heat sources has been observed, and the origin of the distention investigated. The $^{238}PuO_2$ thermoelectric generator design takes advantage of the heat output of $^{238}PuO_2$ fuel and the long 87.7-year half-life of the plutonium to reliably generate electricity on a long timescale. The heat source consists of a $^{238}PuO_2$ ceramic fuel pellet welded into an iridium protective capsule or "clad," vented through an iridium frit to allow the helium from radioactive decay to escape the clad during the service lifetime of the heat source. During manufacture, the vent frit is protected by a thin iridium foil cover, a temporary fixture which protects the vent frit during the final decontamination steps that prepare the clad for use. This decontamination cover usually remains intact until immediately before the clad is put into service.

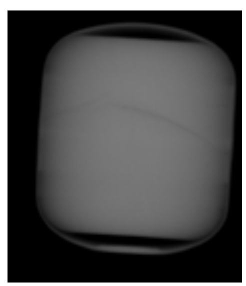
Distended clads have been studied in detail. Measurement of engineering strain, radiography of the fuel configuration, and measurement of the pressure and composition of internal gas indicate the condition of the fuel in these heat sources. Free volume within the clad has been measured. Measureable gas in most of these distended clads constitutes less than 1% of the total helium emitted over time. Gas pressure in these clads has been released through the vent frit, as designed, and through the decontamination cover and weld. Radiography suggests that the fuel swells until the emitted helium breaches the decontamination cover weld. Helium is then freely released by the fuel, and the fuel dimensions become stable. In hot environments, gas is evolved promptly from the fuel. The heat sources that have resided in hot environments show cracking of the pellet and very little distension of the fuel pellet volume. In the one example of a clad where the decontamination cover was deliberately removed, uniform swelling of the fuel pellet appears to have been arrested before the pellet occupied the entire volume. Fuel behavior has been characterized as a function of age and clad history, and analyzed in terms of previously measured helium release behavior of $^{238}PuO_2$ fuel.



FCO 201 0°
17 years old



FCO 371 0°
14 years old



FCO 009 90°
23 years old

**Keywords:** Pu-238, fuel aging, fuel swelling





# Investigation of Pu-238 Heat Source Modifications to Increase Power Output Through (α,n) Reaction-Induced Fission

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**Abstract.** The objective of this study is to improve upon the current $^{238}PuO_2$ fuel technology for space and defense applications. Modern RTGs (radioisotope thermoelectric generators) utilize the heat generated from the radioactive decay of $^{238}Pu$ to create heat and electricity for long term and remote missions. Application of RTG technology is limited by the scarcity and expense of producing the isotope, as well as the power output which is limited to only a few hundred watts. The scarcity and expense makes the efficient use of $^{238}Pu$ absolutely necessary. By utilizing the decay of $^{238}Pu$, not only to produce heat directly but to also indirectly induce fission in $^{239}Pu$ (which is already present within currently used fuel), it is possible to see large increases in temperature which allows for a more efficient conversion to electricity and a higher power-to-weight ratio. This concept can reduce the quantity of $^{238}Pu$ necessary for these missions, potentially saving millions on investment, while yielding higher power output.

Current work investigating radioisotope power systems have focused on improving efficiency of the thermoelectric components and replacing systems which produce heat by virtue of natural decay with fission reactors. The technical feasibility of utilizing (α,n) reactions to induce fission within current radioisotopic fuels has not been investigated to any appreciable detail, and our study aims to thoroughly investigate the performance of many such designs, develop those with highest capabilities, and facilitate experimental testing of these designs. In order to determine the specific design parameters that maximize power output and the efficient use of $^{238}Pu$ for future RTG units, MCNP6 simulations have been used to characterize the effects of modifying fuel composition, geometry, and porosity, as well as introducing neutron moderating, reflecting, and shielding materials to the system. Although this project is currently in the preliminary stages, the final deliverables will include sophisticated designs and simulation models that define all characteristics of multiple novel RTG fuels, detailed enough to allow immediate fabrication and testing.

Preliminary work has consisted of developing a benchmark model to accurately represent the $^{238}PuO_2$ pellets currently in use by NASA; this model utilizes the alpha transport capabilities of MCNP6 and agrees well with experimental data. In addition, several models have been developed by varying specific parameters to investigate their effect on (α,n) and (n,fission) reaction rates. Current practices in fuel processing are to exchange out the small portion of naturally occurring $^{18}O$ and $^{17}O$ to limit (α,n) reactions and avoid unnecessary neutron production. However, we have shown that enriching the oxide in $^{18}O$ introduces a sufficient (α,n) reaction rate to support significant fission rates. For example, subcritical fission rates above $10^8$ f/cm$^3$-s are easily achievable in cylindrical $^{238}PuO_2$ fuel pellets with an $^{18}O$ enrichment of 100%, given an increase in size and a $^9Be$ clad. Many viable designs exist and our intent is to discuss current results and future endeavors on this project.

**Keywords:** RTG, radioisotope thermoelectric generators, Pu-238, subcritical reactors, (alpha,n) reactions

# Particle Size and Characterization of Fuel for $^{238}PuO_2$ Heat Source Fabrication

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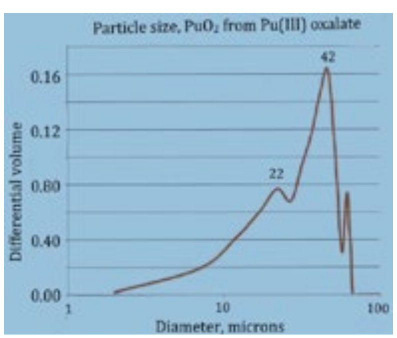
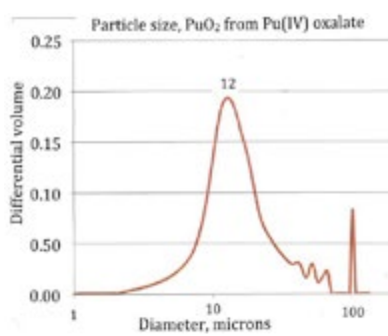
**Abstract.** Particle sizes and morphologies of $^{238}PuO_2$ particulate material obtained from different processing steps differ with details of processing. Understanding variations in particle size as functions of variations in processing improves the understanding of the relationship between the strength of the final ceramic and the particulate that was used in fabricating the ceramic. Particle size and particle surface asperities are related to surface energy, which strongly influences the integrity of the ceramic pressing. Particle sizes arising from two unrelated aqueous processing protocols are compared to reveal similarities and differences. Differences are observed between oxides derived from oxalate precipitation of Pu(III) (below, left) and Pu(IV) (below, right). Other variations in details of aqueous purification of $^{238}PuO_2$ also influence particle size. In addition, time is a factor. Anecdotal evidence suggests that 24 hours of aging is sufficient to produce changes in the particle size distribution of low-fired oxide fuels, and in the observed performance of these fuels in pressing of a strong ceramic pellet. Particle size distributions from ball-milling have been measured as a function of time to evaluate agglomeration that may occur as fuel ages.

Sintered fuel granules of a given size vary noticeably in density, consistent with known variation in the processing histories of the fuel lots. The measured values for bulk density of this fuel are lower than expected for the least dense possible regular packing for $PuO_2$ spheres of a single diameter. The measured densities suggest that the individual particles making up the oxide are themselves quite porous, with a bulk density of between 7.95 g/cm$^3$ and 8.84 g/cm$^3$ (between 31% porous and 23% porous).

Anecdotal relationships between particle history and the integrity of pressed pellets are examined in light of measured parameters of these several types of fuel.




**Keywords:** Pu-238, particle size, fuel aging





# The Pulsed Fission-Fusion (PuFF) Propulsion System – Overall Concept and Mission Analysis

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**Abstract.** This paper discusses the PuFF propulsion concept, a z-pinch powered fission-fusion device. Specific attention is given to the overall system, from ignition to thrust generation and the recharge circuit used to power the next impulse. Particular attention is given to the scaling relations and the minimum viable engine model. This engine model is integrated into several vehicle concepts that are being considered for fast sprint missions to Mars and interstellar precursor missions. Vehicle subsystems as well as mission astrodynamics and operational timelines are also covered.

**Keywords:** fusion, z-pinch, advanced propulsion

# Propulsion through Direct Conversion of Fusion Energy

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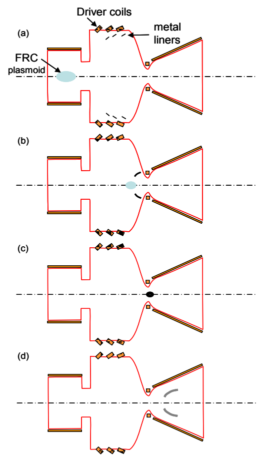
**Abstract.** Even with spectacular breakthroughs in electronics, materials science, and computer technology in the past 50 years, human exploration of space has not progressed beyond what was accomplished in the 1970s. We are in this predicament despite the substantial financial commitment and passionate interest of virtually every modern nation on the planet. There are two fundamental reasons for this – it takes too long and costs too much. The future of manned space exploration and development of space depends critically on the creation of a dramatically more proficient propulsion system for in-space transportation.

The Fusion Driven rocket (FDR) represents a revolutionary approach to fusion propulsion where the fusion plasma releases its energy directly into the propellant, not requiring conversion to electricity. It employs a solid lithium-based propellant that requires no significant tankage mass. Several low-mass, magnetically-driven metallic liners are inductively driven to converge radially and axially to form a thick blanket surrounding the target plasmoid compressing the plasmoid to fusion ignition conditions. Virtually all of the radiant, neutron and particle energy from the plasma is absorbed by the encapsulating, thick metal blanket. This combined with a large buffer region of high magnetic field isolate the spacecraft from the energetic plasma created by the fusion event. This paper represents the culmination of the FDR program to date. This work includes finalized mission architectures for a favorable single launch 210 day manned Mars mission. It also outlines several mission options for increased payload or faster trip times. Since the most recent publication on the FDR concept (*34th International Electric Propulsion Conference,* Hyogo-Kobe, Japan, July 4–10, 2015, paper IEPC-2015-68), a much more detailed 1D physics model of the liner implosion process with optimization of the fusion gain as a function of liner mass and kinetic energy has been carried out. In addition to these new results, experimental efforts with metallic liner compression will be presented and a realistic, low-cost path for a future fusion producing experiment will be detailed.




**Schematic of the inductively driven metal propellant compression of an FRC plasmoid for propulsion**. (a) Thin hoops of metal are driven at the proper angle and speed for convergence onto target plasmoid at thruster throat. Target FRC plasmoid is created and injected into thruster chamber. (b) Target FRC is confined by axial magnetic field from shell driver coils as it translates through chamber eventually stagnating at the thruster throat. (c) Converging shell segments form fusion blanket compressing target FRC plasmoid to fusion conditions. (d) Vaporized and ionized by fusion neutrons and alphas, the plasma blanket expands against the divergent magnetic field resulting in the direct generation of electricity from and the back emf and a directed flow of the metal plasma out of the magnetic nozzle.

**Keywords:** Nuclear Fusion, Magneto Inertial Fusion, Lithium Plasma, Fusion Propulsion.





# Thermal-control Consideration and Preliminary Analysis of a Heat Pipe Cooled Space Reactor Power System

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**Abstract.** Thermal-control design is the core of space reactor power systems. This paper presents the authors' comprehension and suggested research routes of thermal control in space reactor power systems. Based on a general analysis of energy transfer and conversion processes in the power systems, independent system parameters for design and optimization are extracted. Similar to the design of the Safe Affordable Fission Engine (SAFE), a design of a heat pipe cooled space reactor power system is proposed. Steady-state thermal-control analyses are performed, and the results verify that the design is physically feasible. For building a transient physical model of the whole power system, an integration of a point-kinetics model for the reactor, a temperature front model for the heat pipes, an isothermal model for the Stirling engines and a one-dimensional thermal-hydraulic model for the radiator is suggested.

**Keywords:** Thermal control; System parameter; Heat pipe; Transient model.

# Neutron Irradiation Experiments on Various RPS Materials such as $Bi_2Te_3$ Based Thermoelectric Modules

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**Abstract.** Radioisotope Power Systems (RPS) must be able to successfully function for long duration space missions under extreme inter-planetary and planetary surface environments. These environments can subject the RPS to a wide range of temperatures, vacuum/pressures, atmospheres, and radiation levels. Depending on the mission profile, the nuclear power system could be subjected to radiation from two general sources: 1) external, such as from solar flares/wind, cosmic radiation, etc.; and 2) internal, from the selected RPS fuel being used for spacecraft power and/or as a heat source. Over the last several years, UDRI has performed several series of neutron irradiation experiments on potential RPS materials at The Ohio State University-Nuclear Reactor Laboratory (OSU-NRL). The 500 kw pool-type research reactor available at OSU-NRL has multiple beam ports and dry tubes with a maximum thermal neutron flux of ~1 x $10^{13}$ n/cm$^2$/s. For experimentation purposes, the reactor can yield neutron fluences which are a very good representation of the total neutron environments expected in various RPS mission profiles. In addition, OSU-NRL has gamma-ray spectroscopy capabilities which can be employed to determine any activated species formed during an irradiation experiment. It is recognized that reactor experiments provide “acute” short-term neutron exposures compared to the “chronic” long-term neutron exposures witnessed in actual space missions.

UDRI has performed neutron irradiation experiments on a number of RPS related materials including: various metals, ceramic insulation materials, thermoelectrics, and recently $Bi_2Te_3$-based thermoelectric (TE) modules. These particular types of $Bi_2Te_3$ modules are being considered for application by the University of Leicester in a European designed RPS based on the use of americium-241 oxide as the ceramic fuel. Several of the TE modules were exposed to an acute neutron irradiation equivalent to a twelve year mission scenario. The actual evaluation of the thermoelectric properties pre- and post-irradiation obtained utilizing impedance spectroscopy (IS) is a subject of another paper at this conference authored by R. Mesalam (University of Leicester, UK). The U.S. currently-utilized thermoelectric, TAGS-85, operates at higher temperatures compared to the proposed European $Bi_2Te_3$-based thermoelectric. So the possibility exists that the rejection temperature of U.S. RPSs could potentially act as the hot side temperature for the European developed $Bi_2Te_3$ material, especially since the neutron irradiation experiments on this material have proven promising. A general discussion of RPS materials related neutron experiments performed at OSU-NRL, and the hypothesis of employing both U.S. and European thermoelectrics in a RPS is explored.

**Keywords:** RPS, bismuth telluride, neutron irradiation, TAGS-85, thermoelectrics





# Segmented Thermoelectric Devices for a High-Performance Modular System Concept Upgrade to the GPHS-RTG

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**Abstract.** Radioisotope Thermoelectric Generators (RTGs) have proven to be extremely reliable components of space power systems, enabling the scientific exploration of deep space, Mars, and the moon. These systems are based on technological advances completed in the 1960’s and 1970’s. RTGs such as the heritage GPHS-RTG and the current Multi-Mission RTG (MMRTG) have relied on thermoelectric couple technology based on materials identified and developed over 50 years ago. These generators use a converter array configuration with hundreds of discrete thermoelectric (TE) couples interconnected on the cold side in a series-parallel “laddering” pattern to achieve high redundancy and eliminate single point failures while meeting their output voltage requirement under maximum output power condition. They are also “single point designs,” with their power level at Beginning-of-Life (BOL) at nearly 300 W for the GPHS-RTG and 120 W for the MMRTG.

NASA constantly seeks the development of more capable and high-performing flight systems in support of future science and exploration missions, and it is desirable to identify and develop common energy converter technology “building blocks” that could span a wide range of potential next-generation space nuclear power systems. The use of arrays of discrete couples to assemble into converters becomes impractical either at high power levels (> 1 kW) due to the large quantities and constraints posed by system integration, or at low power levels when requirements dictate a high module output voltage (e.g. 32V), which translates into a large number of couples with high aspect ratio.

The best approach for practical and efficient thermal and mechanical integration with the heat source and heat rejection system components is to assemble these high aspect ratio couples into robust TE module structures. We discuss the versatility of high-performance segmented thermoelectric modules for application to a number of system concepts based on a variety of heat sources, from terrestrial high-grade waste heat recovery to space nuclear power. In particular, we discuss the possibility of “retrofitting” the GPHS-RTG by replacing the Si-Ge couples with higher-efficiency segmented TE modules and how this could enable a modular configuration based on “generator slices” using one or two GPHS modules. Such a Segmented Modular RTG (SMRTG) could cover a wide range of power levels, from about 20 W up to 500 W, which would allow space mission planners to “rightsize” their power system to fit the specific needs of a proposed mission.

Each multi-couple module would utilize a common hot shoe, featuring a compliant metal/ceramic header and cold-side interconnects. The couples are based on technology that is being advanced as part of NASA’s Thermoelectric Technology Development Project, with skutterudites/$La_{3-x}Te_4$/$Yb_{14}MnSb_{11}$ materials capable of providing up to 15% device efficiency (as demonstrated in 2011 for 1273 K/473 K hot and cold junction temperatures). We describe recent progress in this technology, including some proof-of-concept module demonstrations for potential use in a variety of applications.

**Keywords:** Radioisotope, Segmented, Thermoelectric, Module.

# Criticality Safety Design and Analysis of the Heat-Pipe Nuclear Reactor

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**Abstract:** Heat-pipe nuclear reactor was one of the most important reactor type to enable the future deep space exploration missions, due to its passive safety charactor from the heat-pipe. Firstly, the design of heat-pipe nuclear reactor in the past research had been compared in order to re-estimate the criticality safety design of heat-pipe reactor, and then SAFE-400 reactor invented by Los Alamos National Lab (LANL) was chosen as benchmark reactor because of its excellent performance. Secondly, the criticality safety parameters of SAFE-400 reactor was re-analyzed by MCNP, including the control drums¡¯ function, spectrum shifte absorber¡¯s (SSA¡¯s) function and its capability for the launch abortion accident when it lost most of the reactivity control sub-system. The calculation results had shown that it was enough to deal with the immersion accident only relying on the work of the control drums and SSA when SAFE-400 lost most of control drum. Meanwhile, the calculation results had also given out a fact that SAFE-400 criticality safety depended on the number of the broken heat-pipe damaged by the great impact during launch abortion and immersion accident, and it had also shown that mading the heat-pipe nuclear reactor completely broken was a better way to prevent the super-criticality accident and ensure the criticality safety of space nuclear reactor than the method of keeping reactor integret and subcritical after the launch abortion accident happened. This paper was helpful for the designs of heat-pipe nuclear reactor in the future.

**Keywords:** criticality safety, heat-pipe nuclear reactor, SAFE-400, launch abortion accident, MCNP





# Improved Composite Assisted Funneling of Electrons in Nickel Composited $La_{3-x}Te_4$ via Particle Size Reduction

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**Abstract.** Lanthanum telluride ($La_{3-x}Te_4$) has recently emerged as a high efficiency n-type thermoelectric material. The performance of the $La_{3-x}Te_4$ system stems from a complex defect thorium phosphide ($Th_3P_4$) crystal structure with $La^{3+}$ vacancies that produce a wide range of carrier concentrations, resulting in a low lattice thermal conductivity and favorable values for thermopower and electrical conductivities. With an optimized defect stoichiometry, the dimensionless figure of merit, ZT, of this system can attain values as large as ~1.3 at 1275K.

Previously, our group has demonstrated a 30% increase in the ZT of $La_{3-x}Te_4$ with the addition of 12-15 vol% Ni inclusions on the order of 2-3 microns. The enhancement in ZT is a result of composite-assisted funneling of electrons (CAFE), where the inclusions form a charge funneling network that reduces the electrical resistivity of the composite while leaving the thermal conductivity and thermopower virtually unchanged. Further improvements to the ZT of these $La_{3-x}Te_4$-Ni composites have also been demonstrated using nanoscale Ni inclusions at an equivalent volume fraction, leading to a 45% improvement over baseline, vacancy concentration-optimized $La_{3-x}Te_4$. Here we present results of a study investigating the optimal volume fraction of nanoscale-Ni inclusions in the $La_{3-x}Te_4$-Ni composites to maximize ZT across a wide temperature range. Various volume fractions of nano-Ni particles, ranging 0-20 vol%, were combined with $La_{3-x}Te_4$ powder and subsequently densified using high temperature spark plasma sintering. The temperature dependent electrical resistivity, thermopower, and thermal conductivity data of the sintered compacts will be presented and the impact on ZT values will be discussed.

**Keywords:** Thermoelectric, Lanthanum Telluride, Composite

# Simulation Model and Control System Requirements for a Nuclear Thermal Propulsion System

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**Abstract.** A preliminary dynamic simulation model was developed to investigate coolant/propellant pump, control drum, flow performance, and core responses necessary for a successful startup of a moderated Nuclear Thermal Propulsion (NTP) system. The NTP system design parameters are based on the Small Nuclear Reactor Engine (SNRE) design developed at Los Alamos National Laboratory. MatLab/Simulink is used as the modeling software to solve a system of coupled differential equations that describe time-dependent hydrogen flow (coolant and propellant), control drum actuation, core power and system temperatures. Matlab scripts were constructed to interface automatically and execute the simulation model, which allowed rapid, iterative testing over a wide range of operational variables. The results of these simulations are time-dependent profiles for temperature, temperature differentials, core reactivity, and system pressure. Reduced data sets from the time dependent profiles are used to create system response functions for each tested variable. System response functions include behaviors such as peak component temperatures, rate of temperature changes, reactivity, reactor power and coolant pressure and flow. Through the analysis and characterization of the response functions, specific operational limits are identified to ensure the predictability, safety, and reliability of the system during startup. The preliminary simulation tool is designed to be adaptable for future work, using higher fidelity thermo-physical data and models. Results from initial simulations are compared to previous SNRE predictions and the recommended control system constraints resulting from this preliminary investigation are presented.

**Keywords:** Nuclear Thermal Propulsion, SNRE, Control System





# Updated Mars Mission Architectures Featuring Nuclear Thermal Propulsion

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**Abstract.** Nuclear thermal propulsion (NTP) can potentially enable routine human exploration of Mars and the solar system. By using nuclear fission instead of a chemical combustion process, and using hydrogen as the propellant, NTP systems promise rocket efficiencies roughly twice that of the best chemical rocket engines currently available. The most recent major Mars architecture study featuring NTP was the Design Reference Architecture 5.0 (DRA 5.0), performed in 2009. Currently, the predominant transportation options being considered are solar electric propulsion (SEP) and chemical propulsion; however, given NTP's capabilities, an updated architectural analysis is needed. This paper provides a top-level overview of several different architectures featuring updated NTP performance data. New architectures presented include a proposed update to the DRA 5.0 as well as an investigation of architectures based on the current Evolvable Mars Campaign, which is the focus of NASA's current analyses for the Journey to Mars. Architectures investigated leverage the latest information relating to NTP performance and design considerations and address new support elements not available at the time of DRA 5.0, most notably the Orion crew module and the Space Launch System (SLS). The paper provides a top level quantitative comparison of key performance metrics as well as a qualitative discussion of improvements and key challenges still to be addressed. Preliminary results indicate that the updated NTP architectures can significantly reduce the campaign mass and subsequently the costs for assembly and number of launches.

**Keywords:** Nuclear Thermal Propulsion, NTP, Architecture, Transportation, Mars.

# Graphene Superlattice Heterostructures Based Thermoelement for Radioisotope Thermoelectric Generator

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**Abstract.** The lower conversion efficiency of segmented thermoelectric unicouple is the main concern in the present day's Radio Isotope Thermoelectric Generators. The maximum ratio of thermal to electrical efficiency of this thermoelement is limited up to 15 %, due to its lower Seebeck coefficient. This study deals with the replacement of the existing segmented thermoelectric unicouple with the efficient graphene superlattice heterostructures based thermoelement to increase the conversion efficiencies significantly. This graphene superlattice heterostructures based thermoelement consists of two different superlattices with an electric potential controlled defect layer created by a single irregular electrode inserted in between them. The heterostructures can be realized by controlling the different electric potential on the gate electrodes periodically patterned over the graphene superlattice. The metallic gate electrodes are coupled to graphene through a dielectric $SiO_2$ layer and the graphene is deposited on a $SiO_2$ substrate backed by a doped Si substrate. The maximum Seebeck coefficient can be tuned by changing the gate electrode electric potential for flow of electrons with different energy through the graphene superlattice heterostructures caused by the temperature difference. A large Seebeck voltage is generated between the two ends of the graphene superlattice contact electrodes, due to its dependency on the percentage of electronic tunneling state, whose maximum probability density is localized near the interface between the defect layer and one of the superlattices. Initially the gate voltage is supplied from an external voltage source and later switched over to Seebeck potential when it reaches a stable voltage range. The detailed power balance in terms of gate driving power loss and thermo electric power generated is explained in the paper. The detailed calculations of the Seebeck coefficient and thermo power generation are based on a transfer matrix approach. The paper describes the practical feasibility studies of graphene superlattices based RTGs and evaluation of its overall efficiency in contrast to the existing RTGs under the same conditions of temperature gradient & surface area of heat source. Due to higher efficiency, this technique will help in exploring alternative low cost radioisotopes like Americium-241to replace highly scarce plutonium-238 from today's RTGs without compromising the power output & overall weight.

**Keywords:** Graphene Superlattice Heterostructures, Radioisotope Thermoelectric Generator, Defect barrier, Segmented Thermoelectric Unicouple.





# Feasibility Study for a Pluto Orbiter Mission

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**Abstract.** In the months before the epic New Horizons encounter with Pluto, JPL was asked to study the feasibility of a follow-up mission that could actually go into orbit around the dwarf planet. The groundrules for this assessment were to take the New Horizons spacecraft bus as a starting point, and determine whether there is any path using current or planned technologies that would enable this scale of flight system to be put in orbit around Pluto in a reasonable mission duration. The study included an evaluation of state of the art propulsion systems and determined that the only option that offered the required performance would be electric propulsion (EP). This led to an evaluation of current and near term power system options that could provide sufficient power to the EP system at a low enough mass to enable the mission. Current RPS options including MMRTG, eMMRTG and ASRG were evaluated and found to be prohibitive from a mass and packaging standpoint. However, the SMRTG, as described in the recent Nuclear Power Assessment Study (NPAS) report, as well as concepts for high powered Stirling Radioisotope Generators (SRGs) promises to combine the necessary levels of performance, longevity and mass to enable a mission that could achieve Pluto orbit with a duration on the order of 15 years. Further mission analysis also indicated that projected mass and performance of small fission power systems in the 10 kW range could also enable this mission, and deliver significant reductions in flight time, or increases in delivered mass.

**Keywords:** Radioisotope Electric Propulsion (REP), SMRTG, Pluto.

# Zirconium – Rates of Reaction for a Common Getter Material

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**Abstract.** Zirconium can be added to a spacecraft system to getter (i.e., consume) potentially reactive gas species before they can interact with other sensitive materials. Typical processing techniques can minimize most reactive gas species, but some, like water, can be so pervasive and persistent that they are nearly impossible to completely eliminate. The role of a getter, therefore, is to act as a sacrificial material and consume any residual reactive species before they have an opportunity to interact with other sensitive components. This means that a getter needs to provide a mechanism for removing a reactive gas species that is both fast and thermodynamically favorable. While the thermodynamic reactivity of zirconium is well-documented, the reaction rates of zirconium under a variety of conditions are not as well-understood.

Zirconium getters in palladium coffins were placed within a reaction chamber and allowed to react with a controlled atmosphere at 630 ˚C. Composition of the gas phase was quantitatively monitored as a function of time, and reaction rates were calculated. Reaction rates for these palladium encapsulated zirconium getters were measured for water, hydrogen, and methane. The reaction rate for hydrogen was observed to be first-order with respect to the quantity of hydrogen and the surface area of the zirconium. The presence of gas phase water and surface oxide appear to interfere with the reaction between zirconium and hydrogen, causing the reaction rate to slow down. The reaction rate for water was observed to be first-order with respect to the quantity of water and the surface area of zirconium. No interferences with the reaction between water and zirconium were noted. The reaction rate for methane was observed to be first-order with respect to the quantity of methane. In general, the reaction rates for these species are, in descending order: hydrogen, water, and methane. The difference in these rate constants are large enough that in some cases it may be possible to make the assumption that hydrogen will be completely removed by the getter before significant quantities of water can react; and both hydrogen and water will be completely removed before significant quantities of methane can react.

**Keywords:** Zirconium, palladium, getter, reaction rate





# Skutterudite-Based Thermoelectric Technology for Integration into a Proposed eMMRTG: An Update

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**Abstract.** The overall objective of the Skutterudite Technology Maturation (STM) project at NASA's Jet Propulsion Laboratory (JPL) is to advance JPL-developed skutterudite (SKD) technology to a point where it can be considered for use in an enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG). The goal is to be prepared for potential flight unit development readiness by end of FY2018. Conversion efficiency values on the order of 9% have been demonstrated for SKD-based un-segmented couples when operating at a hot junction of 600C and a cold junction of 200C. This represents ~ a 25% improvement over the conversion efficiency of PbTe/TAGS MMRTG couples at beginning-of-life (BOL). The STM project entered its third year at the beginning of FY2016. During the first two years of the project, JPL and Teledyne Energy Systems Inc. (TESI) have collaborated to complete the initial technical technology transfer to TESI. Manufacturing capabilities for SKD TE materials have been established at TESI. TESI has also established the manufacturing capabilities for couples and module thermal insulation. First iteration SKD couples have been fabricated and tested at TESI. Key findings from this initial Phase of the technology maturation project will be summarized. TESI and JPL are currently developing a second iteration of couples and module thermal insulation, incorporating lessons learned from the development and testing of the first iteration of couples and insulation. Progress to date on the development of this second iteration of couples will be presented and discussed. The eMMRTG life performance prediction approach and development status will also be presented.

**Keywords:** Thermoelectric, eMMRTG, skutterudite

# Effects of Laser Marking Versus Mechanical Scribing on DOP-26 Iridium Alloy Material

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**Abstract.** DOP-26 iridium alloy components are used for primary fuel containment in Radioisotope Thermoelectric Generators, which provide electrical power for NASA space science missions such as Cassini, the Curiosity Mars Rover, and Pluto New Horizons. A study was conducted to compare the effects of mechanically scribed and laser-marked serial numbers on the iridium alloy material. Evaluations included characterization of scribing/marking parameters on: 1) character depth, 2) circle grid patterns on formed cups, and 3) tensile impact ductility of tensile impact specimens. This work was done to provide justification for allowing laser marking of prime components.

**Keywords:** DOP-26 Iridium Alloy, Tensile Impact Ductility, Laser Marking, Mechanical Scribing.





# Advanced Integrated Thermal-Thermoelectric Modeling for the eMMRTG

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**Abstract.** The enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) project required the development of improved modeling techniques. Such improvement has been accomplished by means of a transition from the use of SINDA to an in-house developed modeling tool called Centralized Math Engine (CME). Both tools have enabled an integrated thermal-thermoelectric model of the entire eMMRTG. This enables precise solution of temperature gradients and their impact on thermoelectric hot junction temperatures and generator power output. Such knowledge is critical for establishing design constraints consistent with eMMRTG/skutterudite long term operational limits. CME offers up to 20 times the solution speed of SINDA, which has enabled Monte Carlo simulations requiring a million runs to generate sufficient statistics. This paper will present a summary of some key results.

**Keywords:** eMMRTG, thermoelectric, SINDA

# Robust Exploration and Commercial Missions to the Moon Using NTR / LANTR Propulsion and Lunar-Derived Propellants

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**Abstract.** The nuclear thermal rocket (NTR) has frequently been identified as a key space asset required for the human exploration of Mars. This proven technology can also provide the affordable "access through cislunar space" necessary for commercial development and sustained human presence on the Moon. In his "post-Apollo" Integrated Space Program Plan (1970–1990), Wernher von Braun, proposed a reusable nuclear thermal propulsion stage (NTPS) to deliver cargo and crew to the Moon to establish a lunar base before undertaking human missions to Mars. The NTR option was selected by von Braun because it was a demonstrated technology capable of generating both high thrust and high specific impulse ($I_{sp}$ ~900 s) – twice that of today's best chemical rockets. In NASA's Mars Design Reference Architecture (DRA) 5.0 study, the crewed Mars transfer vehicle used three 25 $klb_f$ "Pewee" engines – the smallest and highest performing engine tested in the Rover program – along with graphite composite fuel. Smaller, lunar transfer vehicles – consisting of a NTPS using three ~16.5 $klb_f$ "Small Nuclear Rocket Engines (SNREs)", an in-line propellant tank, plus the payload – can enable a variety of reusable lunar missions. These include cargo delivery and crewed lunar landing missions. Even weeklong "tourism" missions carrying passengers into lunar orbit for a day of sightseeing and picture taking are possible. The NTR can play an important role in the next phase of lunar exploration and development by providing an affordable in-space lunar transportation system (LTS) that can allow initial outposts to evolve into settlements supported by a variety of commercial activities such as in-situ propellant production used to supply strategically located propellant depots and transportation nodes. The utilization of iron-rich volcanic glass or lunar polar ice (LPI) deposits (each estimated at billions of metric tons) for propellant production can significantly reduce the launch mass requirements from Earth and can enable reusable, surface-based lunar landing vehicles (LLVs) using liquid oxygen/hydrogen ($LOX/LH_2$) chemical rocket engines. Afterwards, $LOX/LH_2$ propellant depots can be established in lunar equatorial and polar orbits to supply the LTS. At this point a modified version of the conventional NTR – called the LOX-augmented NTR, or LANTR – would be introduced into the LTS allowing bipropellant operation and leveraging the mission benefits of refueling with lunar-derived propellants for Earth return. The bipropellant LANTR engine utilizes the large divergent section of its nozzle as an "afterburner" into which oxygen is injected and supersonically combusted with nuclear preheated hydrogen emerging from the engine's choked sonic throat—essentially "scramjet propulsion in reverse." By varying the oxygen-to-hydrogen mixture ratio, LANTR engines can operate over a range of thrust and $I_{sp}$ values while the reactor core power level remains relatively constant. Eventually, a LANTR-based LTS can enable a rapid "commuter" shuttle with "one-way" trip times to and from the Moon ranging from 36 to 24 hours. Even if only 1% of the extracted propellant from identified volcanic glass and polar ice deposits were available for use in lunar orbit, such a supply could support daily commuter flights to the Moon for many thousands of years! An evolutionary mission architecture is outlined and a variety of lunar missions and transfer vehicle designs are examined, along with the increasing demands on propellant production as mission complexity increases. A comparison of vehicle features and engine operating characteristics, using both NTR and LANTR engines, is also provided along with a brief discussion on the propellant production issues associated with using volcanic glass and LPI as source material.

**Keywords:** NTR, LANTR, Lunar-Derived Propellant





# Optimization of radiation shielding for space nuclear propulsion

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**Abstract.** A genetic algorithm has been developed for optimization of a radiation shield with applications for nuclear propulsion and for other nuclear technologies. The multi-objective optimization genetic algorithm (MOOGA) searches for ideal combinations of dimensions and material composition among multiple layers of shielding. The methods are currently tailored for development of a shadow-shield for use in a nuclear thermal propulsion (NTP) stage, but the same methods can be extended to nearly any geometry with minimal effort. The algorithm couples with MCNP6 to perform transport calculations upon a population of candidate shield designs, then evaluates the results to compare the mass and transmitted dose or energy. Pareto-search mechanisms are employed to evaluate each candidate's fitness and determine its likelihood of passing traits to the next generation of candidate shield designs. In unconstrained optimization, this method gradually converges upon a set of Pareto-optimal solutions. Benefits of this method over other optimization techniques include the ability to explore the effect of discrete parameter changes to a design (e.g. material composition) in addition to continuous parameters (e.g. layer thickness), greater avoidance of false convergence upon local maxima, and flexibility in evaluating a diverse set of problems. Challenges of maintaining design diversity, expediting calculation time, and selecting appropriate algorithm parameters are also addressed.

**Keywords:** Radiation, shielding, optimization, genetic algorithm.

# RPS-Enabled Micro/CubeSat Mission Opportunities Supporting Planetary Science Objectives

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**Abstract.** Radioisotope power systems have powered many highly successful missions to the far reaches of the solar system as well as the Moon and Mars. These systems, called Radioisotope Thermoelectric Generators (RTG) have relied on converting heat generated by the natural decay of plutonium 238 to electric current via thermoelectric devices. The earliest unit developed supplied about 3 We and over the years the technology developed into producing much higher powered units such as the ~290 We General Purpose Heat Source RTG (GPHS-RTG) developed for Ulysses, Galileo and Cassini missions, and last flown on Pluto New Horizons. The RTG currently being produced is the ~110 We Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) and is powering the Curiosity rover and also planned for the Mars 2020 rover mission. While these systems are obviously too large in power and mass to be practical for a microsat or cubesat mission, development of smaller systems may be warranted. Several concepts were developed during the 1980's that utilized the Radioisotope Heater Unit (RHU) as the heat source. The RHU produces ~1.0 Wth. A system could be designed to produce ~40 mWe when coupled with thermoelectric conversion devices. Past studies have suggested the use of multiple RHUs to produce higher powers in the 240 mWe range or higher. Lunar missions have been discussed that would explore the permanently shadowed regions or craters on the moon to validate abundance and homogeneity of deposits of volatiles and or water ice. Since solar power is not available in these regions and batteries could only support hours of operation, a conceptual assessment of how a long life RHU-based RPS system might fit into a cubesat structure was considered. RHURPS could support more capable Microsats that might explore bodies outside cis-lunar space where solar/battery power is not a practical solution. For example, a short-period, Jupiter family comets such as 46P/Wirtanen mission, with apogees near 5 AU, could greatly benefit from RPS systems. Example mission opportunities enabled by RHURPS will be identified.

**Keywords:** Radioisotope, Power, Micro/cubesat





# Development of Earth Abundant Complex Zintl Phases: Alternates to Skutterudites

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**Abstract.** Since the 1960's, the state-of-the-art power systems for space applications have typically been based up on either Si-Ge alloys or PbTe and TAGS materials. Although reliable and robust, the thermal-to-electric energy conversion efficiency of these systems remains fairly low at only 6.5% with an average thermoelectric figure of merit of about 0.5 across the full temperature differential (1275 to 475 K) available to this technology. A factor of 2 improvements in conversion efficiency is highly desirable to support future space missions. In recent years, complex Zintl phases such as n-type $La_{3-x}Te_4$ and p-type $Yb_{14}MnSb_{11}$ have emerged as practical high efficiency, high temperature thermoelectric materials with peak ZTs of 1.2 at 1275K. The high performance of these materials is attributed to their combination of favorable characteristics such as: semi-metallic behavior due to small band gaps, low glass-like lattice thermal conductivity values due to structural complexity and reasonably large Seebeck values near their peak operating temperatures. Recently, JPL and collaborating institutions have investigated a series of promising p-type Zintl phases. The new Zintl phases include p-type $Ca_9Zn_{4+x}Sb_9$, n-type $Mg_3Sb_2$ and p-type $Yb_{14}MgSb_{11}$ and their performance is competitive to that of filled skutterudites with ZTs greater than 1. Additionally, preliminary measurements indicate that these new high performance Zintl phases have higher thermal stability and are better thermomechanically matched to the higher temperature segments, thereby facilitating device fabrication and performance. We will present an overview of recent research efforts at JPL and collaborating institutions on the thermoelectric properties of these new materials as well as provide a first assessment of their suitability for infusion into advanced TE devices.

**Keywords:** RTGs, Zintl, thermoelectrics

# Radioisotope Power Systems for Outer Planet SmallSats – Enceladus Express Mission Concept

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**Abstract.** The coming decades of planetary science and deep space exploration will likely have a combination of more ambitious missions and ever more constrained budgets. There is an emerging trend in the mission planning community of using smaller spacecraft to lower mission costs while still performing significant science. There is anticipation that SmallSats (100-500 kg) could generate significant science returns at a reasonable cost, and could be enabling for future low-cost exploration of the outer planets, such as investigation of possible life-harboring environments of the moons of Jupiter and Saturn.

However, using SmallSats without Radioisotope Power Systems (RPS) to explore the solar system beyond Mars/Jupiter will prove very challenging. Even as far from the Sun as Saturn, the solar energy density is only 1% of that at Earth. Solar power in the outer solar system could require very large arrays, which in turn could require support from large spacecraft structures. Furthermore, thermal management in the outer solar system could be prohibitively power-expensive. RPS could meet both of these challenges by uncoupling power production from solar insolation, and through use of excess thermal power for spacecraft heating needs, thus eliminating the need for the SmallSat to carry a heater.

Currently available RPS present their own challenges for accommodating SmallSats, chiefly mass and cost. In order to understand the mission requirements on RPS for SmallSats, a concept study was carried out for an Enceladus mission. Enceladus, a small moon of Saturn, has been seen by the Cassini mission to be a site of continuous high geologic activity, with plumes of water and/or vapor pumped hundreds of kilometers above the surface, indeed into Saturn orbit. The internal heating mechanisms of this activity beg for explanation, and more importantly, initial measurements of the suspended contents of these water eruptions give tantalizing clues that the geo-thermal source of the heating is, in fact, maintaining a vast sub-surface sea, which in combination could provide a habitat for life.

This paper will explore how existing and currently available RPS elements may make mission concepts to explore the intriguing science of Enceladus economically tractable, and at the same time provide a generic platform for other small but highly capable RPS-powered spacecraft to explore the outer Solar System. The paper will also discuss the implications for power requirements on future RPS development to enable outer planet SmallSats.

**Keywords:** RPS-powered SmallSat, Outer Planet SmallSat, RPS, Enceladus.





# Alternate Tactical Power Generation for Small Spacecraft

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**Abstract.** The author theorizes that certain space exploration probes, orbiters, and landers are not feasible due to the limits of conventional power systems available for CubeSats, nanosatellites, or even picosatellites. A certain amount of mass and real estate must be sacrificed per platform for the power generating system, which directly impacts the energy budget of a vehicle. Both solar and chemical cell conversion technologies have limitations that translate into compromises on the spacecraft's mission, location, and lifetime. The author will discuss the concept of Tactical Isotope Power Sources (TIPS) as an alternate power generation mechanism for small spacecraft missions.

TIPS are long-lived, high energy density alternatives to conventional batteries and solar cells which require both a radioisotope power source and some type of energy conversion technology. Successful examples include radioisotope thermoelectric generators (RTGs), BetaCel cardiac pacemakers, and Qyncell $^{85}$Kr batteries. By careful consideration of the mission and power requirements, specific radioisotopes and power conversion technologies can be considered. The principle concept of TIPS is to combine a specific platform or mission to an optimal and unique power generation capability.

A major consideration of this type of power strategy is operational flexibility. Current power technologies require some type of solar or chemical reactant to operate. Solar cells also require specific deployment locations or complex drives to ensure optimal efficiency. In contrast, deriving power from TIPS would allow long-term operation in a wider range of environments, increasing the range, capabilities, and science return from a vehicle. As the utility of small spacecraft increases and their use becomes more common, the ability to equip them with radioisotope power systems may enable new missions.

**Keywords:** small spacecraft, radioisotope power, CubeSat, nanosatellite,

# Survey of Fuel System Options for Low Enriched Uranium (LEU) Nuclear Thermal Rockets

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**Abstract.** Nuclear thermal propulsion (NTP) is a non-chemical propulsion technology capable of high specific impulse (850 - 900 s) and high inherent thrust (100 – 2,200 kN), extensively tested in the United States and former Soviet Union. The most recent development efforts have focused on recapturing fuel production capabilities and optimizing small thrust engine designs based on historic NTP programs. However, recent fuel production efforts have shown that fuel cannot be identically recaptured and that future development could benefit from modern manufacturing technologies as demonstrated by the production of cermet fuels by spark plasma sintering. Further, neutronic analyses have shown that low enriched uranium (LEU) fueled nuclear thermal rocket engines can be designed using legacy fuel designs based on past U.S. NTP development programs. LEU engine designs are expected to significantly reduce the high cost and perceived political hurdles of developing nuclear thermal rocket systems traditionally associated with high enriched uranium (HEU) fuel systems. All in all, these findings warrant a review of relevant materials to support future NTP design efforts. The purpose of this presentation is to review high temperature structural materials applicable to NTP fuel systems. Materials will be characterized based upon their limiting thermal-mechanical properties, chemical compatibility, neutronic performance, and manufacturability. The focus of this presentation will be largely on legacy fuel system designs; however, high temperature structural fuel matrix materials explored through other terrestrial nuclear fuel development programs will be assessed.

**Keywords:** Nuclear Thermal Propulsion, Fuel Elements, NERVA/Rover, Composite, CERMET, Carbide





# High Temperature Oxide Thermoelectric Materials for use in RTG's

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**Abstract:** Radioisotope thermoelectric generators (RTG's) utilize thermoelectrics such a PbTe and SiGe for conversion of heat to electricity. One problem with PbTe is that it will sublime at high temperatures and it and SiGe need to use a cover gas to prevent oxidation. In the past few years researchers have been investigating the use of oxide materials as thermoelectrics in RTG's. Oxides do not need a cover gas and will not sublimate at high temperatures. Systems studied include clathrates, Skutteradites, perovskites and ZnO.

Our study is concentrating on singly and co-doped ZnO. This material has the potential to work above 1273 K which would improve thermoelectric generator efficiency. The problem to date with this material limiting its figure of merit is its high thermal conductivity. Our approach consists of "microstructural engineering" in order to obtain a hierarchical grain structure better able to scatter a wider spectrum of phonons which will lead to a lower thermal conductivity.

ZnO powders (20 nm) were purchased and doped with gamma aluminum oxide. The aluminum oxide was first micromilled to obtain particle size of approximately 20 nm. The powders were mixed to obtain 2 atomic weight percent gamma alumina doping. Fifty grams of powder was mixed with 50 ml of methanol in a Turbula using zirconia milling media for 2 hours, then allowed to dry at 120C overnight. This powder was then calcined at 850C for 6 hours in vacuum. Densified samples were made using direct current sintering. The same procedure was followed with ZnO co-doped with gamma alumina and gallium oxide (2 atomic weight percent each). Density of the sintered samples was measured using the Archimedes Principle. Specific heat and thermal diffusivity were measured and along with the density, thermal conductivity was calculated. Resistivity and Seebeck Coefficient was measured for each sample. Using this data the figure of merit was then calculated. All samples exhibited n-type behavior. X-ray diffraction was used to determine the crystal structure and scanning electron microscopy to determine grain size and structure.

In order to form a hierarchical structure, sintered samples were crushed then milled. The milled powders were then resintered in the direct current sintering furnace. It was seen that thermal conductivity decreased at all temperatures after milling and resintering. Thermal conductivity was decreased from 7 W/m K to 3.5 W/m K at 903 K using this process. Scanning Electron Microscopy showed a wider distribution of grain sizes for the reprocessed samples as compared to those only sintering a single time.

# Advanced Skutterudite-based Unicouples for A Proposed Enhanced Multi-Mission Radioisotope Thermoelectric Generator

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**Abstract.** Power is of prime importance factor for enabling long life space missions. Batteries have limited lifetimes, and solar power can be impractical at certain latitudes or environmental conditions. Radioisotope Thermoelectric Generators (RTG's) have been used on several NASA missions for which other power sources were not practical. The current state-of-the-art RTG power source, Curiosity rover's Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), has operated for more than one Martian year (687 earth days) on the red planet. In order to increase the power and conversion efficiency of future MMRTG systems and extend the lifetime of future rover missions, an effort to mature advanced thermoelectric technology for use in a proposed Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) was started in 2013. The eMMRTG would use advanced skutterudite (SKD) based thermoelectric unicouples to convert heat from radioactive material decay into electricity. The new SKD thermoelectric materials not only can provide higher thermoelectric performance, but also can operate at higher maximum operating temperature than MMRTG thermoelectric materials. As a result, an eMMRTG power source could provide up to 25% increase in conversion efficiency over the MMRTG at beginning of life (BOL) and about 50% increase in power output over the MMRTG at 17 years. Here, we will report on the progress for demonstrating manufacturability and validating performance of these advanced SKD unicouples jointly developed and tested by Jet Propulsion Laboratory (JPL) and Teledyne Energy Systems, Inc. (TESI).

**Keywords:** Thermoelectric, radioisotope, MMRTG, eMMRTG, skutterudite.





# Light Weight Radioisotope Heater Unit Dimensional Inspection Qualification Process for the Radioisotope Power Systems Program at Oak Ridge National Laboratory

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**Abstract.** Light Weight Radioisotope Heater Units (LWRHU) are radioisotope fueled heat sources designed to help maintain desired temperatures in crucial locations throughout the spacecraft. These heater units are fabricated from a platinum rhodium alloy. Additionally, the LWRHU were designed and developed to withstand potential accident scenarios.

LWRHU clad assemblies consist of four piece parts (i.e. shim, vent cap, closure cap, and clad body) that are manufactured using various metalworking processes and/or finish machining operations. The parts must meet design requirements through fit, form, and function. Thus, conformance to dimensional requirements is critical. A dimensional inspection qualification process was required to show adequacy of all the dimensional inspections to ensure conformance to the product drawings, procedures, and specifications.

Measuring systems play a significant role in the success of inspection processes and their capabilities. The best measurement system will produce correct measurements each and every time. The selection of instrumentation or gages, calibration standards, methods, operations, fixtures, human operator limitations, software, environment, and the actual characteristics being measured are key components that need to be evaluated to provide the confidence level of measurement reliability. Accuracy, precision, sensitivity, readability, consistency, repeatability and reproducibility are vital concepts of measurement that were considered to effectively design the measurement systems for LWRHU parts. The identification and minimization of variation in the systems lead to stable and consistent inspection processes. Before the Readiness Review, the measurement system analysis of the LWRHU component parts will have to demonstrate process capability. An overview of the dimensional inspection qualification process of the LWRHU will be presented.

# Dynamic Power Convertor Development for Radioisotope Power Systems at NASA Glenn Research Center

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**Abstract.** The Thermal Energy Conversion Branch at NASA Glenn Research Center (GRC) is supporting the development of high-efficiency power convertors in support of Radioisotope Power System (RPS) development. Significant progress was made towards such a system that utilized Stirling conversion machines during the 2001 to 2015 timeframe. Flight development of the Advanced Stirling Radioisotope Generator (ASRG) was cancelled in 2013 by the Department of Energy (DOE) and NASA Headquarters primarily due to budget constraints, and the Advanced Stirling Convertor technology contract was completed in 2015. A new chapter of technology development has recently been initiated by the NASA RPS Program. This new effort will consider all dynamic power convertor options, such as Stirling, Brayton, and Rankine cycles. A request for proposal was recently released, and convertor development contracts supporting this effort will be awarded near the beginning of 2017. The effort will consist of three phases: Design, Fabricate, and Test. The RPS program office seeks high-efficiency convertor concepts that are also reliable and robust, which could support future flight RPS generator development. The performance goals set forth by the RPS program office have followed a different genesis than previous efforts. The goals address the difficulties that were encountered during previous development projects. For example, reliability and robustness are at the forefront now during this initial proof-of-viability stage, so that they will be integral to any convertor concept when flight development begins. Some performance goals have been relaxed compared to the ASRG Project, in an effort to open the design space for addition of margin, robustness, and reliability. Examples include an efficiency goal of 25 percent (thermal to electric), and convertor specific power of 20 W/kg. Additional performance goals that manifested from previous Stirling convertor development projects have been put in place at this early stage. Examples include the need to survive static acceleration (spin stabilization or landing profiles), and an increase in cold-end operating temperature capability (up to 175 °C). Following the design phase, prototype convertors will then be produced in accord with the performance goals specified by the request. These convertors will then undergo independent validation and verification at NASA facilities. This independent validation effort will consist of convertor performance and RPS viability demonstrations. Example tests include launch vibration simulation, performance mapping over the environmental temperature range, and static acceleration exposure. In parallel with this effort, the Thermal Energy Conversion Branch is performing additional research using in-hand Stirling convertor hardware which utilize technologies that are still viable for continued RPS development. These tasks are focused on supplementing the knowledge of flexure-bearing-based machines from the Stirling radioisotope generator (SRG) SRG110 Project era. Evaluations include additional launch vibration simulation, static acceleration exposure, and operation with alternative controllers. One pair of convertors from the SRG110 time period, Technology Demonstration Convertor #13 and #14, will also be part of this activity. These convertors have operated for over 101,000 hours (11.5 years) at full design temperature and power. Their performance over the last six years was examined closely to search for any evidence of degradation, and it was found that the performance has not changed. One of these convertors will ultimately be disassembled and inspected, to characterize the effect of this length of continuous operation.

**Keywords:** Radioisotope Power Systems, Stirling, Energy Conversion





# Testing of NERVA-derived Composite Surrogate Fuel Element in NTREES[1]

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**Abstract.** Oak Ridge National Laboratory, in conjunction with the US Department of Energy and NASA, has been recapturing the graphite-based composite fuel element technology that was successfully demonstrated in the Rover and Nuclear Engine for Rocket Vehicle Application (NERVA) programs. A representative element was successfully tested in the Nuclear Thermal Rocket Element Environmental Simulator (NTREES) at the Marshall Space Flight Center. Graphite-based fuel has several advantages for nuclear thermal propulsion (NTP) applications with perhaps the most significant being a robust and successful operating heritage in NTP reactors. A prototype surrogate fuel element of representative shape and length was prepared by substituting hafnium oxide for the uranium oxide normally contained in the fuel. The element, which was the first element of representative length to be fabricated, had a protective ZrC coating applied to the four internal coolant channels. However, this early element was only made with four out of the usual 19 coolant channels and the coating on those channels could not be characterized prior to testing. Because of the reduced number of cooling channels and the increased wall thickness between them, the temperature and thermal stresses within the element were predicted to be higher than prototypic during the testing. The fuel element performed extremely well at temperatures in excess of 2500K for times relevant to necessary NTP reactor operations with no damage observed in a subsequent visual inspection. In a planned follow-on test-to-failure the element operated at temperatures in excess of 2800K for another seven minutes, demonstrating the robustness of the element to high temperatures and thermal cycling. Post-test examination of the specimen revealed that chemical interactions between the uncoated external element surfaces and the test cover gas led to nitrogen compounds that grew inward to the internal coolant channels causing element cracking. The element performed well beyond predicted performance. The successful demonstration of the first element to be extruded and coated demonstrates the relative ease of fabrication for the graphite fuel forms and the robustness of the composite fuel to the necessary operating temperatures. The NTREES performed well during the tests but several issues were identified that must be resolved before more relevant NTP testing can occur. Current activities include the evolution to a 19-coolant channel element that is the exact NERVA fuel element geometry and development of coating assessment tools for determining the consistency and quality of the protective internal coatings prior to and after testing.

**Keywords:** nuclear, propulsion, composite fuel, testing

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# Autonomy for Space Reactor Power Systems

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**Abstract.** The application of nuclear reactors for space power and propulsion presents unique operational and control challenges. Terrestrial nuclear power plants have relied upon varying degrees of direct human control and decision-making for operations as well as periodic human interaction for maintenance. However, physical inaccessibility of the reactor system, and conditions for planetary or deep-space missions such as communication time delays or blackouts constrain the degree of human interaction possible for space reactor power systems. To provide the necessary mission assurance, the space reactor power system must be able to respond to rapid events and adapt to evolving or degraded conditions without immediate human intervention for operations, or any opportunity for repair or refurbishment. Thus, space reactor power systems must provide capabilities for operational autonomy. The desirable characteristics of autonomous control include intelligence, robustness, optimization, flexibility, and adaptability. This paper will discuss the basis for space reactor autonomy and describe the requirements for autonomous control.

**Keywords:** Autonomy, Reactor Control, Space Reactor





# TERRA Project: a Brazilian View for Nuclear Energy Application to Space Exploration

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**Abstract.** The TERRA project is a Brazilian effort to develop the enabling technologies to generate electric power in space. Those technologies are an independent reactor core concept, a Stirling convertor for small to medium and a Brayton convertor for medium to large electric power output. Besides those technologies, it is also looking into heat pipes design and passive multi fluid turbines. The first reactor core concept was completed this year (2016), a complete paper is being prepared and it is in the review process. A Stirling machine was built and it works quite reasonably. A copy of this Stirling machine was built and is now undergoing testing. The Brayton cycle initial design project was intended to use a gas furnace to simulate the nuclear heat. A design retrofit was necessary and decision was made to change the furnace from gas to electric. A detail electric design project was requested to the market. This detail design was delivered this last august. It is hoped that the 300 kW electric furnace will be requested next year. A couple of new APUs was recently received. One of these APUs will be used in the actual Brayton cycle under construction. 18 kg of Mo13Re was acquired for materials testing in order to produce heat pipes. A program to design heat pipe is being developed to evaluate a combination of the structural and working fluid materials. A new benchmark is under development to test the passive multi fluid turbine. A passive multi fluid turbine is an evolution of the Tesla turbine. All these events will be presented at the conference with a little more of detail.

**Keywords: reactor core concept, Brayton cycle, Stirling machines, heat pipe, passive multi fluid turbine.**

# An Investigation of Material and Processing Variables Affecting Density and Thermal Properties of Carbon Bonded Carbon Fiber Insulation

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**Abstract.** Carbon Bonded Carbon Fiber (CBCF) insulators provide thermal protection to the isotopic fuel in Radioisotope Thermoelectric Generators. The two principal constituents of CBCF are chopped aerospace-grade rayon and a powdered phenolic resin. These starting materials are processed through a series of slurry preparation, vacuum slurry molding, curing and carbonization steps to form insulator billets suitable for machining to final configuration. Although the raw materials and processing steps have remained nominally constant over two decades, some variability in final densities and thermal properties has motivated a detailed investigation of starting materials and processing. An automated image analysis system was employed to characterize fiber length distributions for the chopped rayon and chopped and carbonized rayon at numerous stages in processing. The fiber length distributions, which represent several thousand measurements per analysis, better characterized the starting fiber condition and revealed significant fracturing of the carbonized fiber during slurry preparation. Surface chemistry of the carbonized rayon fibers and phenolic resin powder was recognized as an important variable in controlling wetting behavior in the slurry and initial packing of these constituents in the insulator preforms. Zeta potential measurements were performed to better understand chemical and physical interactions in the water slurry.

**Keywords:** Carbon Bonded Carbon Fiber, Vacuum Slurry Molding, Thermal Conductivity, Zeta Potential.





# Preliminary Overview of Decay Heat Issues in NTP Systems

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**Abstract.** Reactor Decay Heat is problematic for NTP systems. Decay heat removal requires a substantial amount of hydrogen. Work during the SNRE program estimated that a 16,000 lbf thrust class NTP system that ran for 30 minutes would require 1300 kg of hydrogen to cool. Beyond being problematic from a hydrogen usage standpoint, decay heat removal results in $I_{sp}$. low thrust at times other than normal operation which can complicate the trajectory of the spacecraft.

This work will explore heritage estimates of hydrogen usage during decay heat cool down, provide estimates of hydrogen usage for decay heat removal and present decay heat curves for NTP systems produced with Serpent. Furthermore, this work will highlight a number of potential issues in decay heat analyses including change of phase change in the $ZrH_x$ moderator, transient flow issues with orificed fuel elements and thermal shock associated with pulsing hydrogen during cool down.

**Keywords:** Decay heat, NTP, Hydrogen usage

# Initial Investigation of In-element Power Peaking in LEU Cermet NTP Fuel Elements

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**Abstract.** LEU cermet NTP fuel elements have a notable in-element power peaking. On a channel by channel basis the maximum to average power peaking factor can be on the order of 1.5. The In-element power peaking is caused by the inherent spatial self-shielding of the LEU cermet fuel. The spatial self-shielding is due to the large absorption and scattering cross-section for thermal neutrons in the cermet fuel even when the fuel matrix is made of isotopically purified $^{184}$W. This is further exacerbated by the fact many LEU cermet NTP concepts large fuel elements with a flat-to-flat dimension of about 3 cm which is longer than the average path length of a thermal neutron in the fuel element. The in-element power peaking necessitates extensive channel flow orificing to meet NTP performance goals. This will have varying impacts other aspects of NTP modeling and operation.

The present work explores the in-element power peaking for various geometries of LEU cermet NTP fuel using MCNP6, Serpent and WORPH. In addition, possible mitigation strategies and further need for modeling of in element power peaking will be discussed.

**Keywords:** Power profile, LEU, Cermet, NTP, In-element





# Enhanced Control Drums for NTP Submersion Criticality Safety

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**Abstract.** The water submersion criticality accident is a long-standing issue of all space nuclear systems. The accident scenario requires that all space nuclear systems remain subcritical in the event of it becoming fully submerged in water (fresh, salt, wet sand, etc). This is currently an unresolved complication for LEU-NTP cores that must be addressed. In the present paper, we propose a solution that, when properly combined with passive reactivity control to remove control drum movement, is able to resolve the issue. The drums use an innovative approach that significantly enhances their shutdown margin by bringing them into the active core and adding a fuel plate opposite the poison place in the drum. In doing so, two things occur when the drum is rotated into the shut-down position. First, the fuel in the drums is decoupled from the core as it’s distanced from the core and brought into the periphery of the reflector. This serves to remove fissile mass from the active region and reduce the possibility for fission, effectively inserting a large amount of negative reactivity. The second component is that now the poison plate is introduced into the core and can interact directly with the neutron in the core instead of rely on core leakage for control. The net effect is the amplification of the shutdown margin of the drum system as a whole. In the present work, the enhanced drums are developed and implemented in two example cores, showing the performance space in terms of being able to shut down the core for two LEU fuel types (Enriched Tungsten and Graphite Composite).

**Keywords:** control drums, water submersion, LEU.

# ELMOE: Europa Lander, Melter, and Oceanic Explorer

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**Abstract.** The moon Europa is a fully differentiated body orbiting Jupiter. It possesses a metallic core, rocky mantle, liquid water ocean, and icy outer surface. Europa is believed to possess significant geothermal activity due to tidal heating of its mantle from its orbital interaction with Jupiter and the other satellites. As hydrothermal vents on Earth are a source of life that does not require sunlight, it is believed that Europa could possess life on the floor of its liquid ocean.

ELMOE has four main sections. The first is the lander, which stays on the surface of Europa to serve as a relay station for sending information back to Earth. Second is the melt probe which is powered by a reactor. Third is the communications system, which relays data back to the lander for transmission to Earth. Finally, a small battery powered submarine is deployed when the probe reaches the ocean, which would operate for about a week.

To limit the landers exposure to radiation on the surface, the total mission duration won't exceed a few months. The probe melt speed is proportional to the power dissipated into the ice, and inversely proportional to the probe cross sectional area. An outside diameter of 25 cm with a power of 250kWt was found to be optimal. The model used to determine the melt speed was verified through experiments. A nuclear reactor was designed to provide the necessary heat.

Two reactor cores were designed; one which uses HEU and the other which uses LEU. The HEU reactor is smaller and doesn't need active cooling, and so is comparatively simple. The tip of the conical probe contains ~60 kg of uranium nitride (UN), which possesses a high thermal conductivity. Beryllium oxide is used as a movable reflector. The LEU reactor does require active cooling due to the larger core volume, but is politically and economically more attractive. The final LEU design uses NaK coolant to carry heat out of the core to the tip of the melt probe. The LEU core is composed of a square lattice of metallic uranium fuel pins in a zirconium hydride moderator. The pins and zirconium hydride are clad in zirconium carbide. Beryllium oxide is used as an upper and lower reflector. The core thermal hydraulics for both cases were simulated in the multiphysics code COMSOL.

The dose limit for the instrumentation inside the submarine was estimated to be 2.08 rad/hr for a four-month mission. Using this estimate, MCNP and hand calculations were made to determine shielding requirements. Tungsten was chosen as the photon shield while lithium hydride was chosen as the neutron shield. Calculations showed that shielding materials combined would need to be greater than 1 meter thick, which would be impractical. Further study of the shielding is therefore required.

To relay data back to Earth, a series of transceiver modules will be left behind the probe as it melts through the ice. Each transceiver module will communicate with the one directly above and below itself via radio frequency at 500 MHz. The antennas will be circularly polarized square patch antennas with a single feed. Additional work needs to be done with the circularly polarized antennas. This system of several transceiver modules will eliminate the single point of failure possible with a communication tether attached to the melt probe, while also providing a communication link that will last the months long mission.

The submarine would explore Europa's ocean. This submarine would carry instrumentation for data collection and analysis, and power supply for the submarine as well as for the instruments on board. The diameter of the submarine is 21 cm and it is 147 cm in length. This submarine is designed to fit behind the melt probe and withstand external pressure up to 30 MPa. The simplest model is a vertically oriented submarine, and it weighs only 50 kg. It requires less than 50 W electric power when all the instruments are in use. A horizontal submarine was also examined that can move vertically as well as horizontally in Europa's ocean. It weighs about 100 kg, and more power is necessary as compared to the vertical submarine.

**Keywords:** Europa, Jupiter, melt probe, communications, reactor, submarine





# Separation and Purification of Np-237 and Pu-238 from a Simulated Irradiated Target

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**Abstract.** Radioisotope power systems use plutonium-238, which is produced from neptunium-237 in a nuclear reactor. Prior to use, plutonium-238 must be chemically separated from irradiated targets containing neptunium and fission products. An experiment to demonstrate the feasibility of separating neptunium-237, plutonium-238, and simulated fission products from an acidic nitrate solution using an alternative ion exchange approach was performed. A feed solution was prepared to simulate a dissolved, irradiated neptunium oxide target containing approximately 10% plutonium-238 and 1% simulated fission products. To limit gamma radiation fields and allow operations to be performed in a radiological glove box rather than a hot cell, fission products were simulated using a cocktail previously prepared for inter-laboratory experiments with the ALSEP (Actinide Lanthanide SEParation) solvent extraction process. Process steps were monitored using UV/Vis spectroscopy. Mass spectrometry results indicated excellent separation of plutonium and fission product simulants from neptunium. Analysis of the plutonium fraction by gamma spectroscopy and alpha spectroscopy are planned.

**Keywords:** plutonium-238, neptunium-237, radioisotope power system, ion exchange, solvent extraction.

# Production of $PuO_2$ and $NpO_2$ Microspheres

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**Abstract.** PNNL has established capabilities to produce and characterize neptunium oxide and plutonium oxide microspheres using radiological glove boxes for containment. Internal gelation sol-gel techniques are used as a way to process aqueous actinide solutions into oxide microspheres with desired diameters. Plutonium oxide microspheres may be used directly as heat sources or pressed into pellets. "Wet" sol-gel processing produces heat source granules directly, reducing fine-particulate contamination that is associated with precipitation and ball milling activities. Additionally, sol-gel particle sizes are well above the respirable threshold of 10 µm. Production of actinide microspheres is in development while established capabilities to make non-radioactive surrogate microspheres have been used to generate hot-pressed pellets from cerium oxide microspheres in collaboration with the University of Dayton Research Institute. Progress on microsphere production and work with surrogate materials will be presented, along with PNNL's related capabilities.

**Keywords:** plutonium-238, radioisotope power system, sol-gel, microspheres.





# Description of a Novel Target for the Production of $^{238}Pu$ in Commercial Nuclear Reactors

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**Abstract.** PNNL has developed a target design that can support production of $^{238}Pu$ in a commercial reactor. Over the last several decades, NASA has consumed on average, several kilograms per year of $^{238}Pu$ to support radioisotope power systems and the existing inventory has been depleted. Since production potential is roughly proportional to power level, a commercial reactor rated at 3000 $MW_{th}$ represents a significant production capability. Further, since the reactor operating and fuel costs are covered by electricity sales, there is potential for the marginal cost of supporting $^{238}Pu$ production in a commercial reactor to be fiscally attractive. Historically, $^{238}Pu$ production in the US had been performed in defense reactors that operated at relatively low temperatures. Therefore, these legacy targets are not appropriate for use in commercial reactors that operate at relatively high temperatures. In addition, targets used in commercial reactors must demonstrate acceptable performance during a wide range of off-normal and accident events. There have been previous attempts in the 1970's to develop targets that were suitable for use in commercial reactors, but these designs did not demonstrate efficient material recovery following irradiation. A detailed description of the PNNL target design, and its expected performance in terms of in-reactor behavior, as well as material recovery, will be provided.

**Keywords:** $^{238}Pu$, commercial reactors, radioisotope power system

# The Paucity Problem: Where Have All the Space Reactor Experiments Gone?

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**Abstract.** The Handbooks of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and the International Reactor Physics Experiment Evaluation Project (IRPhEP) together contain a plethora of documented and evaluated experiments essential in the validation of nuclear data, neutronics codes, and modeling of various nuclear systems. Unfortunately, only a minute selection of handbook data (twelve evaluations) are of actual experimental facilities and mockups designed specifically for space nuclear research. There is a paucity problem, such that the multitude of space nuclear experimental activities performed in the past several decades have yet to be recovered and made available in such detail that the international community could benefit from these valuable historical research efforts. Those experiments represent extensive investments in infrastructure, expertise, and cost, as well as constitute significantly valuable resources of data supporting past, present, and future research activities. The ICSBEP and IRPhEP were established to identify and verify comprehensive sets of benchmark data; evaluate the data, including quantification of biases and uncertainties; compile the data and calculations in a standardized format; and formally document the effort into a single source of verified benchmark data.

The recovery of space nuclear experiments before they become permanently lost plays a synergistic role with current-day needs and could be of great service to unknown future efforts. Numerous experiments were performed investigating the capability to construct and operate autonomous compact nuclear reactors in harsh, remote locations. Such capabilities are of interest supporting development of small modular reactors for terrestrial applications. Unique materials such as tungsten, tantalum, lithium, and potassium, to name a few, were investigated in some of the space programs. Some of these experiments may represent our best, if not only, experiments available for refinement and integral validation of some nuclear data libraries. Interest in advanced modeling and simulation of multiphysics experiments can benefit from modern space nuclear experimentation, which includes the measurement of thermal, hydraulics, or material effects coupled with the neutronic conditions. Fission product buildup, minor actinide cross sections and decay properties, and radiation shielding aspects for building advanced fast reactors have needs that must be addressed to support both terrestrial and space nuclear applications.

So where have all the space reactor experiments gone? More importantly, what must be done to preserve these components of our nuclear heritage before the usefulness of what remains to be recovered becomes insignificant? Recorded knowledge beyond summary reports and journal articles such as logbooks, memos, and drawings need located and digitized. While the time and cost necessary to completely evaluate all space nuclear experiments is limited, the first key step is to recover and preserve what can be found, making that information publicly available such that we enable our next generation of nuclear scientists and engineers to someday evaluate and apply the information before designing and implementing next generation test facilities and reactors. Otherwise, if we continue to ignore, and effectively support, this paucity problem, our next generation may well take its first steps reinventing heritage space nuclear research.

**Keywords:** Benchmarks, Data, Experiments, Preservation, Validation.





# DEMOCRITOS : Nuclear Electric Propulsion to EUROPA and MARS

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**Abstract.** DEMOCRITOS (Demonstrators for Conversion, Reactor, Radiator And Thrusters for Electric Propulsion Systems) is an international project founded by the European Commission to enable a realization of a mega-watt class electric propulsion spacecraft. The project is a follow-on activity of the successful European-Russian cooperation in the frame of the MEGAHIT (Megawatt Highly Efficient Technologies for Space Power and Propulsion Systems for Long-duration Exploration Missions) project. The primary focus of the project is the ground demonstration of the core technologies. Furthermore, a preliminary design of the spacecraft including all subsystems shall be developed by utilizing the Concurrent Engineering (CE) process at DLR in Bremen. DEMOCRITOS aims to develop key technologies required for realisation of a number of sophisticated missions in the future. The current baseline spacecraft (S/C) design consists of two modules of 20 tons mass each and shall be assembled in orbit. However, all sub-systems shall be developed in modular way (modular building blocks) to enable a realization of a mission dedicated spacecraft in the future. Depending on the mission a number of building blocks which have different functionalities will be assembled in orbit. The reactor shall provide electrical energy of 1MWe to fulfil different mission requirements.

The results of the international DEMOCRITOS project (European Commission funded European & Russian consortium members, Brazil as a guest observer and by means of consultancy from ASL, NASA and JAXA) will be highlighted. DEMOCRITOS results are the first version of system and subsystem designs of the International Nuclear Power and Propulsion System (INPPS) flagship towards Jupiter moon Europa and Mars exploration in the second half of the 2020th. Moreover it will be sketched the concepts of the nuclear and ground based demonstrators realization until the middle of the 2020th and the strategic roadmap for technical feasibility, scientific excellence, political acceptance, industrial and public supports.

**Keywords:** Nuclear Electric Propulsion, EUROPA, MARS, DEMOCRITOS, INPPS

# An RTG-Powered New Frontiers Titan Lander Concept

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**Abstract.** A Titan Lander for New Frontiers 4 is discussed. The January 2016 NASA Community Announcement pertaining to the New Frontiers 4 mission proposal call identified 'Ocean Worlds', and specifically Titan and Enceladus, as science targets for missions with launch circa 2025. Unfortunately, this launch date, with arrival in the mid-2030s, precludes a cost-effective single-element mission to Titan's northern seas, like the Titan Mare Explorer (TiME) mission proposed in 2010 to the Discovery program (with planned arrival in 2023). The reason is Titan's seasons : 2023 is late Northern Summer, when Earth is visible from the ~400km-wide Ligeia Mare at 80N, and so direct-to-Earth communication is possible. In the mid-2030s, either a sea/lake lander must be supported by a relay orbiter, a precision descent system is needed to permit safe targeting in the much smaller Ontario Lacus in Titan's south polar regions, or a land lander at low latitudes must be considered.

In fact, the 2007 NASA 'Titan Explorer' Flagship mission study led by APL (https://solarsystem.nasa.gov/multimedia/downloads/Titan_Explorer_Public_Report_FC_opt.pdf ) identified a lander, aimed at Titan's giant dunefield Belet as the highest-value in-situ element (offering stronger science return than a balloon). The payload of this lander (without tight cost constraints) was determined by a NASA-appointed Science Definition Team, chaired by this author. The payload included the following : Seismometer, Meteorology Package, Surface Sampler and Chemical Analyzer, Microscopic Imager, Near-IR Spectrometer, Panoramic Imager, Descent Imager, Magnetometer and Radio Science. The 900-kg lander was to be powered by two Advanced Stirling Radioisotope Generators (ASRGs) with a notional output of ~255 W and could perform both orbiter-relayed and direct-to-Earth communication, with launch in 2018 and arrival in 2028.

At the time of the study, Titan's seas had not been mapped, and the Belet sand sea was the largest contiguous region on Titan whose terrain could be considered to be relatively free of rock and gully hazards, permitting an unguided entry and descent, with impact control by parachute and Pathfinder-like airbags.

The New Frontiers 4 opportunity prompts consideration of a similar concept, powered by one or more Radioisotope Thermoelectric Generators (RTGs) with direct-to-Earth communication from this low-latitude landing site. The cost constraints of New Frontiers may require that only a subset of the payload identified above can be supported, and the electrical energy budget of the lander will map directly into the data return that can be supported.

Important considerations in the formulation of such a mission are (1) the rather disappointing degradation of the thermoelectric converters in the MultiMission RTG (MMRTG), (2) the performance of an RTG in the Titan atmosphere, and (3) the possible influence of waste heat from an RTG on the lander's environment. Nonetheless a scientifically-appealing mission within this framework, addressing the complex prebiotic chemistry of the Titan surface environment, can be conceived.

**Keywords**: Planetary Science; Radioisotope Power; Titan; Ocean Worlds ; New Frontiers





# Status update of the Department of Energy's Transient Test Program and its Capabilities For Space Power and Propulsion Reactor Fuels Testing

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**Abstract.** The United States Department of Energy is resuming transient testing of nuclear fuels by restarting operations of the Transient Reactor Test (TREAT) reactor at the Idaho National Laboratory's Materials and Fuels Complex. The TREAT reactor has a 19 GW peak transient power, is air cooled and is fueled by 4-inch by 4-inch by 8 feet long metal clad graphite-uranium oxide dispersion fuel elements in a 19 by 19 square array. The core of the reactor is easily accessed via a top-side rotating shield that allows for the installation of an transient experiment vehicle in any one or number of fuel locations. Typically, experiments are located in the center most position of the core. Due to the ease and rapidity of reconfiguring the TREAT core in between experiments, the reactor can accommodate diverse experiments back to back of one another. Experiments may be performed to examine the transient behavior of nuclear fuels during operational ramps to power or during prototypical accidental power excursions. Other experiments may be performed to examine the dominating heat transfer mechanisms or thermal performance of a fuel system or power conversion loop. Many other types of experiments can be employed at the TREAT reactor including high-energy physics and instrumentation testing in the intense neutron and gamma radiation fluxes that can be achieved. The peak temperatures that can be achieved by nuclear heating of experimental fuel specimens in the TREAT reactor are limited only by the enrichment of the test specimens and the insulation materials and schemes used to encapsulate an experiment. The status of the TREAT restart activities will be presented in addition to progress in the preparation of the first new experiments that will be performed in TREAT. Similarly, examples of experiments that can be conducted within the TREAT reactor in support of space nuclear power and propulsion system fuels development will also be presented.

**Keywords:** TREAT, Transient, Testing, Reactor, Fuels

# Conceptual design of light-weight small core with fast spectrum for nuclear propulsion rocket

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**Abstract.** A nuclear thermal rocket (NTR) is a technology for spacecraft propulsion. In a NTR a working fluid, usually liquid hydrogen, is heated to high temperature in a nuclear reactor, and then expands through a rocket nozzle to create thrust. This design typically deliver specific impulses (Isp) on the order of 850 to 1000 seconds, which is about twice that of liquid hydrogen-oxygen ones. In this study, Small Engine Reactor, a thermal reactor fueled with highly enriched uranium carbide (UC), designed by Los Alamos Scientific Laboratory in 1972 was used as a reference NTR core. The total mass of this core is 2,550[kg] (core: 643[kg]). If a lighter and smaller NTR core than reference design is realized, it will be possible not only to increase the payload of the rocket but also to allow longer operation time as a result of increased amount of hydrogen.

The purpose of this study is to design a light-weight and small NTR core by using highly enriched uranium or plutonium in a NTR core with fast neutron spectrum and to examine the neutronics and thermal hydraulics feasibility of this NTR.

Therefore, this study performed criticality calculations by changing the fuel material (UC → UN or PuN) and neutron spectrum (thermal → fast). In thermal hydraulic analysis, cooling performance of the core was analyzed by solving the one-dimensional heat conduction equation for an unit cell geometry consisting of single cylindrical hydrogen channel and a surrounding annular fuel region.

According to the calculation result of neutronics, the minimum critical mass of UN is 117[kg] and the PuN is 57[kg]. The radius of the core are 8.5[cm] for UN and 4.7[cm] for PuN in the case of the same core height as the reference core (89[cm]). Namely, the weight and radius of a fast spectrum core with PuN were reduced by 1/10 and 1/6, respectively, compared with the original core.

However, downsizing of the reactor core leads to an increase in power density and a decrease in flow area of hydrogen. As a result, the temperature of fuel region could exceed the melting point of the region. The simple way to satisfy the limit is to increase the mass flow rate or the lower thermal power. In this study, the limit value was satisfied by selecting an appropriate thermal power. The thermal power was reduced from 367[MWt] of reference core to 196[MWt] for UN and 170[MWt] for PuN.

On the other hand, decrease in flow area of hydrogen causes an increase in pressure loss and velocity at the inlet of cooling channel. To reduce these values, this study optimized the radius and the number of coolant channels. The calculation results indicated that the inlet velocity is less than the velocity of sound by designing 61 coolant channels in a diameter of 1.0[cm],

In conclusion, it is feasible to design a light-weight small fast spectrum core for nuclear propulsion rocket from viewpoints of neutronics and thermal-hydraulic parameters such as the fuel temperature, coolant velocity and pressure drop. The core weight is reduced to 1/10 compared to reference core of NTR. The reactivity control scheme and structural integrity of the core should be confirmed.

**Keywords:** Nuclear thermal propulsion, Fast spectrum, Nitride fuel, HEU, Pu





# Preliminary Conceptual Neutronic, Thermal and Mechanical Design for $^{238}$Pu Advanced Test Reactor Targets

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The $^{238}$Pu Supply Program led by Oak Ridge National Laboratory (ORNL) has the objective of reestablishing the domestic capability for producing $^{238}$Pu[(I)]. In order to meet the quantities of $^{238}$Pu needed to support NASA space missions, the Advanced Test Reactor (ATR) located at Idaho National Laboratory (INL) is an important asset to achieve the desired production of the radioisotope. To determine the constraints and parameters needed to maximize the production of $^{238}$Pu at ATR, initial analyses for a preliminary target design were recently performed. Finally, an investigation of the feasibility of using lower-flux ATR positions for $^{238}$Pu is also being investigated.

In order to mainstream, optimize and lower the cost of production, targets for both reactors will be manufactured at ORNL and then shipped to ATR. The targets for ATR will have the same design parameters as the ORNL targets to the extent practicable, except for target length. A trade study was performed to assist in selecting the optimal target length for ATR[(II)]. Target length is a key parameter because of the difference in core height between the two facilities. Four different target length options were analyzed: a single HFIR target centered at the ATR core midplane, two stacked targets centered at the ATR core midplane, a single long target centered at the ATR core midplane, and two stacked targets not centered at the ATR core midplane. Each target option was evaluated with a plenum length-to-pellet stack length ratio equal to that used in the HFIR target design, as well as with a reduced ratio. Each target option and plenum/pellet ratio combination was evaluated in five different ATR irradiation positions: northeast flux trap (NEFT), Inner-A, Outer-A, Small-B, and Large-B positions. Based on the neutronics analysis results, a 52-inch long concept target was conceptually design. The new concept target will be able to take advantage of ATR's core length without requiring significant modifications to the manufacturing process.

After completion of the target length trade study the selected target was evaluated from the standpoint of the ATR nuclear safety requirements. The evaluation consisted of performing neutronics, thermal and structural analyses. The analyses were performed for the 52-inch long concept target in a Small-B position (B6). Position B6 was selected due to the fact that its geometrical configuration, coupled with the target design, highly restricts the removal of heat by the coolant, thus providing a bounding scenario.

Finally, a study to investigate alternative production schemes at ATR is also being performed. This study consists of assessing highly available lower magnitude flux positions at ATR (e.g., large and medium I positions). This option is attractive due to the availability and larger diameter, as well as the high thermal-to-fast flux ratio at those positions.

**Keywords:** $^{238}$Pu, radioisotope, Advanced Test Reactor

[I] Oak Ridge National Laboratory, "ORNL Achieves Milestone with Plutonium-238 Sample," https://www.ornl.gov/news/ornl-achieves-milestone-plutonium-238-sample, published December 22, 2015, web page visited January 26, 2016.

[II] INL/MIS-15-34366, "INL ATR Neptunium Qualification Target Length Trade Study," Rev. 0, February 2015.

# Turbo-Brayton Power Converter for Spaceflight Applications

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**Abstract.** Future NASA space missions require advanced systems to convert thermal energy into electric power. Closed-loop Brayton converters are attractive for these applications because they have high efficiency and specific power. They also consist of discrete components that can be packaged to fit optimally with other subsystems, and their continuous gas flow can communicate directly with remote heat sources and heat rejection surfaces without ancillary heat transfer components and intermediate flow loops.

Development of turbo-Brayton converter technology for space is under way at Creare. The approach builds upon a nearly 40-year foundation of advanced turbo-Brayton components and systems Creare has developed for numerous NASA, DoD, and DOE applications; including the NICMOS Cryogenic Cooler on the Hubble Space Telescope. This prior work provides critical technology and expertise regarding spaceflight Brayton systems, which is now being leveraged to develop power converters for space. The technology is readily scalable for power levels from tens of watts to hundreds of kilowatts and beyond. Potential near-term NASA applications include Radioisotope Power System (RPS) devices, “Kilopower” spacecraft, and Fission Surface Power (FSP).

Hydrodynamic gas bearings and clearance seals are key features. Gas bearings support the turbomachine rotor with no mechanical contact between moving surfaces. This lack of contact enables extremely high rotational speeds, which is important for high efficiency and low mass. In addition, gas bearings eliminate wear and the need for lubricants, which enables extremely long maintenance-free lifetimes and makes the resulting systems ideal for space applications. Similarly, clearance seals limit internal bypass leakage without mechanical contact. Several reliability demonstrations have been completed, including a 14-year endurance test with no maintenance or wear, and compressor and turbine assemblies each exposed to 10,000 start/stop cycles with no maintenance or wear. Additionally, the NICMOS Cryogenic Cooler has accumulated over 6.5 years of operation in space.

The near-term focus is to demonstrate a laboratory-grade converter with a viable path for future spaceflight versions. This achievement will demonstrate the most critical elements of the technology at prototypical operating conditions. A power level of 1 $kW_e$ was selected for the initial prototype to provide a relevant demonstration with capability to scale up or down in the future. The laboratory converter design is relatively simple with significant emphasis on low-risk features. A low-risk design was specified to limit development effort and help ensure successful technology demonstration within budget limitations. Future development efforts are envisioned to push operational limits further and create more advanced features for greater power conversion efficiency and specific power.

Creare is developing the laboratory converter with SBIR Phase II funding. Component fabrication is complete, and testing has begun.

**Keywords:** Brayton, power converter, turbomachine





# Using CANDU Reactors for $^{238}$Pu Production for Space Exploration

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**Abstract.** The current inventory of $^{238}$Pu available to support deep space missions using radioisotope power systems is limited and efforts are underway to produce a new supply. Pacific Northwest National Laboratory (PNNL) has developed a neptunium oxide-based target design that can support production of $^{238}$Pu in the high temperature environment of a commercial nuclear reactor. The use of commercial nuclear reactors offers the potential for significant production capacity of $^{238}$Pu at a reasonable cost. Ontario Power Generation (OPG) and its wholly owned services subsidiary Canadian Nuclear Partners (CNP) believe that they have an important role to play to address the shortage. This paper will discuss the necessary functional requirements and qualification process for the new bundles as well as the operational activities required to allow the irradiation of neptunium oxide targets in OPG’s reactors. Successful qualification for use in OPG’s reactors could support a significantly increased production rate of $^{238}$Pu for space missions.

**Keywords:** $^{238}$Pu, commercial reactors, radioisotope power system, CANDU, Ontario Power Generation, Canadian Nuclear Partners

# Plutonium-238: An Option to Improve RPS Throughput and Availability

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**Abstract.** An affordable, long-term solution to producing radioisotope power systems is required to perform missions of interest to space agencies domestically and internationally. For nuclear power sources in the 100s of watts electric, plutonium-238 is the isotope of choice. While past national defense infrastructure subsidized Pu-238 production and processing through dual-use facilities and personnel, today the full cost for Pu-238 rests on the space exploration community. To maximize the science return per dollar invested, historic plutonium-238 production and processing techniques must evolve to reduce cost and waste as well as conform to the new reality of existing nuclear infrastructure and regulatory environments. A vision to supply radioisotope power sources to space agencies using plutonium-238 produced in a commercial nuclear reactor will be presented.

**Keywords:** Plutonium-238, commercial nuclear reactors, radioisotope power system, neptunium





# Advanced Insulation Material for eMMRTG Flight Modules

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**Abstract.** All spacecraft, satellites, and landers require the use of thermal insulations considering the extreme environments encountered in space and on extraterrestrial bodies. At TESI, the efforts have focused on optimization of the material components and the network in the structure of the innovative hybrid thermal insulation. This hybrid silica-based aerogel insulation is fabricated under ambient conditions, presenting superior properties such as high mechanical strength and thermal stability while retaining low thermal conductivity through a wide temperature range. In particular, this insulation can prolong the operational lifetime of thermoelectric couples due to its ability to suppress the sublimation of volatile constituents of the thermoelectric materials. In this presentation, more details of the characterization and performance will be reviewed and discussed.

**Keywords:** Thermal insulation, characterization, performance, thermoelectrics, RTG

# Status of the Kilowatt Reactor Using Stirling TechnologY (KRUSTY)

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**Abstract.** The Kilopower project is developing a scalable fission-based power system capable of delivering 1 – 10 kW of electric power with a specific power ranging from 2.5 - 6.5 W/kg. These systems could enable high power science missions or could be used to provide surface power for manned missions to the Moon or Mars. NASA has partnered with the Department of Energy's National Nuclear Security Administration (NNSA), Los Alamos National Labs, and Y-12 National Security Complex to develop and test a prototypic reactor and power system using existing facilities and infrastructure. This system, referred to as the Kilowatt Reactor Using Stirling TechnologY (KRUSTY) will undergo nuclear ground testing in the summer of 2017 at the Nevada Test Site.

Figure 1. 1 $kW_e$ Kilopower System in a dual-opposed configuration.

A 1 $kW_e$ Kilopower system, shown in figure 1, consists of a 4 $kW_t$ highly enriched Uranium-Molybdenum reactor, operating at 800 °C coupled to sodium heat pipes. The heat pipes deliver heat to the hot ends of eight 125 W Stirling convertors producing a net electrical output of 1 kW. Waste heat is rejected using titanium-water heat pipes coupled to carbon composite radiator panels. The KRUSTY test uses a prototypic highly enriched uranium-molybdenum core coupled to prototypic sodium heat pipes. The heat pipes transfer heat to two Advanced Stirling Convertors (ASC-E2's) and six thermal simulators, which simulate the thermal draw of full scale Stirling power conversion units. The thermal simulators and Stirling engines are gas cooled. The decision to use thermal simulators and ASC engines were budget driven, since design and fabrication of eight full scale convertors was cost prohibitive. The ASC-E2 units were originally produced for NASA's radioisotope power system program and repurposed and modified for KRUSTY. The decision to use gas cooling instead of radiative cooling was driven by the special constraints of the Comet test stand at the Device Assembly Facility (DAF), where final nuclear testing will take place.

The major accomplishments of the project in 2016 are the completion of non-nuclear system level testing at NASA Glenn Research Center (GRC) using an electrically heated stainless steel core surrogate (Figure 2) and the fabrication and delivery of a depleted uranium core surrogate from Y-12 to GRC. System level tests at GRC have validated performance predictions and have demonstrated system level operation and control in a test configuration that replicates the facility constraints of the DAF. Delivery of the depleted uranium core will allow for higher fidelity system level testing at GRC, but more importantly, has developed the casting molds and processes required for fabrication of the highly enriched core. Testing of the depleted Uranium core at GRC will begin by end of CY 2016 with the enriched core nuclear ground testing at the DAF to begin in the summer of 2017.

Figure 2. Electrically Heated Stainless Steel core surrogate with sodium heat-pipes during fueling.





# Titanium Water Heat Pipes for Kilopower System

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**Abstract.** NASA Glenn Research Center is examining small fission power systems that address the gap between Radioisotope Power Systems (RPS) and Fission Surface Power Systems (FPS) for future spacecraft applications and Lunar and Martian surface missions. The Kilopower system, operating in the 1 to 10 kWe range, uses alkali metal heat pipes to supply heat to Stirling convertors to produce electricity. The waste heat is removed by titanium water heat pipes to radiators where it is rejected to space. The design of the heat pipes must allow for testing of the Kilopower system on earth, operation in space, survival during launch, and adverse orientations (evaporator above condenser). Advanced Cooling Technologies, Inc. (ACT) is designing and fabricating hybrid screen-groove titanium water heat pipes as solely grooved wicks are insufficient for the varied operating environments. This paper reports on the fabrication and test results for the titanium water heat pipes and radiators and future development efforts. A screened annular evaporator which interfaces to the cold end of the Stirling convertor was designed, fabricated, and welded to the grooved heat pipe previously developed. The hybrid heat pipe was then tested for heat transport capability. Heat pipe radiators were fabricated by joining solid aluminum facesheets to titanium heat pipes using S-Bond. The heat pipe radiators were cycle tested under vacuum for bond integrity and performance tested in ambient conditions for radiator effectiveness.

**Keywords:** Heat pipe, Kilopower, titanium

# High Temperature Heat Pipes for Space Fission Power

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**Abstract.** This paper reports on the final stage of development of alkali metal heat pipes for the Kilopower System to be tested at NASA Glenn Research Center (GRC). Currently, fission power systems are being developed by NASA GRC for future space, Lunar and Martian surface power applications. The systems are envisioned in the 10 to 100kWe range and address the gap between thermoelectric and fission surface power systems. The heat generated by the nuclear reactor is carried by the alkali metal heat pipes to the Stirling convertors for power generation. The entire system must be tested on Earth before launch and must be able to operate in micro-gravity, as well as on the Moon and Mars. Grooved and arterial wicks are the traditional design for heat pipes operating in micro-gravity; however, these heat pipes are not suitable for a nuclear power system since they must also be capable of operating in the following orientations: operation in space, with zero gravity; operation on earth, with a slight adverse orientation; ground testing, with the heat pipes operating gravity aided; and launch, with the evaporator elevated above the condenser. During vertical ground testing, the heat pipe wick will de-prime, and will need to re-prime for operation in space after launch. Hybrid groove-screen and self-venting arterial heat pipes were chosen for this application, since they are able to spontaneously re-prime. This paper reviews the performance of self-venting arterial and hybrid groove-screen heat pipes developed by Advanced Cooling Technologies, Inc. (ACT) for the Kilopower system. The recently developed hybrid groove heat pipe demonstrated satisfactory performance and provided insight for improvement in future development efforts. In addition, the enhancements to the alkali metal heat pipes for ground testing of the depleted uranium system by NASA GRC are also included.

**Keywords:** Self-venting heat pipes, alkali metal, Kilopower





# Manufacturability and Performance of Skutterudite Thermoelectric Couples for the eMMRTG

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**Abstract.** The primary goal of the Skutterudite Technology Maturation Program (SKD Tech Mat) is to advance the thermoelectric technology developed at NASA's Jet Propulsion Laboratory from a well-defined laboratory level material and couple with "promising" performance, into a "flight-ready" thermoelectric couple and module that can be integrated in an *enhanced* Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG). The synthesis of well-performing skutterudite materials was achieved in the previous phase of the program, but some challenges were presented at the couple level that involved the unfavorable reaction of antimony vapor sublimed from the thermoelectric materials with the metallic braze and electrode materials. Recent development efforts on the couple level have yielded more robust thermoelectric couples with improved (lower) degradation rates. The details of these efforts and the current status of couple and module manufacturability will be presented and discussed.

**Keywords:** Skutterudite, eMMRTG, Thermoelectric.

# Comparative Studies for the MHD Modeling of Annular Linear Induction Pumps for Space Applications

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**Abstract.** Nuclear fission-based power systems are the best suited power sources for surface missions requiring high power in difficult environments. Liquid metal-cooled fission reactors are typically very compact and they can be used in regular electric power production, for naval and space propulsion systems or in fission surface power systems for planetary exploration. These type of reactors are both moderated and cooled by a liquid metal solution.

Liquid alloy systems have a high degree of thermal conductivity far superior to ordinary non-metallic liquids and inherent high densities and electrical conductivities. This results in the use of these materials for specific heat conducting and/or dissipation applications. Uniquely, they can be used to conduct heat and/or electricity between non-metallic and metallic surfaces. The motion of liquid metals in strong magnetic fields generally induces electric currents, which, while interacting with the magnetic field, produce electromagnetic forces. Electromagnetic pumps exploit the fact that liquid metals are conducting fluids capable of carrying currents source of electromagnetic fields useful for pumping and diagnostics.

The standard method used to design electromagnetic pumps of the annular linear induction type is the electric circuit approach which relies on the assumption that the flow is laminar. Hence the electromagnetic and hydrodynamic phenomena can be separated. Then the theory of linear induction machines and electric circuits can be used. This method is not very accurate and it doesn't provide an understanding of the phenomenology and instabilities involved. The latter is truth because the coupling between the electromagnetics and thermo-fluid mechanical phenomena observed in liquid metal thermo-magnetic systems, and the determination of its geometry and electrical configuration, gives rise to complex engineering magnetohydrodynamics and numerical problems where the different physical phenomena involved cannot always be decoupled.

The use of first principles to design annular linear induction pumps leads to a more accurate design process while the analysis of the couple physical phenomena leads to a better understanding of the magnetohydrodynamics and instabilities in place.

Besides the numerical complexity that arises during computer simulation, the adoption of the right modeling methodology is fundamental. One of the important issues found is to numerically maintain the conservation of magnetic flux condition to avoid any unphysical effects. During the development of computational tools for the design of annular linear induction pumps using first principles several modeling methods with specific flaws and virtues where found.

We will discuss some of these modeling methodologies and its properties.

**Keywords:** EM pumps; liquid metal; MHD; multiphysics; ALIP; modeling and simulation.





# Alternate Siting for Nuclear Thermal Propulsion Ground Testing

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**Abstract.** Nuclear thermal propulsion (NTP) is an enabling technology for the mission to Mars. An NTP system could provide high thrust at a specific impulse above 900 seconds, roughly double that of state-of-the-art chemical engines. Characteristics of fission and NTP indicate that useful NTP systems will provide a foundation for future systems with extremely high performance. Feasibility studies for all candidate options for a ground test of an NTP system need to be completed to enable a down-select among the options. The current baseline candidate for the ground test is a fully contained test in which engine hydrogen exhaust is burned at high temperatures with oxygen and produces steam to be cooled, condensed, and collected for controlled processing and disposal at Stennis Space Center in Mississippi; however, this option is likely to cost several billion dollars with a high probability of never achieving a license to operate due to safety (and security if the fuel is highly enriched uranium, HEU) concerns related to above-ground siting. Feasibility of a ground test should evenhandedly compare the full spectrum of issues, especially regarding safety and security for all potential sites. One location that has not been adequately explored is the Nevada National Security Site, formerly the Nevada Test Site, which hosted the former NTP test facility named the Nuclear Rocket Development Station (NRDS). The NRDS remained operational for nearly two decades, supporting the U.S. government-sponsored nuclear rocket reactor program named Project Rover and the Nuclear Engine for Rocket Vehicle Application engine development program. A feasibility study for this option necessarily begins with regulatory requirements analyses involving 11 separate activities: environmental impact statement, risk management, environmental programs compliance, radiation protection, quality assurance, project and risk management, reactor disposal/disposition, transportation, safety basis, security, and emergency services/fire and rescue requirements. Based on statements in the Final Site-Wide Environmental Impact Statement and the associated Record of Decision for the Continued Operation of the Department of Energy/National Nuclear Security Administration Nevada National Security Site and Off-Site Locations in the State of Nevada, it will be necessary to conduct a National Environmental Policy Act review. Selection of underground placement for these tests would significantly mitigate the costs based on application of the graded approach for safety basis development and readiness activities. Security requirements will need to be assessed based on the choice of fuel and enrichment. If the fuel is HEU, then underground siting would dramatically mitigate the operational security costs. The final task for the regulatory requirements analysis will involve assessment of activities associated with operational risk management, emergency response, fire prevention and protection, and management of emergency services.

**Keywords:** Nuclear thermal propulsion, mission to Mars, nuclear rocket ground testing

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## Dynamic Power Conversion for future Radioisotope Power Systems

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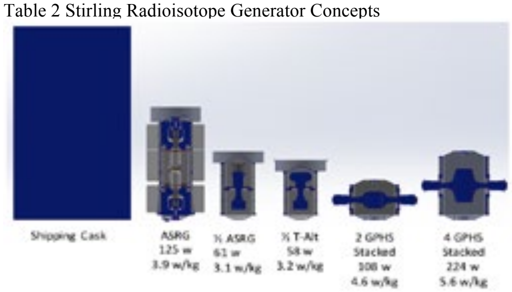
**Abstract.** Dynamic power conversion offers the potential to produce Radioisotope Power Systems (RPS) that produce higher power conversion efficiency than the current Multi-Mission Radioisotope Thermoelectric Generators (MMRTG). This increased efficiency would use less of the scarce Pu-238 radioisotope and thus increase the total potential electrical power output of the current and plannedPu-238 inventory. In addition to the increased available power output, these systems should have a much lower power degradation rate than past RTGs thereby allowing spacecraft to utilize a greater fraction of their Beginning- of-Life (BOL) electrical power after many years of operation. Because of these factors the NASA Radioisotope Power System Program Office (RPS-PO) in conjunction with the Department of Energy (DOE) sponsored the Dynamic Radioisotope Power System project (DRPS) to study future DRPS and ascertain their challenges and benefits. One part of the DRPS includes studying how future dynamic power systems might be configured and how they may perform. Two assumptions are made in these studies which drive generator design. The first is that the General Purpose Heat Source (GPHS) is the building block used in the development of future RPS. Each GPHS provides about 250 watts of heat at its BOL and the Pu-238 contained in each GPHS has a half-life of about 90 years. Second, the existing GPHS infrastructure at Idaho National Laboratory (INL) and the equipment necessary to move future GPHS based systems are likely to remain the same due to the costs associated with modifications. The DOE shipping cask is one of the components that limits the size of future DRPS. Interior dimensions of the shipping cask are a cylinder 135 cm in height and 76 cm in diameter. Performance goals for any future DRPS must show significant improvement over the previous or current RTG systems available. NASA has set a goal efficiency (DC power output / heat input) of 20% for BOL performance of future DRPS with generator power output from 200 to 500 We. Table 1 shows acomparison of Brayton, Stirling and organic Rankine cycles using conservative assumptions for each system's performance. This analysis suggests that achieving both the 20% efficiency target and the 200 We output while fitting within the shipping cask may be a challenge for both Brayton and organic Rankine systems.

A wide range of conceptual designs were considered and analyzed for mass and performance (Table 2). Generator designs in which the GPHS modules are stacked allowing the Stirling convertors to share the centrally located heat source as well as designs that did not allow heat source sharing were assessed. Redundancy was considered both at the individual generator level and by allowing individual generators to be stacked within the shipping cask.

Table 1 Comparison of Dynamic RPS Generators

| | Stir | Bray | ORC |
|---|---|---|---|
| THOT | 1035 | 1035 | 675 |
| BOM kWe | 198 | 153 | 148 |
| Rad m2 | 0.4 | 0.6 | 1.5 |
| **Efficiency** | **19.8%** | **15.3%** | **14.8%** |
| Max W/kg | 5.8 | 4.2 | 3.4 |
| Optimal Tc (C) | 227 | 202 | 127 |
| Tc to obtain 20% efficiency (C) | 277 | 27 | 27 |
| Radiator Area at 20% Efficiency | 0.4 | 4.6 | 4.6 |
| Power Output @ 20% Efficiency | 200 | 200 | 200 |
| **Power Output Using Total Cask Area** | **260** | **180** | **148** |

Table 2 Stirling Radioisotope Generator Concepts




**Keywords:** Stirling, Radioisotope, Brayton, Rankine, Dynamic





# Multiscale NTP Fuel Element Materials Simulation

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**Abstract.** NASA's Nuclear Thermal Propulsion (NTP) Project is focused on determining the feasibility and affordability of an NTP engine for exploration of Mars and beyond. Although the technology was demonstrated in the 1960's, many questions concerning the development and affordability still remain. A key technology challenge for an NTP system is the fabrication of a stable high temperature fuel. Current work is focused on optimizing tungsten-uranium dioxide (W-$UO_2$) CERMET fuels using low enriched uranium. Initial testing of fuel element materials will include non-nuclear cycles in hot hydrogen and subscale nuclear irradiations. However, verification of the fuel materials will require subjecting prototypical samples to the combined effects of radiation and high-pressure hydrogen at temperatures near 3000 K. There are currently no facilities in the US that are capable of producing the required environment. Modifications to existing test reactor facilities to simulate a relevant environment could take years and be cost prohibitive. The purpose of this paper is to provide details and status on the development of an innovative multiscale fuel element materials simulation capability to predict the CERMET fuel performance and reduce overall testing needs.

The simulation work is based on a multiscale modeling approach pioneered for light water reactor (LWR) fuels (Ref 1-3). The current objective is to conduct proof-of-concept simulations and illustrate the applicability of existing MARMOT (mesoscale) and BISON (macroscale) codes to CERMET Fuels in NTP conditions. The illustrations will be accomplished by determining the effective thermal conductivity in MARMOT and simulating heat conduction in a fuel element in BISON. Simulating the degradation of properties in CERMET fuels under the harsh conditions will require innovative computational analysis not currently available. The goal is to adapt the unique processing, microstructure, and performance relationships to proven fuel performance codes, which is challenging due to the complex microstructure evolution and thermodynamic materials degradation at operating conditions (Ref 4). The paper will also provide details on the CERMET fuel testing requirements and development of an affordable performance verification approach.

1. *"Development of a multiscale thermal conductivity model for fission gas in UO2"*. M. Tonks, X. Liuc, D. Anderssonc, D. Perezb, A. Chernatynskiyd, G. Pastoreb, C. Stanek, R. Williamson, Journal of Nuclear Materials, Vol 469, 2016, pp 89–98.
2. *"Multi-scale modeling of microstructure dependent intergranular brittle fracture using a quantitative phase-field based method"*. P. Chakraborty, Y. Zhang, M. Tonks, Computational Materials Science, Vol 113, 2016, pp 38–52.
3. *"Advanced multiphysics coupling for LWR fuel performance analysis"*. J. Hales, M. Tonks, F. Gleicher, B. Spencer, S. Novascone, R. Williamson, G. Pastore, D. Perez, Annals of Nuclear Energy, Vol 84, 2015, pp 98–110.
4. *"Literature Review of Thermal and Radiation Performance Parameters for High Temperature Uranium Dioxide fueled CERMET Materials"*. C. Haertling, R.J. Hanrahan. Journal of Nuclear Materials, V366, 2007, pp. 317-355.

**Keywords:** Nuclear, Propulsion, Fuel, Modeling and Simulation.

NETS At-A-Glance

## Monday, February 27, 2017

| | Captiva A | | Captiva B | | Captiva C | |
|---|---|---|---|---|---|---|
| 7:00 AM - 8:15 AM | Registration | | | | | |
| 8:15 AM - 10:00 AM | Plenary Session I (Amelia/Sanibel Ballroom) | | | | | |
| 10:00 AM - 10:20 AM | Break | | | | | |
| 10:20 AM - 10:40 AM | 20181 | Track I: Next Generation Energy Conversion in Space | | | 19763 | Track III: Nuclear-Enabled Space Science and Mission Concepts |
| 10:40 AM - 11:00 AM | 20187 | | 21281 | Track II: Uranium Fuels for Space Flight Applications | 20177 | |
| 11:00 AM - 11:20 AM | 20194 | | 20547 | | 20510 | |
| 11:20 AM - 11:40 AM | 21147 | | 20164 | | 20540 | |
| 11:40 AM - 12:00 PM | | | 20573 | | 20543 | |
| 12:00 PM - 12:20 PM | | | | | 20544 | |
| 12:20 PM - 1:30 PM | Lunch (on your own) | | | | | |
| 1:30 PM - 3:10 PM | Panel I : Beyond the Decadal Study: Horizons for Nuclear-Powered Space Exploration (Amelia/Sanibel Ballroom) | | | | | |
| 3:30 PM - 3:50 PM | 20482 | Track I: Nuclear Thermal Propulsion | 20550 | Track II: Novel Thermoelectric Materials Development | 20591 | Track III: Space Science and Mission Concepts (cont.) |
| 3:50 PM - 4:10 PM | 20588 | | 20505 | | 21106 | |
| 4:10 PM - 4:30 PM | 21141 | | 20542 | | 20118 | Track III: Project and Mission Architectures |
| 4:30 PM - 4:50 PM | 20048 | | 20419 | | 20484 | |
| 4:50 PM - 5:10 PM | 20585 | | 20463 | | 20599 | |
| 7:00 PM - 9 PM | **Opening Reception Sponsored by National Nuclear Laboratory (Capri Ballroom)** | | | | | |

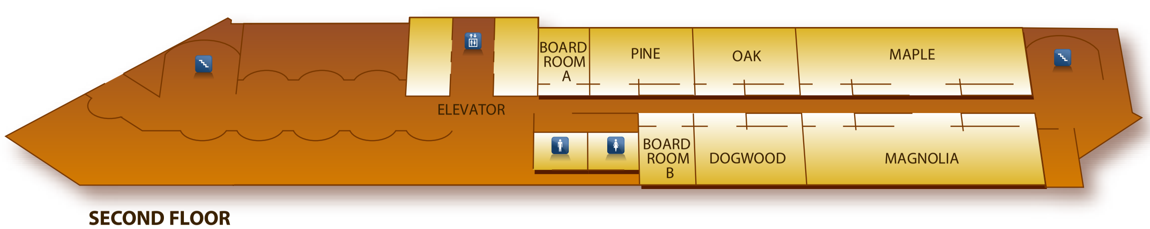
## Tuesday, February 28, 2017

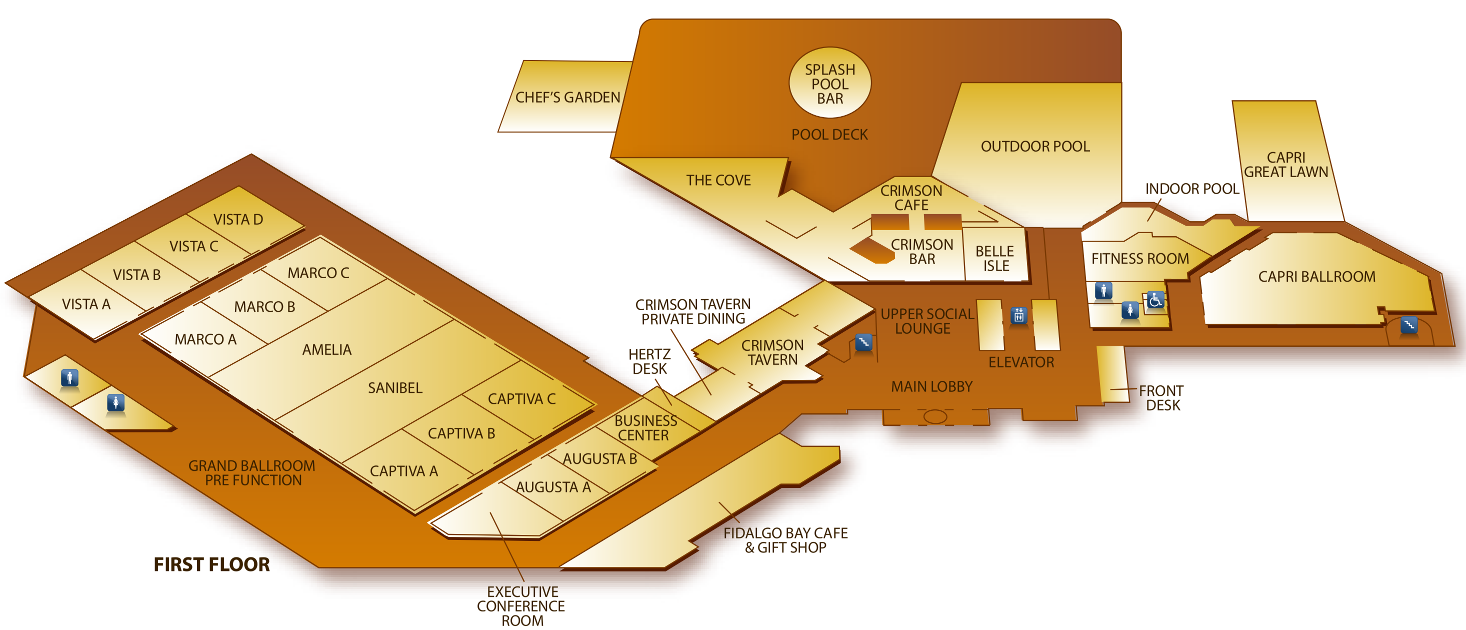
| | Captiva A | | Captiva B | | Captiva C | |
|---|---|---|---|---|---|---|
| 7:00 AM - 8:00 AM | Registration | | | | | |
| 8:00 AM - 8:45 AM | Plenary Session II (Amelia/Sanibel Ballroom) | | | | | |
| 8:45 AM - 9:00 AM | Break | | | | | |
| 9:00 AM - 9:20 AM | 20458 | Track I: Shielding and Nuclear Electric Propulsion | 20106 | Track II: Heat Source Fuel Properties and Development | 20149 | Track III: Flight Systems Mission Performance |
| 9:20 AM - 9:40 AM | 20574 | | 20203 | | 20183 | |
| 9:40 AM - 10:00 AM | 20537 | | 20191 | | 20575 | |
| 10:00 AM - 10:20 AM | 20186 | | 20196 | | | |
| 10:20 AM - 10:40 AM | Break | | | | | |
| 10:40 AM - 11:00 AM | 20569 | Track I: Stirling Development and Testing | 21137 | Track II: Reactor Support | 20059 | Track III: Space Nuclear Policy and Regulation |
| 11:00 AM - 11:20 AM | 20195 | | 21145 | | 20100 | |
| 11:20 AM - 11:40 AM | | | 20595 | | 20160 | |
| 11:40 AM - 12:00 PM | | | 21148 | | | |
| 12:00 PM - 1:30 PM | Lunch (on your own) | | | | | |
| 1:30 PM - 3:10 PM | Panel II: Future Applications of Small Spacecraft for Exploration Missions (Amelia/Sanibel Ballroom) | | | | | |
| 3:10 AM - 3:30 AM | Break | | | | | |
| 3:30 PM - 3:50 PM | 21154 | Track I: Thermoelectric Development and Testing | 19821 | Track II: RTG Fuel Production | 20099 | Track III: Space Power Programs |
| 3:50 PM - 4:10 PM | 20139 | | 20176 | | 20152 | |
| 4:10 PM - 4:30 PM | 20526 | | 19882 | | 20213 | |
| 4:30 PM - 4:50 PM | 20533 | | 20592 | | 20157 | Track III: Spacecraft Design Concepts |
| 4:50 PM - 5:10 PM | 20551 | | 20105 | | 20169 | |
| 5:10 PM - 5:30 PM | 20596 | | 20594 | | 20972 | |

## Wednesday March 1, 2017

| | Captiva A | | Captiva B | | Captiva C | |
|---|---|---|---|---|---|---|
| 7:00 AM - 8:00 AM | Registration | | | | | |
| 8:00 AM - 8:45 AM | Plenary Session III (Amelia/Sanibel Ballroom) | | | | | |
| 8:45 AM - 9:00 AM | Break | | | | | |
| 9:00 AM - 9:20 AM | 20224 | Track I: Thermal Management | 20188 | Track II: Materials Properties and Development for Nuclear Systems | 21181 | Track III: Infrastructure and Capabilities |
| 9:20 AM - 9:40 AM | 20583 | | 20582 | | 20536 | |
| 9:40 AM - 10:00 AM | 21152 | | 21150 | | 20050 | |
| 10:00 AM - 10:20 AM | 21153 | | 20512 | | 20182 | |
| 10:20 AM - 10:40 AM | Break | | | | | |
| 10:40 AM - 11:00 AM | 21151 | Track I: Component Development and Testing | 20174 | Track II: Materials Properties (Cont.) | 20565 | Track III: Infrastructure (Cont.) |
| 11:00 AM - 11:20 AM | 20189 | | 20141 | | 21149 | |
| 11:20 AM - 11:40 AM | 20190 | | 20264 | | 20530 | |
| 11:40 AM - 12:00 PM | 21155 | | | | | |
| 12:00 PM - 1:30 PM | Lunch (on your own) | | | | | |
| 1:30 PM - 3:10 PM | Panel III: Radioisotope Power System Challenges (Amelia/Sanibel Ballroom) | | | | | |
| 3:10 AM - 3:30 AM | Break | | | | | |
| 3:30 PM - 3:50 PM | 20184 | Track I: Advanced Concepts | | | | |
| 3:50 PM - 4:10 PM | 20214 | | | | | |
| 4:10 PM - 4:30 PM | 20159 | | | | | |
| 4:30 PM - 4:50 PM | 20201 | | | | | |
| 7:00 PM - 9 :00 PM | **Closing Banquet Sponsored by Aerojet Rocketdyne (Capri Ballroom)** | | | | | |





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The open exchange of ideas, freedom of thought and expression, and productive scientific debate are central to the mission of the American Nuclear Society (ANS). These require an open and diverse environment that is built on dignity and mutual respect for all participants and ANS staff members, and is free of bias and intimidation. ANS is dedicated to providing a safe, welcoming, and productive experience for everyone participating in Society events and other Society activities regardless of age, color, creed, disability, ethnicity, gender identity and expression, marital status, military service status, national origin, parental status, physical appearance, race, religion, sex, or sexual orientation. Creation of a safe and welcoming environment is a shared responsibility held by all participants.

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The complete Respectful Behavior Policy can be found at http://www.ans.org/about/rbp/. If you have questions about the policy, please contact ANS Executive Director Robert C. Fine at 708-579-8200 or rfine@ans.org.