

Program and Abstract Book

# Nuclear & Emerging Technologies for Space (NETS-2011)

February 7-10, 2011  
Albuquerque, New Mexico

Sponsored by

The American Nuclear Society

(Trinity Section and

Aerospace Nuclear Science and Technology Division)

and

The American Institute of Aeronautics  
and Astronautics



## About the Meeting

The 2011 Nuclear and Emerging Technologies for Space (NETS-2011) meeting is the first stand-alone topical meeting organized by the Aerospace Nuclear Science and Technology Division (ANSTD), a professional division of the American Nuclear Society (ANS). Sponsored by the ANSTD, the ANS Trinity Section, and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA), NETS-2011 is the premier conference covering advanced power and propulsion systems for landed and in-space applications in 2011.

The conference hosts three plenary sessions, invited panels, and numerous technical sessions organized into five technical track areas:

- [1] Missions and Architectures
- [2] Fission Power and Propulsion
- [3] Radioisotope Power Systems
- [4] Nuclear Thermal Propulsion
- [5] Advanced Concepts

With authors hailing from universities, national laboratories, NASA facilities and industry, NETS-2011 will provide an excellent communications network and forum for information exchange.

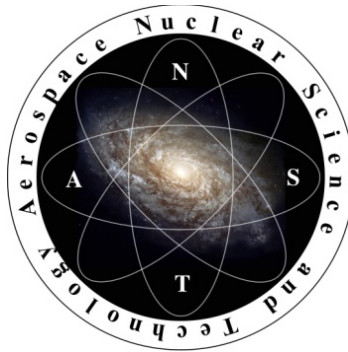
The unique NETS venue attracts papers and presentations from a wide range of experiences and expertise. NETS attendees range from engineers designing space power and propulsion systems, to those completing mission planning and analysis for proposed space missions and scientists who are designing payloads for those missions.

NETS-2011 will allow nuclear professionals to learn about missions that require high power or advanced propulsion systems – and, conversely, it will allow mission designers opportunity to learn more about what advanced power and propulsion systems are available or could be developed to meet the needs of those missions. Establishing these lines of communication – and then working to keep them open through collaborative work – will more rapidly advance technology development, as it will be developed to specifically meet the needs of the user community.

Plans for future NETS meetings will be electronically distributed to meeting attendees and will be posted on the ANSTD website when it becomes available.

Aerospace Nuclear Science & Technology Division  
<http://anstd.ans.org>

## Organization Sponsors



**ANS Division Sponsor:** *Aerospace Nuclear Science and Technology Division*



**ANS Local Section Sponsor:** *ANS Trinity Section*



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*NASA Jet Propulsion Laboratory, Special  
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**Honorary General Chair**  
Harold Finger  
*Retired, formerly held several key positions  
within AEC and NASA*



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# Technical Program Committee

**Technical Program Chair:** Martin Sattison, *Idaho National Laboratory*

## Track I: Missions and Architectures

### Track Chairs

Michael Houts, *NASA Marshall Space Flight Center*  
Leonard Dudzinski, *NASA Headquarters*

## Track II: Fission Power and Propulsion

### Track Chairs

Lee Mason, *NASA Glenn Research Center*  
A. Lou Qualls, *Oak Ridge National Laboratory*

## Track III: Radioisotope Power Systems

### Track Chairs

Thomas Sutliff, *NASA Glenn Research Center*  
Bill Nesmith, *NASA Jet Propulsion Laboratory*

## Track IV: Nuclear Thermal Propulsion

### Track Chairs

Steven Howe, *Center for Space Nuclear Research / Idaho National Laboratory*  
Stanley Borowski, *NASA Glenn Research Center*

## Track V: Advanced Concepts

### Track Chairs

Jon Webb, *Center for Space Nuclear Research / Idaho National Laboratory*  
Gerald Kulcinski, *University of Wisconsin – Madison*

# Technical Program Committee

## Session Chairs and Reviewers

Michael Houts, NASA MSFC	Thomas Godfroy, Maximum Technologies, Inc.
Leonard Dudzinski, NASA HQ	Jean-Pierre Fleurial, JPL
Michael Schoenfeld, NASA MSFC	Bill Nesmith, JPL
Robert Singleterry, NASA LaRC	Alice Caponiti, DOE HQ
John Elliott, JPL	Christopher Steffen, NASA GRC
Thomas Spilker, JPL	Richard Shaltens, NASA GRC
Steven Oleson, NASA GRC	Terri Rodgers, NASA GRC
Steven Howe, CSNR / INL	June Zakrajsek, NASA GRC
Jeffrey King, Colorado School of Mines	Joseph Nainiger, Alphaport, Inc.
James Werner, INL	Thomas Sutliff, NASA GRC
David Poston, LANL	Stephen Johnson, INL
J. Boise Pearson, NASA MSFC	Samit Bhattacharyya, RENMAR Enterprises, Inc.
A. Louis Qualls, ORNL	Robert O'Brien, CSNR
Steven Wright, SNL	C. Russell Joyner, Pratt & Whitney Rocketdyne
Marc Gibson, NASA GRC	Anne Garber, NASA MSFC
Omar Mireles, NASA MSFC	John Metzger, Univ. of Pittsburgh
Maxwell Briggs, NASA GRC	Robert Adams, NASA MSFC
Steve Geng, NASA GRC	
Jon Webb, CSNR / INL	
Cheryl Bowman, NASA GRC	



## Exhibitors

The Expo will be open at the following times:

Monday, February 7	7:00 am – 5:00 pm
Tuesday, February 8	7:30 am – 5:00 pm
Wednesday, February 9	7:30 am – 3:30 pm

Note that all continental breakfasts and breaks will be served in the exhibit hall area.



**Hamilton Sundstrand Rocketdyne**



## Registration

The registration desk, located in conference area lobby, will be open at the following times:

Sunday, February 6	12:00 pm – 5:00 pm
Monday, February 7	7:00 am – 5:00 pm
Tuesday, February 8	7:30 am – 5:00 pm
Wednesday, February 9	7:30 am – 5:00 pm
Thursday, February 10	7:30 am – 12:00 pm

If seats are still available, attendees may purchase additional tickets for the Wednesday evening dinner at the Museum on Monday ONLY (\$30 / ticket).

On-site registration and ticket purchase may be paid via cash, check paid to ANS Trinity Section, or credit card using the PayPal utility on the NETS website (a computer with internet connection will be available at the registration desk for this purpose).

## Speaker Practice Room & Check-In

A computer and LCD projector will be available for speakers to make final preparations for their presentations in the **Santa Fe** room. The room will be open at the following times:

Monday, February 7	7:00 am – 5:00 pm
Tuesday, February 8	7:30 am – 5:00 pm
Wednesday, February 9	7:30 am – 5:00 pm
Thursday, February 10	7:30 am – 12:00 pm

Speakers should plan to attend the continental breakfast on the day of their presentation. Tables will be set-up in **Salon E & F** to meet with session chairs.

Please be prepared to provide your session chair with a brief, printed biography that may be used for introduction in the session. Please also bring your presentation on a USB drive or CD for presentation from a single computer in your session.

## Spouse / Guest Information

NETS would like to welcome all spouses and guests to Albuquerque! A small meeting area will be available for you in the **Carlsbad** room as you plan your days.

Information on area attractions including Old Town, Santa Fe, and local museums is available at the registration desk. Transportation options to these attractions will also be available.



## Program Overview

### Monday, February 7

7:00 – 8:00	Continental Breakfast (Exhibit Hall and Conference Area Lobby)
7:00 – 5:00	NETS Expo (Exhibit Hall: Pecos, Sandia, & Acoma)
8:00 – 10:00	Opening Plenary (Salon E/F)
10:00 – 10:30	Break (Exhibit Hall)
10:30 – 12:30	Plenary II: Science Missions Enabled by Nuclear Power and Propulsion (Salon E/F)
12:30 – 2:00	Lunch (on your own)
2:00 – 5:00	Special Session: Addressing the Non-Technical Challenges of Space Nuclear Technology (Salon E/F)
6:30 – 7:00	Cocktail Hour (no-host bar) (Conference Area Lobby)
7:00 – 9:00	Opening Dinner (included in registration) (Salon E/F)
	<b>Keynote Address:</b> Dr. Glen Schmidt, retired, former test engineer for the SNAP-10a program

### Tuesday, February 8

7:30 – 8:30	Continental Breakfast (Exhibit Hall and Conference Area Lobby)
7:30 – 5:00	NETS Expo (Exhibit Hall: Pecos, Sandia, & Acoma)
8:30 – 10:00	Technical Sessions
10:00 – 10:30	Break (Exhibit Hall)
10:30 – 12:00	Technical Sessions
12:00 – 1:30	Lunch (on your own)
1:30 – 3:00	Technical Sessions
3:00 – 3:30	Break (Exhibit Hall)
3:30 – 5:00	Technical Sessions

## Program Overview

### Wednesday, February 9

7:30 – 8:30	Continental Breakfast (Exhibit Hall and Conference Area Lobby)
7:30 – 3:30	NETS Expo (Exhibit Hall: Pecos, Sandia, & Acoma)
8:30 – 10:00	Technical Sessions
10:00 – 10:30	Break (Exhibit Hall)
10:30 – 12:00	Technical Sessions
12:00 – 1:30	Lunch (on your own)
1:30 – 3:00	Technical Sessions
3:00 – 3:30	Break (Exhibit Hall)
3:30 – 5:00	Technical Sessions
6:00 – 9:00	Banquet Dinner at the National Museum of Nuclear Science and History
	<b>Keynote Address:</b> “Reflections on the Apollo Program” Dr. Harrison “Jack” Schmitt, Apollo 17 Astronaut, fmr. U.S. Senator (N.M.), Currently Secretary-Designate of the New Mexico Energy, Minerals and Natural Resources Department (requires advance registration at additional cost; driving directions available at the registration desk)

### Thursday, February 10

7:30 – 8:30	Continental Breakfast (Exhibit Hall and Conference Area Lobby)
8:30 – 10:00	Technical Sessions
10:00 – 10:30	Break (Conference Area Lobby)
10:30 – 12:00	Technical Sessions
12:00 – 1:00	Lunch (on your own)
1:00 – 5:00	Technical Tours: Sandia National Laboratories (requires advance registration)

## Plenary Sessions: Monday, February 7

### Opening Plenary

8:00 - 10:00 am

Chair: S. Bragg–Sitton, Idaho National Laboratory

#### Welcome to NETS

*S. Bragg–Sitton and M. Houts, General Meeting Chairs*

#### Historical Perspectives on Space Nuclear Power and Propulsion

*H. Finger, retired, formerly held several key positions within AEC and NASA*

#### Potential Mission Applications for Space Nuclear Systems

*J. Casani, NASA Jet Propulsion Laboratory, Special Assistant to the Director*

#### Current NASA Interest in Space Nuclear Power and Propulsion

*J. Adams, Deputy Director, Planetary Science Division, NASA Headquarters*

#### Radioisotope Power Systems: The Quiet Technology

*R. Lange, U.S. DOE, Deputy Assistant Secretary for Business and Technical Support*

#### Viable Development Strategies for Space Fission Power and Propulsion

*M. Griffin, former NASA Administrator and King-McDonald Eminent Scholar for Mechanical and Aerospace Engineering at the University of Alabama in Huntsville*

### Plenary II

10:30 am – 12:30 pm

#### Science Missions Enabled by Nuclear Power and Propulsion

Chair: Dr. Steven D. Howe, Center for Space Nuclear Research / Idaho National Laboratory

#### Panelists

#### Space Nuclear Power and Propulsion: The Good, the Bad, and the Ugly

Dr. Ralph McNutt, Applied Physics Laboratory / Johns Hopkins University

#### Expanding Science Knowledge: Enabled by Nuclear Power

Karla B. Clark, Jet Propulsion Laboratory / California Institute of Technology

#### Increased Science Return and Space Nuclear Power

Dr. Richard Ambrosi, University of Leicester / UK

## Plenary Sessions: Monday, February 7, cont.

### Special Session

2:00 - 5:00 pm

### Addressing the Non-Technical Challenges of Developing Space Nuclear Technology: Navigating the World of Politics and Policy

**Chair: Dr. Michael Griffin**, former NASA Administrator and King-McDonald Eminent Scholar for Mechanical and Aerospace Engineering at the University of Alabama in Huntsville

**Moderator: Dr. Elizabeth Newton**, University of Alabama in Huntsville, Policy Research Program Director

Fluctuations in space exploration goals are a significant, non-technical obstacle for the end-to-end development and implementation of nuclear and emerging technologies for space exploration. These goals are usually the premise upon which research is conducted, serving as the “foundation” from which all other “downstream” decision making stems. When goals change mid-stream, research and development progress and accomplishments may become partially or completely inapplicable with respect to the new goals. If goal fluctuations are more rapid than the time it takes for research efforts to manifest, then the capabilities the technology would have provided are not obtained. The historical record indicates a cyclic nature in these fluctuations. While research documentation can help to cumulatively build progress between cycles, in many cases at least some portion of the acquired knowledge and capability is lost during off-times, leading to a sometimes significant loss of progress.

Explicitly addressing problems stemming from these cycles could be the first step in facilitating implementation of space nuclear systems and other technologies to completion. This session will involve description of the policy making and technical development work environments; identification of problems, their causes, and possible solutions; and discussion of possible implementation strategies.

### Panelists

#### *Policy Representatives*

Dr. Harrison “Jack” Schmitt (US Senate (NM), Ret., and Apollo 17 astronaut)

Mr. Chuck Atkins (Ret. Science & Technology Staffer)

#### *Problem Definition / Recommendations*

Dr. Michael Griffin (Fmr. NASA Administrator)

Mr. Harold Finger (Fmr. Nuclear Manager, AEC & NASA)

#### *Implementation*

Dr. Robert Lightfoot (Director, NASA MSFC ) or designee *invited*

Dr. George Schmidt (NASA GRC, Research & Technology Directorate, Deputy Director)

Dr. Stephen Johnson (INL, Space Nuclear Systems & Technology Division, Director)

## Technical Program Overview

### Track I: Missions & Architectures

Mission Applications for Fission Power Systems	Tues. pm
Nuclear-Enabled Deep Space Missions	Tues. pm
Mars Sample Return / Advanced Concepts	Wed. am
Radioisotope Thermal Propulsion Mission Applications	Thurs. am
Space Radiation: Effects and Mitigation	Thurs. am

### Track II: Fission Power and Propulsion

Reactor Design	Tues. am
Liquid Metal Technology	Tues. am
Heat Rejection Technology	Tues. pm
Reactor Simulation	Tues. pm
Testing and Validation 1	Wed. am
System Concepts 1	Wed. am
Tools and Modeling	Wed. pm
Panel: The Path Forward to Fission Power Systems	Wed. pm
Systems Concepts 2	Thurs. am
Testing and Validation 2	Thurs. am

### Track III: Radioisotope Power Systems

Panel: Pu-238 Supply and Production	Tues. am
Thermoelectric Components and Systems	Tues. pm
Isotope Heat Sources	Tues. pm
Stirling Components & Modeling	Wed. am
Stirling Systems	Wed. pm
Mechanical, Thermal & Electrical Integration	Wed. pm
Testing, Validation & Advanced Power Conversion	Thurs. am

### Track IV: Nuclear Thermal Propulsion

Fuels Development	Tues. am
Testing	Tues. pm
Systems Performance	Wed. am

### Track V: Advanced Concepts

Advanced Nuclear Systems Concepts	Wed. am
Multimegawatt Fission Reactor Concepts	Thurs. am

*Abstracts for all papers are included at the end of this program booklet. Abstracts are organized by day and time and are grouped within their appropriate sessions.*

## Detailed Technical Program

**Tuesday, February 8**

**8:30 am – 10:00 am**

### **Track II: Fission Power and Propulsion**

**Reactor Design**

**Salon A/B**

Session Chairs: J. Werner, Idaho National Laboratory, and D. Poston, Los Alamos National Laboratory

Reactivity Control Options for a Space Fission Power System  
*M. Worrall and Z. Shayer (Colorado School of Mines)*

Challenges in Structural Analysis for Deformed Nuclear Criticality Assessments  
*D. Villa, T. Tallman, and J. Smith (SNL)*

Evaluation of HEU-Beryllium Benchmark Experiments to Improve Computational Analysis of Space Reactors  
*J.D. Bess, K.C. Bledsoe (INL), and B.C. Rearden (ORNL)*

### **Track III: Radioisotope Power Systems**

**Panel Session: Pu-238 Supply and Production**

**Salon I/J**

Session Chair: T. Sutliff, NASA Glenn Research Center

*Session Description: The current supply of plutonium-238 ( $^{238}\text{Pu}$ ), used to power deep space missions for the National Aeronautics and Space Administration (NASA), is nearly exhausted. Previous facilities that supplied  $^{238}\text{Pu}$  at the Savannah River Site are now closed. A new supply chain is planned using existing reactors at Oak Ridge National Laboratory (ORNL) and Idaho National Laboratory (INL) and in existing chemical recovery facilities at ORNL. However, this plan requires that preparations for target design qualification, target fabrication, irradiation, and chemical recovery begin now in order to establish the infrastructure necessary to supply the amounts needed and to ensure the availability of new material at the end of 2015.*

#### Panelists

*L. Dudzinski, NASA Headquarters*

*A. Caponiti, DOE Headquarters*

*R. Wham, Oak Ridge National Laboratory (associated full paper in conference proceedings)*

*S. Johnson, Idaho National Laboratory*



## **Tuesday, February 8, cont.**

**10:30 am – 12:00 pm**

### **Track II: Fission Power and Propulsion**

#### **Liquid Metal Technology**

Salon A/B

Session Chairs: J.B. Pearson, NASA Marshall Space Flight Center, and A.L. Qualls, Oak Ridge National Laboratory

Design of an Annular Linear Induction Pump for Nuclear Space Applications  
*C.O. Maidana, J.E. Werner, and D.M. Wachs (INL)*

Circular Electromagnetic Thermoelectric Pump Simulation  
*E.M. Borges, F.A. Braz Filho, L.N.F. Guimarães, and G.P. Camillo (Institute for Advanced Studies (IEAv), Brazil)*

Sealed Mechanical Pump for High Temperature NaK  
*D.E. Bradley (NASA Marshall Space Flight Center)*

Water-Cooled Electromagnetic Flow Meter for High Temperature NaK  
*D.E. Bradley and D. Childers (NASA MSFC)*

### **Track IV: Nuclear Thermal Propulsion**

#### **Fuels Development**

Salon G/H

Session Chairs: S. Bhattacharyya, RENMAR Enterprises, Inc., and R. O'Brien, Center for Space Nuclear Research

SPS Fabrication of Tungsten and Tungsten Rhenium Alloys in Support of NTR Fuels Development  
*J.A. Webb (Center for Space Nuclear Research and Univ of Idaho), I. Charit (Univ of Idaho), D.P. Butt, M. Frary (Boise State Univ), and M. Carroll (INL)*

Nuclear Thermal Propulsion (NTP) Fuel Element Development and Testing for Future Transportation Systems  
*R. Hickman, W. Emrich, R. Litchford, J. Broadway, M. Shoenfeld, M. Houts, J. Martin, and J.B. Pearson (NASA MSFC)*

A Combined Neutronic-Thermal Hydraulic Model of a Tungsten CERMET NTR Fuel Element  
*J.A. Webb, B. Gross, and W. Taitano (Center for Space Nuclear Research)*

**Tuesday, February 8, cont.**

**1:30 pm – 3:00 pm**

**Track I: Missions and Architectures**

Mission Applications for Fission Power Systems

Salon C/D

Session Chairs: M. Houts, NASA Marshall Space Flight Center, and L. Dudzinski, NASA HQ

"Scotty, I Need More Power" - The Fission System Gateway to Abundant Power for Exploration  
*D. Palac (NASA Glenn Research Center)*

Extensibility of the Fission Surface Power (FSP) System from the Moon to Mars  
*D.I. Poston (Los Alamos National Laboratory)*

A Small Fission Power System for NASA Planetary Science Missions  
*L. Mason (NASA GRC), J. Casani, J. Elliot, J-P. Fleurial, D. MacPherson, B. Nesmith (JPL), M. Houts (NASA MSFC), R. Bechtel (DOE), J. Werner (INL), R. Kapernick, D. Poston (LANL), A.L. Qualls (ORNL), R. Lipinski, R. Radel (SNL), S. Bailey (Bailey Engineering and Management, Inc.), and A. Weitzberg (Consultant)*

Fission Surface Power System Power Control Strategies  
*A.L. Qualls (ORNL) and D.J. Walter (The Pennsylvania State Univ)*

**Track II: Fission Power and Propulsion**

Heat Rejection Technology

Salon A/B

Session Chairs: M. Gibson, NASA Glenn Research Center, and J.B. Pearson, NASA Marshall Space Flight Center

Manufacture, Testing and Model Validation of a Full-Scale Radiator for Fission Surface Power Applications  
*D. Ellis (NASA GRC), J. Calder (Material Innovations Inc.) and J. Siamidis (NASA GRC)*

Evaluating Heat Pipe Performance in 1/6 g Acceleration: Problems and Prospects  
*D.A. Jaworske (NASA GRC), T.A. McCollum (Hagerstown Community College), M. Gibson (NASA GRC), J.L. Sanzi (Sest, Inc.), and E.A. Sechkar (ASRC Aerospace Corp., NASA GRC)*

Ultra-Light Heat Pipe Radiators for Fission Surface Power  
*J.C. Rozzi and J.K. Hilderbrand (Create, Inc)*

Heat Pipes and Heat Rejection Component Testing at NASA-GRC  
*J.L. Sanzi (Sest, Inc.) and D.A. Jaworske (NASA GRC)*

**Tuesday, February 8, cont.**

**1:30 pm – 3:00 pm, cont.**

**Track III: Radioisotope Power Systems**

**Thermoelectric Components and Systems**

Salon I/J

Session Chairs: J-P. Fleurial, NASA Jet Propulsion Laboratory, and B. Nesmith, NASA Jet Propulsion Laboratory

**Advanced High Temperature Bulk Thermoelectric Materials**

*J-P. Fleurial, S.K. Bux, C-K. Huang, B.J. Cheng, T. Vo, P. von Allmen, T. Caillat (JPL), Y. Pei, A. Lalonde, A. Zevalkin, E. Toverer, G.J. Snyder (California Inst of Technology), A.F. May (ORNL), D.J. King, K.E. Star, J. Ma, R.B. Kaner, B.S. Dunn (Univ of California at Los Angeles), C. Cox, and S.M. Kauzlarich (Univ of California at Davis)*

**The Scanning Seebeck Coefficient Technique for Detecting Inhomogeneities in Thermoelectric Materials**

*S. Iwanaga and J. Snyder (California Inst of Technology)*

**High Temperature Couple Development for the Advanced Thermoelectric Converter (ATEC) Project**

*S.A. Firdosy (JPL)*

**Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) Engineering Unit (EU) Testing**

*T.E. Hammel, R. Bennett (Teledyne Energy Systems, Inc.), W. Otting and L Gard (Pratt & Whitney Rocketdyne)*

**Tuesday, February 8, cont.**

**3:30 pm – 5:00 pm**

**Track I: Missions and Architectures**

**Nuclear-Enabled Deep Space Missions**

Salon C/D

Session Chairs: J. Elliott, NASA Jet Propulsion Laboratory, and S. Oleson, NASA Glenn Research Center

**Saturn Ring Observer Concept Architecture Options**

*T.R. Spilker, C.S. Borden, W. Smythe, B. Cole, A. Petropoulos (JPL), J. Dankanich, H. Kamhawi, P. Schmitz, L. Mason (NASA GRC), J. Elliott, N. Strange, R. Moeller (JPL), P. Nicholson, M. Tiscareno (Cornell University), L. Spilker (JPL), L. Dudzinski (NASA HQ), K. Reh (JPL), and S. Benson (NASA GRC)*

**Trojan Tour Mission Concepts Provide Several Options for Cost-Effective Break-Through Science**

*K.E. Hibbard, R. Gold (Johns Hopkins Univ), J. Dankanich (Gray Research, NASA GRC), A. Rivkin, M. Schwinger, and H. Seifert (Johns Hopkins Univ)*

**Joint Radioisotope Electric Propulsion Studies – Neptune System Explorer**

*M.O. Khan, R. Amini, J. Ervin, J. Lang, D. Landau (JPL), S. Oleson (NASA GRC), T. Spilker, N. Strange (JPL)*

**Uranus Mission Concept Options**

*R. Gold, D.A. Eng, Y. Guo (Johns Hopkins Univ), J. Dankanich (Gray Research), E.P. Turtle (Johns Hopkins Univ), S. Oleson (NASA GRC), E. Adams and H. Seifert (Johns Hopkins Univ)*

**Kuiper Belt Object Orbiter Using Advanced Radioisotope Power Sources and Electric Propulsion**

*S. Oleson, M. McGuire (NASA GRC), J. Dankanich (Gray Research), A. Colozza (ANALEX Corp), P. Schmitz (Power Computing Solutions), O. Khan (JPL), J. Drexler (NASA GRC), and J. Fittje (ANALEX Corp)*

**Tuesday, February 8, cont.**

**3:30 pm – 5:00 pm, cont.**

## **Track II: Fission Power and Propulsion**

### **Reactor Simulation**

Salon A/B

Session Chairs: M. Houts, NASA Marshall Space Flight Center, and S. Wright, Sandia National Laboratories

Calculation of Kinetics Parameters for the Affordable Fission Surface Power Reference Design  
*E.M. Dughie (Univ of Michigan), D.D. Dixon (Univ of Tennessee-Knoxville), and D.I. Poston (LANL)*

Design and Test of Advanced Thermal Simulators for an Alkali Metal-Cooled Reactor Simulator  
*A.E. Garber and J.B. Pearson (NASA MSFC)*

Design and Build of Reactor Simulator for Fission Surface Power Technology Demonstrator Unit  
*T.J. Godfroy, R. Dickens (Maximum Technology Corp), M. Houts, J.B. Pearson, K. Webster (NASA MSFC), M. Gibson, A.L. Qualls (ORNL), D. Poston (LANL), J. Werner (INL), and R. Radel (SNL)*

System Modeling Comparisons of the Fission Surface Power (FSP) System and the FSP Technology Demonstration Unit (TDU)  
*D.I. Poston (LANL)*

## **Track III: Radioisotope Power Systems**

### **Isotope Heat Sources**

Salon I/J

Session Chair: A. Caponiti, DOE HQ, and C. Steffen, NASA Glenn Research Center

Laser Simulated Re-entry Oxidation Experiments on Possible Replacement Materials for FWPF in  $^{238}\text{PuO}_2$  Fueled Space Power Systems  
*D.P. Kramer, C.D. Barclay, S.M. Goodrich (Univ of Dayton Research Institute), and D. Cairns-Gallimore (US DOE)*

Alternative Radioisotopes for Heat and Power Sources  
*T.P. Tinsley, M. Sarsfield, and T. Rice (National Nuclear Laboratory, UK)*

Tritium Based Radioisotopic Thermoelectric Generators  
*C.A. Applett, T. Johnson, A. Shugard, D. Wesolowski, D. Dobranich, N. Spencer, and P. Zablocki (SNL)*

**Tuesday, February 8, cont.**

**3:30 pm – 5:00 pm, cont.**

**Track IV: Nuclear Thermal Propulsion**

Testing

Salon G/H

Session Chairs: A. Garber, NASA Marshall Space Flight Center, and J. Metzger, University of Pittsburgh

Hyperthermal Environments Simulator for Nuclear Thermal Rocket Fuels Development  
*R. Litchford, J. Foote, W.B. Clifton, R. Hickman, T-S. Wang, and C. Dobson (NASA MSFC)*

An Overview of Facilities and Capabilities to Support the Development of Nuclear Thermal Propulsion  
*J.E. Werner (INL), S. Bhattacharyya (RENMAR Enterprises, Inc.) and M. Houts (NASA MSFC)*

NERVA-Derived Concept for a Bimodal Nuclear Thermal Rocket - An Update  
*C.R. Joyner, P. Gill, D.J. Levack (Pratt & Whitney Rocketdyne), C-Y. Lu (Hamilton Sundstrand Rocketdyne)*



**Wednesday, February 9**

**8:30 am – 10:00 am**

**Track I: Missions and Architectures**

**Mars Sample Return / Advanced Concepts**

**Salon C/D**

Session Chairs: L. Dudzinski, NASA HQ, and M. Houts, NASA Marshall Space Flight Center

Feasibility Study of a Three-Stage Radioisotope-Powered Mars Ascent Vehicle

*T.M. Chlapek, R.E. Allen, J.Y. Guan, S. Rao, and S.D. Howe (CSNR)*

Preliminary Mission Architecture For Mars Sample Return Utilizing Nuclear Thermal Rockets

*R.E. Allen, B.T. Manning (CSNR, Stanford Univ), T.M. Chlapek (CSNR, Univ of Missouri), J.Y. Guan (CSNR, Univ of Illinois), S.S. Rao (CSNR, Univ of Texas-Arlington), R.S. Ferrulli (CSNR, Univ of Washington), and S.D. Howe (CSNR)*

In-situ Missions for the Exploration of Titan's Lakes

*J.O. Elliott (JPL / California Inst of Technology) and J.H. Waite (Southwest Research Institute)*

Fusion Power Sources for Mars Exploration

*G.H. Miley and X. Yang (Univ of Illinois)*

**Track II: Fission Power and Propulsion**

**Testing & Validation 1**

**Salon A/B**

Session Chairs: A.L. Qualls, Oak Ridge National Laboratory, and C. Bowman, NASA Glenn Research Center

Performance of a Kilowatt Class Stirling Power Conversion System in a Thermodynamically-Coupled Configuration

*M. Briggs, S. Geng (NASA GRC), and D. Hervol (QinetiQ North America)*

Transient Response to Rapid Cooling of a Stainless Steel Sodium Heat Pipe

*O. Mireles and M.G. Houts (NASA MSFC)*

Experimental Studies of NaK in a Simulated Space Environment

*M.A. Gibson (NASA GRC), J.L. Sanzi (Sest, Inc.), and D. Ljubanovic (Gilchrest Electric)*

Design and Test Plans for a Non-Nuclear Fission Power System Technology Demonstration Unit

*L.S. Mason, D. Palac, M. Gibson (NASA GRC), M. Houts (NASA MSFC), J. Warren (NASA HQ), J. Werner (INL), D. Poston (LANL), A.L. Qualls (ORNL), R. Radel (SNL) and S. Harlow (DOE)*

## **Wednesday, February 9, cont.**

**8:30 am – 10:00 am, cont.**

### **Track IV: Nuclear Thermal Propulsion**

#### **Systems Performance**

Salon G/H

Session Chairs: S. Howe, Center for Space Nuclear Research / Idaho National Laboratory, and C.R. Joyner, Pratt & Whitney Rocketdyne

Thermal-hydraulics Analysis of a Radioisotope-Powered Mars Hopper Propulsion System  
*R.C. O'Brien (CSNR), A.C. Klein (Oregon State Univ), W.T. Taitano (CSNR), J. Gibson, B. Myers (Oregon State Univ), and S.D. Howe (CSNR / INL)*

Exergy Analysis of Two Proposed Mars Hopper Propulsion Configurations  
*J. Hasenoehrl and J. Crepeau (Univ of Idaho)*

The Mars Hopper: A Radioisotope Powered, Impulse Driven, Long-Range, Long-Lived Mobile Platform for Exploration of Mars

*S.D. Howe, R.C. O'Brien, W. Taitano, D. Crawford, N. Jerred, S. Cooley (CSNR), J. Crepeau (Univ of Idaho), S. Hansen (Utah State Univ), A. Klein (Oregon State Univ), and J. Werner (INL)*

**10:30 am – 12:00 pm**

### **Track II: Fission Power and Propulsion**

#### **System Concepts 1**

Salon A/B

Session Chairs: M. Houts, NASA Marshall Space Flight Center, and S. Geng, NASA Glenn Research Center

A Small Fission Power System with Stirling Power Conversion for NASA Science Missions  
*L.S. Mason (NASA GRC) and C. Carmichael (Saint Louis Univ)*

Space Nuclear Power & Propulsion Heritage

*W.R. Determan, G.A. Johnson, A.J. Zillmer, T.E. Dix (Pratt & Whitney Rocketdyne), C-Y. Lu, M. Tosca, and L.A. Trager (Hamilton Sundstrand Rocketdyne)*

Sub-Kilowatt Class Fission Heat Source Thermoelectric Power Study  
*W.R. Determan and G.A. Johnson (Pratt & Whitney Rocketdyne)*

The Design and Development of a 12 kWe Stirling Power Conversion Unit for Fission Power Technology Demonstration

*J.G. Wood, E. Holliday, T. Cale, and J. Stanley (Sunpower Inc)*

**Wednesday, February 9, cont.**

**10:30 am – 12:00 pm, cont.**

**Track III: Radioisotope Power Systems**

**Stirling Components & Modeling**

**Salon I/J**

Session Chairs: R. Shaltens, NASA Glenn Research Center, and T. Sutliff, NASA Glenn Research Center

Advanced Stirling Converter (ASC) Technology Maturation in Preparation for Flight  
*W.A. Wong and P. Cornell (NASA GRC)*

Advanced Stirling Converter (ASC-E2) Performance Testing at NASA Glenn Research Center  
*S. Oriti and S. Wilson (NASA GRC)*

Stirling Converter Dynamic Analysis Using Phasor Diagrams  
*L.L. Shayer and E.J. Lewandowski (NASA GRC)*

**Track V: Advanced Concepts**

**Advanced Nuclear Systems Concepts**

**Salon C/D**

Session Chairs: R. Adams, NASA Marshall Space Flight Center, and J. Webb, Center for Space Nuclear Research / Idaho National Laboratory

Self-Fueling Fusion Hybrid Reactor for Space Power and Propulsion  
*T. Kammash (Univ of Michigan)*

Fusion Space Propulsion using Fast-Ignition Inertial Confinement Fusion (FI-ICF)  
*G.H. Miley, X. Yang (Univ of Illinois), K.A. Flippo (LANL), and H. Hora (Univ of New South Wales)*

A Method for Improving the Efficiency of Energy Amplifiers with Multiple Subcritical Cores  
*L. Beveridge (Embry-Riddle Aeronautical Univ)*

## Wednesday, February 9, cont.

1:30 pm – 3:00 pm

### **Track II: Fission Power and Propulsion**

Panel Session: Path Forward for Fission Power Systems

Salon C/D

Session Chair: L. Mason, NASA Glenn Research Center

*Session Description: The history of space fission power systems has included many program starts and stops, and only one U.S. flight system launched into space. The object of this panel session is to tap the knowledge of several “grey beards” who have participated in these programs, and learn what steps should be taken to secure a successful outcome. The session will include short presentations by the panelists on establishing mission pull, essential building blocks for a successful program, the relationship of government and industry, and lessons from our past. Following the presentations, the audience will have the opportunity for questions and discussion with the panelists to debate the best path forward for space fission power.*

#### Panelists

*J. Nainiger, Alphaport, Inc.*

*S. Bhattacharyya, RENMAR Enterprises, Inc.*

*S. Bailey, Bailey Engineering and Management, Inc.*

*A. Weitzberg, Consultant*

### **Track III: Radioisotope Power Systems**

Stirling Systems

Salon I/J

Session Chairs: R. Shaltens, NASA Glenn Research Center, and T. Rodgers, NASA Glenn Research Center

Natural Convection Cooling of the Advanced Stirling Radioisotope Generator Engineering Unit  
*E.J. Lewandowski (NASA GRC) and D. Hill (Lockheed Martin Space Systems Company)*

Advanced Stirling Radioisotope Generator Flight Design Project Overview  
*T.J. Hoe, D.C. Tantino and J. Chan (Lockheed Martin Space Systems Company)*

The Four-GPHS Stirling Generator: XP300

*J. Reyes, M. Britton, J.R. White (Lockheed Martin Space Systems), and J.G. Wood (Sunpower, Inc.)*

## Wednesday, February 9, cont.

3:30 pm – 5:00 pm

### **Track II: Fission Power and Propulsion**

#### **Tools & Modeling**

Salon A/B

Session Chairs: D. Poston, Los Alamos National Laboratory, and J. Webb, Center for Space Nuclear Research / Idaho National Laboratory

Modeling Impact-Induced Reactivity Changes Using DAG-MCNP

*B.M. Smith and P.P.H. Wilson (Univ of Wisconsin-Madison)*

Experimental Correlation of an RPCSIM Model

*M.D. Carlson (Univ of Wisconsin-Madison; SNL), R.F. Radel, K. Mount, and S. Wright (SNL)*

Operation of a Closed Brayton Cycle Using Simulated Reactivity Feedback

*T.M. Conboy, R.F. Radel, M.D. Carlson, and S.A. Wright (SNL)*

Implementation of a Sage-Based Stirling Model into a System Level Numerical Model of the Fission Power System Technology Demonstration Unit

*M. Briggs (NASA GRC)*

### **Track III: Radioisotope Power Systems**

#### **Mechanical, Thermal & Electrical Integration**

Salon I/J

Session Chairs: J. Zakrajsek, NASA Glenn Research Center, and J. Nainiger, Alphaport, Inc.

Mechanical Properties of Advance Thermoelectric Materials and Thermo-Mechanical Modeling of High Efficiency Thermoelectric Couples

*S. Firdosy (JPL)*

High Thermoelectric Figure of Merit in Heavy-hole Dominated PbTe

*Y. Pei (California Institute of Technology) and J. Lensch-Falk (SNL)*

Variable Conductance Heat Pipes for Long-Lived Venus Landers

*C. Tarau, W.G. Anderson and C.J. Peters (Advanced Cooling Technologies, Inc.)*

Three Practical ESPA-Class and Similar Satellite Sterling Radioisotope Generator Power System Designs

*M.B. Trubilla and S.D. Howe (CSNR)*

**Thursday, February 10**

**8:30 am – 10:00 am**

**Track I: Missions and Architectures**

Radioisotope Thermal Propulsion Mission Applications

Salon C/D

Session Chairs: S. Howe, Center for Space Nuclear Research / Idaho National Laboratory, and J. King, Colorado School of Mines

Advanced Materials and Optimization of a Radioisotope Thermal Rocket Motor for a Mars Hopper

*H.R. Williams, R.M. Ambrosi, N.P. Bannister (Univ of Leicester), M-C. Perkinson, J. Reed (Astrium Ltd), S.D. Howe and R.C. O'Brien (CSNR)*

Development of a Propulsion System and Component Test Facility for Advanced Radioisotope Powered Mars Hopper Platforms

*R.C. O'Brien, N.D. Jerred and S.D. Howe (CSNR)*

**Track II: Fission Power and Propulsion**

Systems Concepts 2

Salon A/B

Session Chairs: O. Mireles, NASA Marshall Space Flight Center, and M. Briggs, NASA Glenn Research Center

HTGR Power System Technology for Space Exploration Missions

*M. Worrall and Z. Shayer (Colorado School of Mines)*

Basic Research and Development Effort to Design a Micro Nuclear Power Plant for Brazilian Space Application

*L.N.F. Guimaraes (Institute for Advanced Studies, Brazil; Faculdade de Tecnologia Sao Francisco), G.P. Camillo (Institute for Advanced Studies, Brazil), G.M. Placco, A.G. Barrios Junior (Faculdade de Tecnologia Sao Francisco), J.Alves do Nascimento, E.M. Borges, P. David de Castro Lobo (Institute for Advanced Studies, Brazil)*

Space Molten Salt Reactor Concept for Nuclear Electric Propulsion and Surface Power

*M. Eades, J. Flanders, N. McMurray, R. Denning, X. Sun, W. Windl, and T. Blue (Ohio State Univ)*

Design of a Low Specific Mass 10 kWe Nuclear Reactor for Space Propulsion

*N. Hoifeldt, R. Ferrulli, L. Sudderth, W. Deason, M. Gupta, J. Reneau and S.D. Howe (CSNR)*



## **Thursday, February 10**

**8:30 am – 10:00 am, cont.**

### **Track III: Radioisotope Power Systems**

Testing, Validation and Advanced Power Conversion

Salon I/J

Session Chair: C. Steffen, NASA Glenn Research Center, and S. Johnson, Idaho National Laboratory

Life Testing of Yb<sub>14</sub>MnSb<sub>11</sub> for High Performance Thermoelectric Couples

*J-A. Paik, E. Brandon, T. Caillat, R. Ewell, and J-P. Fleurial (Jet Propulsion Laboratory)*

Highly Integrated Quality Assurance - An Empirical Case

*D. Kirkham, A. Powell, and L. Rich (Idaho National Laboratory)*

10 kW Radioisotope Power Pulsed Brayton Cycle For Space Application

*S. Morgan, B. Manning, N. Addanki (CSNR), M. Trubilla (Air Force Academy), S.D. Howe (CSNR), and J. King (Colorado School of Mines)*

**10:30 am – 12:00 pm**

### **Track I: Missions and Architectures**

Space Radiation: Effects and Mitigation

Salon C/D

Session Chairs: M. Schoenfeld, NASA Marshall Space Flight Center, and R. Singleterry, NASA Langley Research Center

Comparisons of Planetary Space Radiation Environments and Effects - A Review

*H.B. Garrett, M. Kokorowski (JPL, California Inst of Technology) and R.W. Evans (Mori Associates)*

A Hypothesis on Biological Protection from Space Radiation Through the Use of New Therapeutic Gases

*M.P. Schoenfeld (NASA MSFC), R.R. Ansari (NASA GRC), A. Nakao (Univ of Pittsburgh), and D. Wink (National Institute of Health)*

Optimization of Interplanetary Transfers of Space Vehicles with Nuclear Thermal Rocket Engine

*O. Dekhtiar and O. Kharytonov (Taras Shevchenko National University of Kyiv)*

**Thursday, February 10**

**10:30 am – 12:00 pm, cont.**

**Track II: Fission Power and Propulsion**

Testing & Validation 2

Salon A/B

Session Chairs: J. Werner, Idaho National Laboratory, and T. Godfroy, Maximum Technology Corporation

Material Studies Related to the Use of NaK Heat Exchangers Coupled to Stirling Heater Heads  
*I.E. Locci, C.L. Bowman, S.M. Geng and M.G. Robbie (NASA GRC)*

SNAP 10A Safety Test Program

*W.R. Determan, G.A. Johnson, A.J. Zillmer, T.E. Dix (Pratt & Whitney Rocketdyne), C-Y. Lu, M. Tosca, and L.A. Trager (Hamilton Sundstrand Rocketdyne)*

Fission Power Conversion Components Radiation Specifications

*C. Bowman, E.E. Shin (NASA GRC), O.R. Mireles (NASA MSFC), R.F. Radel (SNL), and A.L. Qualls (ORNL)*

Post Test Analysis of a Ten Year Sodium Heat Pipe Life Test

*J.H. Rosenfeld (Thermacore Inc.), J.L. Sanzi, I. Locci and S.M. Geng (NASA GRC)*

**Track V: Advanced Concepts**

Multi-Megawatt Fission Reactor Concepts

Salon C/D

Session Chairs: J. Webb, Center for Space Nuclear Research / Idaho National Laboratory

Multi-MW Closed Cycle MHD Nuclear Space Power via Nonequilibrium He/Xe Working Plasma  
*R. Litchford (NASA MSFC) and N. Harada (Nagaoka Univ of Technology)*

Trade Studies for a 20 MWe Low Specific Mass Nuclear Power System for Space Propulsion

*W. Deason, R. Ferrulli, M. Gupta, N. Hoifeldt, J. Reneau, and L. Sudderth (CSNR)*

A Conceptual Multi-Megawatt Reactor System Based on a Tungsten CERMET Reactor

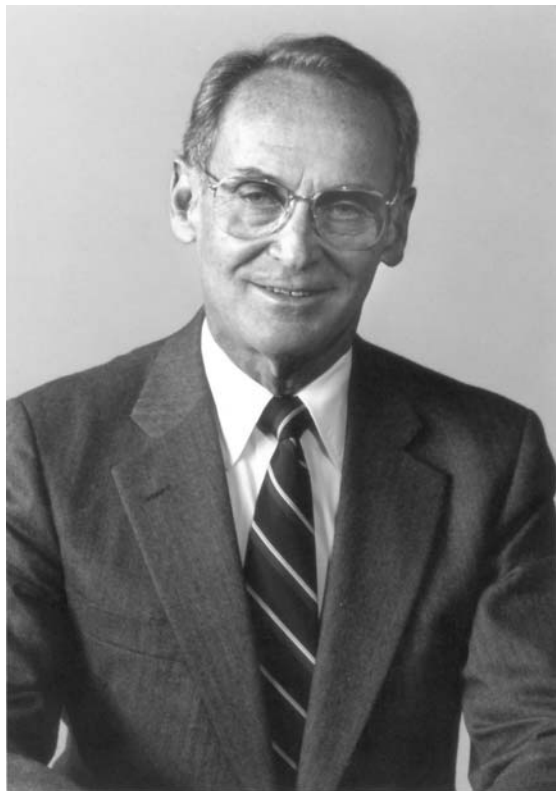
*J. Webb and B. Gross (CSNR)*



# Key Speaker Biographies

## Mr. Harold Finger

### NETS-2011 Honorary General Chair



Harold B. Finger has been working as an independent consultant since his retirement in May 1991 from the U.S. Council for Energy Awareness, where he served as President and CEO since January 1983. He is consulting in energy policy and programs, space systems and programs, urban development and housing issues, and government management working with government, industry, and non-profit organizations.

Mr. Finger received a BS Degree in Mechanical Engineering from the City College of New York in 1944 and an MS in Aeronautical Engineering from the Case Institute of Technology in 1950. In 1957-1958, he also had special training in Nuclear Engineering at NASA's predecessor, the National Advisory Committee for Aeronautics (NACA) Lewis Flight Propulsion Laboratory in

Cleveland, Ohio.

After graduating from the City College in 1944, Mr. Finger joined the NACA as an Aeronautical Research Scientist responsible for aircraft engine and compressor and turbine research. He held increasingly responsible positions and in October 1958, when the National Aeronautics and Space Administration was established, he was asked to come to Washington to lead NASA's space power and nuclear energy programs. From 1960-67, he managed the newly established Space Nuclear Propulsion Office, a joint office of the Atomic Energy Commission and NASA, responsible for nuclear rocket propulsion development while also serving as Director of NASA's Space Power and Nuclear Systems. (He'll be discussing the accomplishments of those programs in providing a capability for deep space exploration in the opening session of the 2011 NETS Program.) In 1965, he was also appointed Director of the AEC's Space Nuclear Systems Division including responsibility for radioisotope and reactor power systems. He left those three positions to serve from 1967-69 as NASA's Associate Administrator for Organization and Management including all administrative functions as well as university programs and aerospace technology applications.

In March 1969, Mr. Finger was appointed the first Assistant Secretary for Research and Technology in the U.S. Department of Housing and Urban Development where he established a broad program in housing assistance, housing technology, housing management, community development and urban planning. Many of these led to new approaches to help provide our nation's housing needs.

Mr. Finger left the government at the end of 1972 to join the General Electric Company as General Manager of a new Center for Energy Systems in Washington and as Manager of the Electric Utility Engineering Operation in Schenectady, NY. In 1980, he was named Staff Executive of GE's Power Systems Strategic Planning and Development at the corporate headquarters. In January 1983, Mr. Finger left GE to become President and CEO of the U.S. Council for Energy Awareness, an energy analysis and public information organization involved mainly with electric utility matters, including nuclear energy systems. That organization later became the current Nuclear Energy Institute after Harold Finger retired in 1991.

Since Mr. Finger retired, he has continued to be involved in all these fields of his past experience. He is President of the NASA Alumni League. Mr. Finger has been a Fellow of the National Academy of Public Administration since 1970 and has served on its Board and serves on many of its Panels. He is a life-time Trustee of the Board of the National Housing Conference. He served on the Technical Advisory Committee of the DOE's Solar Energy Research Institute. He has received many honors and awards including NASA's Outstanding Leadership Medal, is an honorary member of the American Institute of Architects, has been elected a Fellow of the American Association for the Advancement of Science and the American Institute of Aeronautics and Astronautics and has received its James H. Wyld Propulsion Award. He is a member of the American Nuclear Society, the American Society for Public Administration, the American Astronautical Society and the Planetary Society. He has received the Society of Automotive Engineers' Manley Memorial Award, the Schreiber-Spence Award of the University of New Mexico for contributions to space nuclear power and propulsion, and was elected a member of the Cosmos Club in 1975.



## Dr. John Casani

### **NETS-2011 Honorary General Chair NASA Jet Propulsion Laboratory, Special Assistant to the Director**



John Casani is currently Special Assistant to the Director at the Jet Propulsion Laboratory. He has been a leader in the development and management of spacecraft systems. The majority of his career has been in systems engineering and project management. He was Project Manager for three major space missions at JPL: Voyager, Galileo, and Cassini. He held senior project positions in many of the early space programs, including Explorer, Pioneer, Ranger, and Mariner.

Dr. Casani is the recipient of the National Academy of Engineering Founders Award, and the National Aerospace Museum Lifetime Achievement Award. He is an Honorary Fellow of the AIAA and a member of the International Astronautics Academy. He has received several NASA awards, including the

Distinguished Service Medal, the Exceptional Achievement Medal, and the Medal for Outstanding Leadership. He received the AIAA Space System Award and the von Karman Lectureship, the National Space Club Astronauts Engineer Award, and the AAS Space Flight Award.

Dr. Casani has a BSEE and an Honorary Doctor of Science degree from the Pennsylvania and an honorary degree in Aerospace Engineering from the University of Rome.

## Mr. Jim Adams

### Deputy Director, Planetary Science NASA Headquarters



Mr. Adams has over 30 years of aerospace engineering and management experience, both in the private sector and as a civil servant at NASA. He has extensive Program and Project management experience and is currently serving as a Senior Executive in the Science Mission Directorate. Jim has a broad background in acquisition, planning, implementation and execution of both large and small scale spacecraft missions, as well as ground systems and infrastructure.

Since 2007, Mr. Adams has been serving as the Deputy Director of the Planetary Science Division (PSD) where he is responsible for a \$1.3B annual portfolio, encompassing planetary activities in various stages of development and numerous supporting activities ranging from operations systems, to technology investments to

international partnerships. He is also the Program Director for the Discovery, New Frontiers and Lunar Quest programs within PSD.

Prior to his assignment at NASA Headquarters, Mr. Adams served for 17 years at NASA's Goddard Space Flight Center in a variety of capacities.

Mr. Adams was employed by the General Electric Company in Valley Forge, PA from 1979 to 1989 as a Systems Engineer where he helped design Military and Civil Communications spacecraft.

He has worked on over 25 successful currently operating space missions, received 3 NASA medals recognizing exceptional service and leadership including NASA's Outstanding Leadership Medal. Mr. Adams holds a B.S. in Physics from Westminster College in New Wilmington, PA (1979) and a M.S. in Electrical Engineering from Villanova University in Villanova, PA (1989).

## Dr. Michael Griffin

**King-McDonald Eminent Scholar and Professor of Mechanical and Aerospace Engineering and Director, Center for System Studies, University of Alabama in Huntsville**

**Former NASA Administrator**



Michael Griffin is the King-McDonald Eminent Scholar and Professor of Mechanical and Aerospace Engineering, and the Director of the Center for System Studies at The University of Alabama in Huntsville. From 2005-09 he was the Administrator of NASA. Prior to re-joining NASA he was Space Department Head at the Johns Hopkins University Applied Physics Laboratory. He has also held numerous executive positions with industry, including President and Chief Operating Officer of In-Q-Tel, Chief Executive Officer of Magellan Systems, General Manager of Orbital Science Corporation's Space Systems Group, and Executive Vice President and Chief Technical

Officer at Orbital.

Mike's earlier career includes government service as both Chief Engineer and Associate Administrator for Exploration at NASA, and as the Deputy for Technology at the Strategic Defense Initiative Organization. Prior to joining SDIO in an executive capacity, he played a key role in conceiving and directing several "first of a kind" space tests in support of strategic defense research, development, and flight testing. These included the first space-to-space intercept of a ballistic missile in powered flight, the first broad-spectrum spaceborne reconnaissance of targets and decoys in midcourse flight, and the first space-to-ground reconnaissance of ballistic missiles during the boost phase. He also played a leading role in other space missions in earlier work at the JHU Applied Physics Laboratory, NASA's Jet Propulsion Laboratory, and the Computer Science Corporation.

Mike previously taught for thirteen years as an adjunct professor at the University of Maryland, the Johns Hopkins University, and George Washington University, offering courses in spacecraft design, applied mathematics, guidance and navigation, compressible flow, computational fluid dynamics, spacecraft attitude control, astrodynamics, and introductory aerospace engineering. He is a Registered Professional Engineer in Maryland and California, and is the lead author of over two dozen technical papers and the textbook *Space Vehicle Design*.

Griffin is member of the National Academy of Engineering and the International Academy of Astronautics, an Honorary Fellow of the American Institute of Aeronautics and Astronautics, a Fellow of the American Astronautical Society, and a Senior Member of the Institute of Electrical and Electronic Engineers. He is the recipient of numerous honors and awards, including the NASA Exceptional Achievement Medal, the AIAA Space Systems Medal and Goddard Astronautics Award, the National Space Club's Goddard Trophy, the Rotary National Award for Space Achievement, and the Department of Defense Distinguished Public Service Medal, the highest award which can be conferred on a non-government employee.

Mike obtained his B.A. in Physics from the Johns Hopkins University, which he attended as the winner of a Maryland Senatorial Scholarship. He holds Master's degrees in Aerospace Science from Catholic University, Electrical Engineering from the University of Southern California, Applied Physics from Johns Hopkins, Civil Engineering from George Washington University, and Business Administration from Loyola College of Maryland. He received his Ph.D. in Aerospace Engineering from the University of Maryland.

Mike was born in 1949 in Aberdeen, Maryland. His hobbies include golf, flying, amateur radio, skiing, and scuba diving. He is a Certified Flight Instructor with instrument and multiengine ratings, and holds an Extra Class radio amateur license.

## Mr. Robert Lange

### **Deputy Assistant Secretary Office of Nuclear Energy (NE), Department of Energy**



Robert Lange joined the Office of Nuclear Energy thirty years ago, and has actively participated in the development and production of space nuclear power supplies during a significant portion of his career. He was the Program Director for the multi-agency SP-100 space nuclear reactor power system, and was the director of the office responsible for the fabrication and delivery of the three radioisotope thermoelectric generators for the Cassini mission, launched in 1997. He also served as the technical advisor to the State Department on space nuclear power supplies. Presently, Mr. Lange has four major offices for which he is responsible; personnel, budget, uranium and the Office of Space and Defense Power Systems.

Mr. Lange received a B.S. degree in mechanical engineering from the University of Maryland and a M.S. degree in engineering administration from George Washington University. He received his naval commission from Naval Officers Candidate School in Newport, Rhode Island.

## Dr. Steven D. Howe

### Director, Center for Space Nuclear Research



Dr. Steven Howe is currently the Director of the Center for Space Nuclear Research (CSNR) in Idaho Falls, ID. The CSNR is engaged in facilitating research and education of nuclear technologies for space exploration. Prior to this position, Howe was a staff member in the Thermonuclear Applications group of the Applied Physics Division (X Division) at the Los Alamos National Laboratory (LANL). In this position, Howe was investigating the importance of energetic nuclear reactions in modeling the weapons physics of a nuclear device.

Prior to the position in X-Division, Dr. Howe was the Program Element manager of the Reactivity and Compression element in the Nuclear Weapons Stockpile Stewardship Program at the LANL. As

such, Howe managed research funding in nuclear science to support the nuclear weapons effort in the Lab. Dr. Howe was also a senior advisor to the Division Leader of the Los Alamos Neutron Science Center (LANSCE). LANSCE has been a major research facility at LANL that comprises a high-intensity, 800 MeV proton beam for a variety of applications.

While working at LANL for almost twenty-three years, Dr. Howe developed new programs for the Laboratory in the areas of advanced space propulsion, space exploration technologies, bio-medical instrumentation, defense programs, nuclear systems, and hypersonic flight. Howe was the Laboratory's project coordinator of the nuclear propulsion effort, team leader of the gas core nuclear rocket project, project manager for the Zero-g Float Zone Furnace, and Design Physicist for the Villita nuclear test. The program development activity required both an understanding of new front-edge technologies and the ability to communicate the potential of these technologies to potential sponsors.

## **Dr. Richard Ambrosi**

**UK Technical Lead, Mars XRD  
Lecturer, Department of Physics and Astronomy  
Space Research Centre, University of Leicester**

Dr. Richard Ambrosi graduated with a PhD in physics from the University of the Witwatersrand, Johannesburg, South Africa. Richard's work in South Africa focused on accelerator based fast neutron resonance radiography for mining and security applications. In 2000 Richard moved to the University of Leicester, UK to work on the Swift Gamma Ray Burst Observatory's X-ray Telescope as CCD calibration scientist. Richard is currently a Lecturer at the University of Leicester and is the UK Technical Lead for the ExoMars X-ray diffraction instrument, Mars-XRD. Richard is working on a number of space nuclear power projects funded by the European Space Agency including: leading a European RTG breadboard development project and working in partnership with a number of institutes on a radioisotope encapsulation and aeroshell study.



## Dr. Ralph McNutt

### Principal Professional Staff, The Johns Hopkins University Applied Physics Laboratory



RALPH L. McNUTT, JR. is a Physicist and a member of the Principal Professional Staff of The Johns Hopkins University Applied Physics Laboratory. He received his B.S. in Physics (summa cum laude) at Texas A&M University in 1975 and his Ph.D. in Physics at the Massachusetts Institute of Technology in 1980. He has been at APL since 1992 and before that held positions at Visidyne, Inc., M.I.T., and Sandia National Laboratories in Albuquerque.

Dr. McNutt is Project Scientist and a Co-Investigator on NASA's MESSENGER mission to Mercury, Co-Investigator on NASA's Solar Probe Plus mission to the solar corona, Principal Investigator on the PEPSSI investigation on the New Horizons mission to Pluto, a Co-Investigator for the Voyager PLS and LECP instruments, and

a Member of the Ion Neutral Mass Spectrometer Team on the Cassini Orbiter spacecraft.

He has held various NASA grants and served on various NASA review and planning panels and Science and Technology Definition Teams for Solar Probe (twice) and Interstellar Probe. He has also served on a variety of National Research Council committees, including as Co-Chair of the NRC Committee on Radioisotope Power Supplies (2008-2009) and currently as a Member of the Steering Committee, Solar System Exploration Decadal Survey (29 May 2009 – 18 Aug 2011).

He is a Member of International Academy of Astronautics, Fellow of The British Interplanetary Society, Associate Fellow of the American Institute of Aeronautics and Astronautics, Member of the American Astronomical Society and its Division for Planetary Sciences, the American Geophysical Union, Sigma Xi, The Planetary Society, and the American Nuclear Society. Dr. McNutt is the recipient of eleven NASA Group Achievement Awards. He has published over 150 science and engineering papers and over 250 scientific and engineering abstracts and given over 150 professional and popular talks.



## Dr. Elizabeth Newton

### **Director for Space Policy, Center for System Studies University of Alabama in Huntsville**



Dr. Newton is the Director for Space Policy in the Center for System Studies at the University of Alabama in Huntsville (UAHuntsville). She is responsible for developing the Center's policy analysis capability to complement the Center's technical focus on complex, publicly funded engineering programs and their performance for society's benefit.

Dr. Newton brings to her role 20 years of experience in the aerospace and high technology business sectors. Prior to joining the university, Dr. Newton combined her technical and policy knowledge with business acumen to create and lead the strategic planning and integration office at NASA Marshall Space Flight Center. She led the development of new tools for analyzing the center's business base, markets and competitive position, and she re-engineered the center's technology investment

program. She was the principal in designing and subsequently managing the center's new governance system to foster more integrated, strategic decision-making and accountability, a system which subsequently served as a benchmark for the rest of the agency. In her position, Dr. Newton also oversaw communication strategy and executive communication.

In addition to her experience in the public sector, Dr. Newton was co-founder and vice-president of operations of a high-technology start-up, providing sophisticated transaction, search, and marketing software to consumer technology and financial services companies. She authored the business plan which secured more than \$10 M in angel and series A equity investments, including DeutscheBanc/Alex Brown Ventures' first venture capital investment in the state of Alabama. She created and led the

Operations team, encompassing customer service, production, quality assurance, and information technology, delivering millions of dollars of products and services to high-profile clients such as IBM, Gateway, HP, CDW, Sony, CNET, ADP, and CCBN.

Following the completion of her Ph.D. in physics, Dr. Newton worked as a space scientist for NASA and as a program manager at Dynetics Inc., a contractor supporting the National Missile Defense Program Office. Earlier in her career, Dr. Newton worked as a policy analyst, first at the United Nations' Economic Commission for Europe in Geneva, Switzerland, then at NASA Jet Propulsion Laboratory's Flight Projects Office, where the U.S.'s collaborations with the U.S.S.R. in planetary exploration were defined and advanced. While with the federally funded research and development center ANSER, Dr. Newton provided policy analysis for the Office of the President's National

Space Council staff, the U.S. Air Force's Space Systems Division, and NASA Headquarters.

Dr. Newton's long-standing community involvement focuses on advancing the availability of educational opportunities to North Alabama's young men and women as well as grade school girls. She is the area chairperson for Cornell University's Alumni Ambassadors Admission Network which reaches out to high school seniors who have applied to Cornell and supplies the admissions office with supplemental information. She serves on the Board of Girls, Inc., a non-profit dedicated to helping girls become *strong, smart, and bold* TM through after-school literacy, enrichment, and mentoring activities. She is an alumna and volunteer for Leadership Huntsville/Madison County, where she is responsible for planning and executing its semi-annual service projects, and she served on the Board of the UAHuntsville Alumni Association. For more than 13 years she has belonged to the Philanthropic Education Organization for women (P.E.O. International) which funds scholarships and loans to women pursuing higher education degrees.

Dr. Newton earned her Bachelor's degree in government from Cornell University as a Phi Beta Kappa, Cornell National Scholar, and Maryland Distinguished Scholar. She earned a certificate in international relations from l'Institut de Hautes Etudes Internationales, Geneva, Switzerland. Her advanced degrees include a Master's degree in political science from the University of California Berkeley, where she was a Congressional Jacob K. Javits Fellow, and Master's and Doctoral degrees in physics from UAHuntsville.

## **Mr. Charles (Chuck) Atkins**

### **Chief of Staff to the U.S. House of Representatives Committee on Science and Technology, Retired**

Chuck Atkins served as Chief of Staff to the U.S. House of Representatives Committee on Science and Technology for five years until 2009 (minority 2005-2006, majority 2007-2009). The Committee is responsible for legislation and oversight of Federal government civilian research and development programs. These programs include space, aeronautics, energy, transportation, basic research, math and science education, cooperative industry-government R&D and the environment. As Chief of Staff he served as senior policy advisor to the Chairman, managing a staff of 45 professionals, including scientists, engineers and attorneys, in carrying out the oversight and legislative agenda for the Committee. He holds Top Secret and DOE "Q" security clearances.

Chuck began his service in Congress in 1993 after managing the successful campaign of former Congressman Scotty Baesler of Kentucky and serving as his Chief of Staff until 1999. In 1999 he became Chief of Staff to Congressman Bart Gordon of Tennessee.

In 1995 Chuck was elected and served one term as president of the House Administrative Assistants'/Chiefs' of Staff Association, a non-partisan professional and educational association of senior House staff leaders. In 1997 he was selected to serve as a John C. Stennis Center for Public Service Congressional Staff Fellow for the 105<sup>th</sup> Congress.

Other career milestones include founding a community development and housing consulting firm, Atkins-Elrod and Associates in 1977. In addition to consulting, he formed real estate investment partnerships to re-develop historic properties. Chuck also taught political science and public policy at the university level for ten years during his career as a consultant. Prior to consulting he served as Local Government Services Director for a Kentucky regional planning and development district.

He served in the United States Marine Corps from 1966-1968. His service included a tour of duty in Vietnam with the 2<sup>nd</sup> Battalion/4th Marine Regiment.

Mr. Atkins earned a B.S., with honors, from Georgia State University in 1972 with majors in Psychology and Urban Administration. He earned an M.A. in public administration from The Ohio State University in 1973.

## Dr. Harrison “Jack” Schmitt

### **Apollo 17 Astronaut, Fmr. U.S. Senator (NM) Current Secretary-Designee for the NM Dept of Energy, Minerals and Natural Resources**



Harrison Hagan Schmitt, a native of Silver City, NM, has the diverse experience of a geologist, pilot, astronaut, administrator, businessman, writer, and U. S. Schmitt received his B. S. from Caltech, studied as a Fulbright Scholar at Oslo, and attended graduate school at Harvard. Geological field studies in Norway formed the basis of his Ph.D. in 1964. As a civilian, Schmitt received Air Force jet pilot wings in 1965 and Navy helicopter wings in 1967, logging more than 2100 hours of flying time.

Selected for the Scientist-Astronaut program in 1965, Schmitt organized the lunar science training for the Apollo Astronauts, represented the crews during the development of hardware and procedures for lunar surface exploration, and oversaw the final preparation of the Apollo 11 Lunar Module Descent Stage. He served as Mission Scientist in support of the Apollo 11 mission. After training as back-up Lunar

Module Pilot for Apollo 15, Schmitt flew in space as Lunar Module Pilot for Apollo 17 - the last Apollo mission to the moon. On December 11, 1972, he landed in the Valley of Taurus-Littrow as the only scientist and the last of 12 men to step on the Moon.

In 1975, after two years managing NASA's Energy Program Office, Schmitt fulfilled a long-standing personal commitment by entering politics. Elected in 1976, he served a six-year term in the U.S. Senate beginning in 1977. Harrison Schmitt became Chairman of the NASA Advisory Council in November 2005, and served until October 2008. He also consults, speaks, and writes on policy and constitutional issues of the future, the science of the Moon and Planets, history of space flight and geology, space exploration, space law, climate change, and the American Southwest. He presently is Honorary Associate Professor of Engineering, University of Wisconsin-Madison, teaching "Resources from Space." He is on the staff of the Institute for Human and Machine Cognition of Pensacola, Florida. Current board memberships include Orbital Sciences Corporation, Edenspace Systems Corporation, PhDx Systems, Inc., and The Heartland Institute. In 1997, Schmitt co-founded and became Chairman of Interlune-Intermars Initiative, Inc., advancing the private sector's acquisition of lunar resources and Helium-3 fusion power and clinical use of medical isotopes produced by fusion-related processes. He is the author of, "Return to the Moon" (2006 Springer-Praxis) that describes a private enterprise approach to providing lunar helium-3 fusion energy resources for use on Earth.

Harrison Schmitt is currently the Secretary-Designate of the New Mexico Energy, Minerals, and Natural Resources Department.

## Dr. George Schmidt

### Deputy Director, Research and Technology Directorate, NASA Glenn Research Center



Dr. George Schmidt is the Deputy Director of Glenn's Research and Technology Directorate, which conducts a broad range of research and technology development projects in space propulsion, aeropropulsion, power, communications, materials and structures, instrumentation and physical sciences.

Prior to this assignment, Dr. Schmidt served as Manager of the Propulsion Research Center at Marshall Space Flight Center, where he led a variety of cutting-edge research projects covering a broad range of advanced propulsion technologies. He also served as Deputy Manager of Marshall's Test Laboratory, where he assisted in directing operation of 40 major rocket, vacuum and structural test facilities. Dr. Schmidt spent several years at NASA

Headquarters serving as the Program Executive for Nuclear Power Systems, and oversaw development of the Advanced Stirling Radioisotope Generator (ASRG) and other nuclear power technologies for NASA space science missions. Dr. Schmidt started his NASA career in 1989 leading research and technology projects focused on cryogenic fluid management. Prior to that, he worked at Booz-Allen & Hamilton and Boeing Aerospace supporting NASA efforts on International Space Station and Orbital Transfer Vehicles.

Dr. Schmidt earned his B.S. and M.S. degrees in Mechanical Engineering from Stanford University, an M.S. degree in Aeronautics and Astronautics from the University of Washington, and a Ph.D. in Mechanical Engineering from the University of Alabama in Huntsville, where he was an adjunct professor and taught a course in advanced propulsion. Dr. Schmidt is a member of the American Institute of Aeronautics and Astronautics (AIAA) and has served on several of its technical committees, including chairing the Nuclear and Future Flight Propulsion Technical Committee. He holds a patent and has authored over 70 publications in the areas of space propulsion, cryogenic and microgravity fluid mechanics, and nuclear power and advanced high-energy propulsion.



## Dr. Stephen G. Johnson

**Director, Space Nuclear Systems & Technology Division,  
Idaho National Laboratory**



Currently Director of the Space Nuclear Systems and Technologies Division in the Nuclear Science and Technology Directorate of the Idaho National Laboratory, Dr. Stephen Johnson oversees the Engineering Development Laboratory and manages the Radioisotope Power Systems Program. Most recently this program fueled, tested and will deliver the MMRTG for NASA's Mars Scientific Laboratory mission to the planet Mars. During his tenure, the laboratory successfully pursued involvement in the Radioisotope Power Systems Program and following that involvement the fueling and testing of space and terrestrial power systems operations were transferred from Mound Laboratory to the Idaho National Laboratory (formerly Argonne National Laboratory-West). Further involvement in this program has led to the laboratory being considered for the consolidation of all Pu-238 operations in the DOE complex. Dr. Johnson has over 15 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.

Prior to his current position, he served as facility manager for the Electron Microscopy Laboratory and manager of the Nuclear Waste and Materials section of the Engineering Technology Division of Argonne National Laboratory-West. In this capacity Dr. Johnson oversaw the operations of the Electron Microscopy Laboratory, which includes metallography, scanning electron microscopy and transmission electron microscopy capabilities in a radiological facility. He also oversaw the waste qualification efforts for the two high-level waste forms generated by the electrometallurgical treatment of the EBR-II fuel. He served on the High-level Waste sub-committee for the American Society of Testing and Materials and chaired the task group for revising the product consistency test for applications beyond radioactive glass. He is also a member of the American Chemical Society and the Material Research Society. Dr. Johnson has been affiliated with Purdue University as an Adjunct Professor of Health Sciences and was co-major professor for two students who received their MS degrees in Health Physics. He has also advised a student at Idaho State University to obtain his MS in engineering with emphasis in nuclear engineering. He holds a B.S. degree with a double major in Mathematics and Chemistry from Lake Superior State University of Michigan (1984) and a Ph. D. in Physical Chemistry from Iowa State University (1990). His doctoral research applied low-temperature high-resolution laser spectroscopy to study energy transfer in photosynthetic species. His post-doctoral appointment at Los Alamos National Laboratory involved the study of resonance ionization mass spectrometry for analysis of thorium at low levels for use as a geo-chronological dating method.

## Dr. Glen Schmidt

### Retired, Former SNAP-10a Test Engineer



After graduation from Oregon State College in 1957, Glen joined Atomics International as a Research Engineer to design and develop remote pyro-processing equipment to recover the uranium metal from spent nuclear reactor fuels. A short time later, he was re-assigned to perform lab tests on the first SNAP critical assembly, co-invented by Joe Wetch.

Within the next year, he was assigned to design a small sodium EM pump attached to one end of the combined rotating 3 kw 40,000 rpm SNAP generator. (During lab flow tests at 1200 F and ~ 40,00 rpm, the pump produced 6 psi at 12 gpm.) He was later selected to attend the first start-up and demonstrations of the mercury Rankine cycle 3 kw power conversion systems built by a contractor.

During 1959, the SNAP Experimental Reactor (SER) was built and operated for one year using 1200 °F NaK coolant to collect performance data and verify the basic reactor design. Glen was chosen to be the

Shift Leader of Crew A during continuous operations (there were 3 additional crews) The S2DR was the next reactor to be built and was tested by other reactor crews.

In December 1960, The AEC initiated the SNAP 10A program which included two orbital flight tests identified as SNAPSHOT.

During the next 5 years, the SNAP10A test program involved: component development and acceptance and the assembly and testing of non-nuclear prototypes, flight system mockups, flight system qualification, and nuclear flight system acceptance.

During this period, Glen was first assigned as System Test Supervisor and later as the Group Leader of system assembly, component testing, system testing and qualification, and nuclear flight system acceptance testing.

After the successful flight demonstration of SNAP 10A, Glen was re-assigned as the Superintendent of nuclear Fuel Manufacturing to produce nuclear fuels for the US ETR and ATR reactors and fuel plates for the Japanese JAERI critical assembly.

Glen retired in 1990 from Rockwell to participate in the purchase and test evaluation of Russian TOPAZ II space reactors.

# ABSTRACTS



# Reactivity Control Options for a Space Fission Power System

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**Abstract.** Due to the small reactivity swings associated with space reactors, rotating control drums located in the reflector region containing thin layers of  $B_4C$  are the most common reactivity control system used in fission space reactors today. This control system is also based on vast experience derived from terrestrial applications, mainly in test research reactors such as the ATR at Idaho National Laboratory. The main idea behind this configuration is to introduce some perturbation into the reflectors that will have an impact on the neutrons reflected back to the core resulting in changing the system's reactivity. Ideally, there are two main ways of disturbing the reflector efficiency; first by introducing parasitic absorbers into the reflector and second by changing the reflector properties through the introduction of less effective reflector materials. The selection of appropriate reactivity control depends on the type of reactor core (fast, epithermal or thermal), and the required excess reactivity that needs to be controlled over the entire core lifetime. In the present paper we are investigating several reactivity control system options, and demonstrating their applicability and effectiveness on a small HTGR unit for space applications. The impact of each control system option on power distribution (peaking factor), and their flexibility to control excess reactivity through the core lifetime is studied. The low density parasitic absorbers material that is considered in this research is  $B_4C$ . Partial replacement of an excellent reflector material such as  $BeO$  with a less effective one such as void or  $SiC$  are also investigated. Although the applications are demonstrated on a small HTGR unit, the applicability can be extended and optimized for different small unit concepts. Finally, a new reactivity control system for space reactor is presented.

## Challenges in Structural Analysis for Deformed Nuclear Reactivity Assessments

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**Abstract.** Launch safety calculations for past space reactor concepts have usually been limited to immersion of the reactor in water and/or sand, using nominal system geometries or in some cases simplified compaction scenarios. Deformation of the reactor core by impact during the accident sequence typically has not been considered because of the complexity of the calculation. Recent advances in codes and computing power have made such calculations feasible. The accuracy of such calculations depends primarily on the underlying structural analysis. Even though explicit structural dynamics is a mature field, nuclear reactors present significant challenges to obtain accurate deformation predictions. The presence of a working fluid is one of the primary contributors to challenges in these predictions. The fluid-structure interaction cannot be neglected because the fluid surrounds the nuclear fuel which is the most important region in the analysis. A detailed model of a small eighty-five pin reactor was built with the working fluid modeled as smoothed particle hydrodynamic (SPH) elements. Filling the complex volume covered by the working fluid with SPH elements required development of an algorithm which eliminates overlaps between the hexahedral and SPH elements. The results with and without the working fluid were found to be considerably different with respect to reactivity predictions.

## Evaluation of HEU-Beryllium Benchmark Experiments to Improve Computational Analysis of Space Reactors

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**Abstract.** An assessment was previously performed to evaluate modeling capabilities and quantify preliminary biases and uncertainties associated with the modeling methods and data utilized in designing a nuclear reactor such as a beryllium-reflected, highly-enriched-uranium (HEU)-O<sub>2</sub> fission surface power (FSP) system for space nuclear power. The conclusion of the previous study was that current capabilities could preclude the necessity of a cold critical test of the FSP; however, additional testing would reduce uncertainties in the beryllium and uranium cross-section data and the overall uncertainty in the computational models. A series of critical experiments using HEU metal were performed in the 1960s and 1970s in support of criticality safety operations at the Y-12 Plant. Of the hundreds of experiments, three were identified as fast-fission configurations reflected by beryllium metal. These experiments have been evaluated as benchmarks for inclusion in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (IHECSBE). Further evaluation of the benchmark experiments was performed using the sensitivity and uncertainty analysis capabilities of SCALE 6. The data adjustment methods of SCALE 6 have been employed in the validation of an example FSP design model to reduce the uncertainty due to the beryllium cross section data.

# Design of an Annular Linear Induction Pump for Nuclear Space Applications

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**Abstract.** The United States Department of Energy's (DOE) Office of Nuclear Energy, Science, and Technology is supporting the National Aeronautics and Space Administration (NASA) in evaluating space mission power, propulsion systems and technologies to support the implementation of the Vision for Space Exploration (VSE). NASA will need increased power for propulsion and for surface power applications to support both robotic and human space exploration missions. As part of the Fission Surface Power Technology Project for the development of nuclear reactor technologies for multi-mission spacecrafts, an Annular Linear Induction Pump, a type of Electromagnetic Pump for liquid metals, able to operate in space has to be designed. Results of such design work are described as well as the fundamental ideas behind the development of an optimized design methodology. This project, which is a collaboration between Idaho National Laboratory (INL), Pacific Northwest National Laboratory (PNNL) and Marshall Space Flight Center (MSFC), involves the use of theoretical, computational and experimental tools for multi-physics analysis as well as advanced engineering design methods and techniques.

# Circular Electromagnetic Thermoelectric Pump Simulation

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**Abstract.** This paper simulates and evaluates the performance of a circular electromagnetic thermoelectric pump (EMTE), which can be used to control flow of primary and secondary loops of liquid Lithium in a space nuclear reactor, similar to the SP-100. The BEMTE-3 software (developed at Institute for Advanced Studies - IEAv) calculates the EMTE pump head, pressure losses in the primary and secondary loops of the space, and the system performance values, for the thermal reactor studied. The results demonstrate a good thermal system performance.

# Sealed Mechanical Pump for High Temperature NaK

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## ABSTRACT

The use of alkali liquid metal Na-K as a reactor coolant for use in fission surface power applications has been proposed and considerable hardware development and testing has been undertaken in this direction. The predominant method for NaK circulation in such a cooling system has employed both conduction and induction electro magnetic pumps. A fully-sealed, mechanical pump for high temperature operation is proposed as an alternative to electromagnetic pumps. Key design features are a magnetically coupled drive system which is hermetically isolated from all Na-K-wetted surfaces and pump impeller shaft bearing surfaces lubricated with process fluid (Na-K). A prototype pump has been assembled from a commonly available, low-cost, 316 stainless steel water pump augmented with mechanical bearings and a sealed neodymium magnetic coupling. Successful operation has been demonstrated at temperatures ranging from 25°C to 420°C. Efficiencies are dependent primarily on impeller/pump housing design which average 55% for typical centrifugal pumps. Ultimate efficiencies of 15% to 20% including the drive system are expected.

# Water-Cooled Electromagnetic Flow Meter for High Temperature NaK

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## ABSTRACT

The use of alkali liquid metal Na K as a reactor coolant for use in fission surface power applications has been proposed and considerable hardware development and testing has been undertaken in this direction. An electro magnetic volumetric flow meter is proposed whereby an EMF is generated by the flow of conductive NaK through a mutually orthogonal magnetic field. Signal output is a linear function of flow velocity. Key design features of the flow meter are water-cooling of rare-earth magnets to maintain isothermal conditions, positive mechanical indexing of the magnetic field structure to the sealed NaK flow channel and the use of a one-piece, magnetically permeable bale for both channeling magnetic flux and focusing field lines in the vicinity of the NaK flow channel. A reliable and repeatable output signal has been demonstrated for very low volumetric flow rates at temperatures from 25°C to 400°C.

## SPS Fabrication of Tungsten-Rhenium Alloys in Support of NTR Fuels Development

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**Abstract.** Tungsten metal slugs were fabricated via Spark Plasma Sintering (SPS) of powdered metals at temperatures ranging from 1575 K to 1975 K and hold times of 5 minutes to 30 minutes, using powders with an average diameter of 7.8  $\mu\text{m}$ . Sintered tungsten specimens were found to have relative densities ranging from 83% to 94% of the theoretical density for tungsten. Consolidated specimens were also tested for their Vickers Hardness Number (VHN), which were plotted as a function of relative density. Concurrently, tungsten and rhenium powders with average respective diameters of 0.5  $\mu\text{m}$  and 13.3  $\mu\text{m}$  were pre-processed either by High-Energy-Ball-Milling (HEBM) or by homogeneous mixing to yield W-25at.%Re mixtures. The powder batches were sintered at temperatures of 1975 K and 2175 K for hold times up to 60 minutes yielding relative densities in the range 94% to 97%. The combination of HEBM and sintering showed a significant decrease in the intermetallic phases compared to that of the homogenous mixing and sintering.



## **Nuclear Thermal Propulsion (NTP) Fuel Element Development and Testing for Future Transportation Systems**

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**Abstract.** The announcement of the FY2011 budget with increased focus on enabling technologies has generated a renewed interest in nuclear thermal propulsion (NTP). A key technology for NTP systems is the fabrication of a stable high temperature fuel form. MSFC has significant experience with the development and evaluation of NTP fuel materials including recent fabrication of graphite composite, CERMET, and carbide test samples. In addition, MSFC has developed a low cost method for rapid screening of candidate materials in a sub-scale Arc-Heater and larger full size component Nuclear Thermal Rocket Element Environmental Simulator (NTREES). The current effort is focused on the development of fuel element manufacturing processes using surrogate and depleted uranium oxide, nitride, and carbide materials. Processing includes Hot Isostatic Pressing (HIP), traditional pressing/sintering, and the development of a fluidized bed CVD system for coating of ceramic powders. Uncoated and coated powders are being consolidated into samples for material characterization and hot hydrogen testing. The samples also have prototypical component features such as integral channels, coatings, and complex geometries to help evaluate fabrication limitations and feasible design concepts. The goal is early “non-nuclear” development to help validate requirements and minimize technical, cost, and schedule risks prior to committing funds for expensive testing. This paper will provide details on the current results of the project.

# A Combined Neutronic-Thermal Hydraulic Model of a CERMET NTR Reactor

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**Abstract.** Two different CERMET fueled Nuclear Thermal Propulsion reactors were modeled to determine the optimum coolant channel surface area to volume ratio required to cool a 25,000 lb<sub>F</sub> rocket engine operating at a specific impulse of 940 seconds. Both reactor concepts were computationally fueled with hexagonal cross section fuel elements having a flat-to-flat distance of 3.51 cm and containing 60 vol.% UO<sub>2</sub> enriched to 93wt.%U<sup>235</sup> and 40 vol.% tungsten. Coolant channel configuration consisted of a 37 coolant channel fuel element and a 61 coolant channel model representing 0.3 and 0.6 surface area to volume ratios, respectively. The energy deposition from decelerating fission products and scattered neutrons and photons was determined using the MCNP monte carlo code and then imported into the STAR-CCM+ computational fluid dynamics code. The 37 coolant channel case was shown to be insufficient in cooling the core to a peak temperature of 3000 K; however, the 61 coolant channel model shows promise for maintaining a peak core temperature of 3000 K, with no more refinements to the surface area to volume ratio. The core was modeled to have a power density of 9.34 GW/m<sup>3</sup> with a thrust to weight ratio of 5.7.

## Summary Of The Manufacture, Testing And Model Validation Of A Full-Scale Radiator For Fission Surface Power Applications

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**Abstract.** A full-scale radiator for a lunar fission surface power application was manufactured by Material innovations, Inc., for the NASA Glenn Research Center. The radiator was designed to reject  $6 \text{ kW}_t$  with an inlet water temperature of  $400 \text{ K}$  and a water mass flow rate of  $0.5 \text{ kg/s}$ . While not flight hardware, the radiator incorporated many potential design features and manufacturing techniques for future flight hardware. The radiator was tested at NASA Glenn Research Center for heat rejection performance. The results showed that the radiator design was capable of rejecting over  $6 \text{ kW}_t$  when operating at the design conditions. The actual performance of the radiator as a function of operational manifolds, inlet water temperature and facility sink temperature was compared to the predictive model developed by NASA Glenn Research Center. The results showed excellent agreement with the model with the actual average face sheet temperature being within  $\pm 1\%$  of the predicted value. The results will be used in the design and production of NASA's next generation fission power heat rejection systems. The NASA Glenn Research Center's Technology Demonstration Unit will be the first project to take advantage of the newly developed manufacturing techniques and analytical models.

## Evaluating Heat Pipe Performance in 1/6 g Acceleration: Problems and Prospects

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**Abstract.** Heat pipes composed of titanium and water are being considered for use in the heat rejection system of a fission power system option for lunar exploration. Placed vertically on the lunar surface, the heat pipes would operate as thermosyphons in the 1/6 g environment. The design of thermosyphons for such an application is determined, in part, by the flooding limit. Flooding is composed of two components, the thickness of the fluid film on the walls of the thermosyphon and the interaction of the fluid flow with the concurrent vapor counter flow. Both the fluid thickness contribution and interfacial shear contribution are inversely proportional to gravity. Hence, evaluating the performance of a thermosyphon in a 1 g environment on Earth may inadvertently lead to overestimating the performance of the same thermosyphon as experienced in the 1/6 g environment on the moon. Several concepts of varying complexity have been proposed for evaluating thermosyphon performance in reduced gravity, ranging from tilting the thermosyphons on Earth based on a cosine function, to flying heat pipes on a low-g aircraft. This paper summarizes the problems and prospects for evaluating thermosyphon performance in 1/6 g.

# Ultra-Light Heat Pipe Radiators for Fission Surface Power

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**Abstract.** Due to the large amounts of waste heat generated by Fission Surface Power (FSP) systems, a key consideration is the development of lightweight, highly efficient heat rejection systems (HRS). At Creare, we have been developing ultra-light, high-efficiency heat pipe radiators to address this need over a range of heat rejection temperatures for several years. Specifically, we have developed Creare-custom heat pipes that are based on titanium 15-3 alloy (15% V–3% Cr–3% Al–3% Sn), resulting in a significantly reduced mass compared to the commonly used CP2. To enable performance at high temperatures, we have developed unique, metal-to-metal bonding processes that enable a direct, high-conductance bond between the heat pipe and the fin material. For lower temperature applications, we are currently developing an adhesively bonded panel that enables high-efficiency performance while reducing overall manufacturing cost. As a concrete example, for a 400 K evaporator surface temperature and a 200 K sink temperature, the Mass Per Unit Heat Rejection (MPUHR) of our approach is 1.2 kg/kW. This figure includes the Z-93 coated panel, the charged heat pipes, and the panel support structure. In addition, the thermal efficiency of our approach is nearly 90%. In this paper, we will review our radiator development work by describing the overall designs and modeling approaches, reviewing our test results, and describing how our approach will benefit FSP systems.

# Heat Pipes and Heat Rejection Component Testing at NASA Glenn Research Center

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**Abstract.** Titanium-water heat pipes are being evaluated for use in the heat rejection system for space fission power systems. The heat rejection system currently comprises heat pipes with a graphite saddle and a composite fin. The heat input is a pumped water loop from the cooling of the power conversion system. The National Aeronautics and Space Administration has been life testing titanium-water heat pipes as well as evaluating several heat pipe radiator designs. The testing includes thermal modeling and verification of model, material compatibility, frozen startup of heat pipe radiators, and simulating low-gravity environments. Future thermal testing of titanium-water heat pipes includes low-gravity testing of thermosyphons, radiation testing of heat pipes and fin materials, water pump performance testing, as well as Small Business Innovation Research funded deliverable prototype radiator panels.

# **“Scotty, I Need More Power” – The Fission System Gateway to Abundant Power for Exploration**

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**Abstract.** In planning and in crisis, electrical power has been a key consideration when humans venture into space. Since the 1950’s, nuclear fission (splitting of atoms) power has been a logical alternative in both fact and fiction, due to its ability to provide abundant power with high energy density, reliability, and immunity to severe environments. Bringing space fission power to a state of readiness for exploration has depended on clearing the hurdle of technology readiness demonstration. Due to the happy coincidence of heritage from prior space fission development efforts such as the Prometheus program, foresight from NASA’s Exploration Mission Systems Directorate in the mid-2000’s, and relative budget stability through the late 2000’s, NASA and DOE, with their industry partners, are poised to push through to this objective. Hardware for a 12 kWe non-nuclear Fission Power System Technology Demonstration Unit is being fabricated now on a schedule that will enable a low-cost demonstration of technology readiness in the mid-2010s, with testing beginning as early as 2012. With space fission power system technology demonstrated, exploration mission planners will have the flexibility to respond to a broad variety of missions and will be able to provide abundant power so that future explorers will, in planning or crisis, have the power they need when they most need it.

## **EXTENSIBILITY OF THE FISSION SURFACE POWER (FSP) SYSTEM FROM THE MOON TO MARS**

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**Abstract** – Fission reactors have great near-term potential to power human and robotic missions/outposts on the surface of the Moon and Mars (and potentially other planets, moons, and asteroids). The ability to provide a power-rich environment that is independent of solar intensity, nights, dust storms, etc., is of significant (perhaps enabling) importance to the further expansion of humans into our solar system. NASA's Reference Fission Surface Power (FSP) System is a 40 kWe system that has been primarily designed for lunar applications. This paper examines the extensibility of the FSP design and technology for potential missions on Mars. Possible impacts include the effects of changes in heat sink, gravity, day-night cycles, mission transit time, communication delay, and the chemistry of the regolith and atmosphere. One of the biggest impacts might be differences in the potential utilization of in-situ materials for shielding. Another major factor is that different missions will likely require different performance requirements, e.g. power, lifetime and mass. This paper concludes that the environmental differences between potential mission locations will not require significant changes in design and technologies, unless performance requirements for a specific mission are substantially different than those adopted for the FSP. The primary basis for this conclusion is that the FSP has been designed with robust materials and design margins.



## A Small Fission Power System for NASA Planetary Science Missions

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**Abstract.** In March 2010, the Decadal Survey Giant Planets Panel (GPP) requested a short-turnaround study to evaluate the feasibility of a small Fission Power System (FPS) for future unspecified National Aeronautics and Space Administration (NASA) science missions. FPS technology was considered a potential option for power levels that might not be achievable with radioisotope power systems. A study plan was generated and a joint NASA and Department of Energy (DOE) study team was formed. The team developed a set of notional requirements that included 1-kW electrical output, 15-year design life, and 2020 launch availability. After completing a short round of concept screening studies, the team selected a single concept for concentrated study and analysis. The selected concept is a solid block uranium-molybdenum reactor core with heat pipe cooling and distributed thermoelectric power converters directly coupled to aluminum radiator fins. This paper presents the preliminary configuration, mass summary, and proposed development program.

# Fission Surface Power System Power Control Strategies<sup>\*</sup>

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**Abstract.** The Fission Surface Power System has been developed to a conceptual level, and strategies employed to control reactor power are under investigation. Approximately 1% of the 93% enriched UO<sub>2</sub> fuel core fissions during the eight year mission. To maintain constant reactor power, control drums are used to rotate neutron absorbing material away from the core to compensate for the reactivity loss due to burn-up. Three power control strategies to compensate for this decrease in reactivity were analyzed. The trade-offs among the strategies include the total drum rotation until criticality, the drum step size required to compensate for fuel burn-up, and the ability for drum configurations to respond to drum failures. Drum shifting during operation was also analyzed, and the results show that the system will remain subcritical in the event of all six drums shifting 2 mm during the all-drums-in configuration; however, this can result in up to \$1 of reactivity insertion. A power control strategy that uses one set of drums positioned before the region of peak sensitivity and another beyond it is recommended as the baseline for further evaluation since it offers a balance of increased step size and the ability for the system to respond to credible drum failures. The minimum step size is ~0.50°, which is well within the preliminary drum-positioning calculations, which show precision to ~0.1°. This strategy allows the system to maintain criticality despite single and multiple drum failures occurring after criticality is reached, without sacrificing drum step size. A drum-exercising algorithm that could exercise the drums every two weeks to ensure end-of-life drum mobility works with this strategy and is recommended for further investigation.

## Advanced High Temperature Bulk Thermoelectric Materials

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**Abstract.** Proven state-of-practice Si<sub>0.8</sub>Ge<sub>0.2</sub> alloys have a combined dimensionless figure of merit (ZT) value of only 0.55 when averaged over operating temperatures of 1275 K to 575 K. We present an overview of collaborative research efforts to identify and characterize advanced bulk thermoelectric materials capable of tripling average ZT values while maintaining reliable operation for more than 15 years at temperatures up to 1300 K. The first research area concerns two families of very low lattice thermal conductivity refractory rare earth compounds, based on n-type La<sub>3-x</sub>Te<sub>4</sub> and p-type Yb<sub>14</sub>MnSb<sub>11</sub>. We report on recent experimental results, guided by first principle electronic structure calculations, in tuning the properties of these rare earth compounds through suitable chemical substitutions and discuss the potential of other refractory Zintl for high ZT values. The other main research area focuses on synthesizing on engineering established thermoelectric materials such as Si-Ge alloys, PbTe and skutterudites by forming bulk homogenous and composite 3-D nanostructures. Such materials present orders of magnitude increases in the density of interfaces, thus scattering phonons very effectively and leading to very large reductions in lattice thermal conductivity values. Other mechanisms leading to significant improvements in electrical properties are also discussed. An assessment of the maturity of selected materials for potential integration into high efficiency long life thermoelectric couples is presented.

## The Scanning Seebeck Coefficient technique for detecting inhomogeneities in thermoelectric materials

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**Abstract.** The thermoelectric power generation technology has been utilized in the Radioisotope Thermoelectric Generator since their first use in the spacecraft developed in the 60's. Several types of doped PbTe and GeTe (TAGS) materials have been developed for use on NASA missions. Since then, various new types of materials have been developed for devices with the higher efficiency. For quality and further improvement in the device level, the homogeneity of thermoelectric properties in the fabricated sample becomes critical. However, traditional processing techniques including solidification often introduce inhomogeneity in materials compositions or defects throughout the sample, causing local variations in the thermoelectric properties. When these variations are in the range of sub-mm scale, they are difficult to be detected by traditional materials characterization techniques such as the x-ray diffraction and the scanning electron microscopy. In this project, the scanning apparatus was built to directly detect local variations of the Seebeck coefficient on the sample. The two dimensional mapping of the Seebeck coefficient on the bulk and thin film samples are demonstrated. These results show that this technique can be utilized for detection of defective regions, as well as phase separations in the sub-mm range.

## High Temperature Couple Development for the Advanced Thermoelectric Converter (ATEC) Project

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**Abstract.** Recent advances in several high temperature thermoelectric materials enable the development of significantly higher efficiency couples, relative to heritage technology, for potential application to advanced Radioisotope Thermoelectric Generators (RTGs). The best conversion efficiencies can be achieved by combining several advanced materials, rare earth compounds and filled skutterudites, into a segmented couple configuration. The ATEC project is focused on the development, fabrication and testing of power generating couples that incorporate these improved thermoelectric materials. Some of the challenges currently faced in developing high reliability, long life components include the scale-up fabrication of thermoelectric leg segments, processing of thermally stable and mechanically compliant leg metallizations and segment bonds/interfaces. The current roadmap to the development of an advanced thermoelectric converter will be presented as well as progress to date in resolving some of these key challenges.

## Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) Engineering Unit (EU) Testing

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**Abstract.** Long-term reliable performance is the key attribute of Radioisotope Thermoelectric Generators (RTGs). The multi-mission RTG (MMRTG) is the most robust, mission flexible RTG yet developed, capable of operating in both planetary surface environments and deep space vacuum. The MMRTG is based on the time-proven SNAP 19 TE couple modified to address current spacecraft power system requirements. To demonstrate the new design could meet all of the multi-mission requirements and to assist in predicting the long term performance of the newly developed MMRTG, a high fidelity MMRTG Engineering Unit (EU) was built, fully tested and put on life test. Testing included electrical performance over the operational range of fin root temperatures and load voltages, operation in a thermal vacuum chamber, magnetics, vibration and shock. The characterization and acceptance testing was fully successful as has been the life testing. The EU life test results have proven to be extremely useful in that they provide the basis for the MMRTG fueled unit life performance model.

## Calculation of Kinetics Parameters for the Affordable Fission Surface Power Reference Design

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**Abstract.** This paper explores methods used to generate kinetics parameters for the Affordable Fission Surface Power System (AFSPS) reference design. The primary focus of the study is to determine the level of sophistication necessary to characterize the nuclear performance of the system in support of the technology demonstration unit (TDU), a non-nuclear system test. The calculated component-level temperature defects, reactivity temperature coefficients (RTCs) and control drum worth will form the basis of a suite of transient simulations, intended to identify differences in prediction of system-limiting parameters (e.g. peak component temperatures). Calculations were performed in MCNP51 using input decks created by MRFLOW<sup>2</sup>. Temperature defect and reactivity coefficients account for both thermal expansion and cross section effects (Doppler and scattering) in the radial reflector, fuel, fuel clad, and core support structure, while control drum worths are examined for a variety of possible operational schemes. These kinetics parameters are then used with the transient analysis tool FRINK in determining key component temperatures for several operational transients

## Design and Test of Advanced Thermal Simulators for an Alkali Metal-Cooled Reactor Simulator

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**Abstract.** The Early Flight Fission Test Facility (EFF-TF) at NASA Marshall Space Flight Center (MSFC) has as one of its primary missions the development and testing of non-nuclear fission reactor simulators for space applications. A key component in these simulated reactors is the thermal simulator, designed to closely mimic the form and function of a nuclear fuel pin using electric heating. Continuing effort has been made to design simple, robust, inexpensive thermal simulators that closely match the steady-state performance of a nuclear fuel pin. A series of these simulators have been designed, developed, fabricated and tested in a number of simulated reactor systems at the EFF-TF. The development of such thermal simulators ensures that non-nuclear testing can be performed at sufficiently high fidelity to allow a cost-effective qualification and acceptance strategy to be used. Recent efforts have culminated in the fabrication of simulators with power capacities of 2300-3000 W per unit. Six of these simulators were installed in a representative core element (the 7-pin bundle) and tested in the alkali metal-cooled Fission Surface Power Primary Test Circuit (FSP-PTC) over a range of liquid metal flow rates and temperatures.



## Design and Build of Reactor Simulator for Fission Surface Power Technology Demonstrator Unit

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**Abstract.** The Nuclear Systems Team at Marshall Space Flight Center (MSFC) focuses on technology development for state of the art capability in non-nuclear testing of nuclear system and Space Nuclear Power for fission reactor systems for lunar and mars surface power generation as well as radioisotope power systems for both spacecraft and surface applications. Currently being designed and developed is a reactor simulator (RxSim) for incorporation into the Technology Demonstrator Unit (TDU) for the Fission Surface Power System (FSPS) Program which is supported by multiple national laboratories and NASA centers. The ultimate purpose of the RxSim is to provide heated NaK to a pair of Stirling engines in the TDU. The RxSim includes many different systems, components, and instrumentation that have been developed at MSFC while working with pumped NaK systems and in partnership with the national laboratories and NASA centers. The main components of the RxSim are a core, a pump, a heat exchanger (to mimic the thermal load of the Stirling engines), and a flow meter when being tested at MSFC. When tested at GRC the heat exchanger will be replaced with a Stirling power conversion engine. Additional components include storage reservoirs, expansion volumes, overflow catch tanks, safety and support hardware, instrumentation (temperature, pressure, flow) data collection, and power supplies. This paper will discuss the design and current build status of the RxSim for delivery to GRC in early 2012.

## System Modeling Comparisons of the Fission Surface Power (FSP) System and the FSP Technology Demonstration Unit (TDU)

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**Abstract.** The Fission Surface Power (FSP) System is a 40 kWe power source that has been primarily designed for lunar and/or Martian applications. A FSP Technology Demonstration Unit (TDU) is currently being constructed to provide non-nuclear end-to-end system testing of an FSP-like system. This testing is meant to help verify the viability of the FSP technologies and their integrated performance. One of the biggest challenges of the TDU effort has been to keep the TDU affordable and successful within a limited budget, while maintaining operating characteristics that are similar to a potential flight FSP system. This paper describes some of the TDU design decisions that were made to balance performance with cost and program risk, and how the performance of the TDU may differ from a typical flight FSP system. The system modeling code FRINK is used to model the steady-state and transient response of the FSP and TDU systems, and the results are compared and analyzed. The paper also considers what could be done to make future ground system testing more prototypic of an actual flight system.

## Saturn Ring Observer Concept Architecture Options

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**Abstract.** A study conducted in April 2010 for the 2012 Planetary Science Decadal Survey's Giant Planets Panel addressed the "Saturn Ring Observer" concept, a mission that would perform detailed, close-up observations of Saturn's rings. There were two study objectives: 1) investigate the method(s) by which such a spacecraft might be placed in a tight circular orbit around Saturn, using chemical or nuclear-electric propulsion or aerocapture in Saturn's atmosphere; and 2) identify technological developments for the next decade that would enable such a mission in the post-2023 time frame (after the next saturnian equinox), with a particular focus on power and propulsion. The "tight circular orbit" is a non-Keplerian orbit displaced 2-3 km perpendicular to the mean ring plane. A spacecraft in such an orbit would appear to "hover" over the ring particles orbiting Saturn directly "beneath" it, so the study team dubbed this the "hover orbit." Operations technologies were found to be important drivers so they were examined also. The extreme delta-V budgets (for then-known trajectories) of previous mission implementation studies made chemical propulsion implementations impractical, so they used nuclear electric propulsion (NEP) or aerocapture. The new study identified types of trajectories that would deliver a spacecraft from Saturn approach to hover orbit initiation for ~3.5 km/s delta-V, within reach of a single chemical bipropellant stage and, for some mission concepts, launch on an Atlas launch vehicle. Hover spacecraft designs using chemical engines, radioisotope electric propulsion (REP), and NEP were considered. This type of mission could use REP and possibly NEP of relatively low specific power. This paper summarizes the results of the new study.

## Trojan Tour Mission Concepts Provide Several Options For Cost-Effective Break-Through Science

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**Abstract.** As one of several dozen studies commissioned by the National Research Council (NRC)'s Planetary Decadal Survey to explore the technical readiness, feasibility and affordability of scientifically promising mission scenarios, JHU/APL (APL) helped to develop several Trojan Tour Mission concepts. The purpose of this study was to define a preferred approach along with the risk/cost trade space for a Trojan Tour Mission launched in the 2019-2023 timeframe and targeted to be within a \$1B cost cap in FY15 dollars. Trojan asteroids are unexplored science targets that share Jupiter's orbit, yet may originate from the Kuiper Belt. Principal mission science objectives included characterizing the bulk chemical composition of a Trojan asteroid surface, observing the current geologic state of the surface and infer past evolution and the relative importance of surface processes, characterizing the bulk physical properties and interior structure of a Trojan asteroid, and searching for or constraining outgassing from subsurface volatiles. Two nuclear powered mission concepts were developed to assess the feasibility of a mission with one or more flybys of Trojan asteroids before an extended rendezvous with a different Trojan asteroid. The concepts included one with chemical propulsion and two ASRGs for power, while the other was a Radioisotope Electric Propulsion (REP) design with six ASRGs for power and electric propulsion. The ballistic trajectory option allowed the full payload to be carried on an Atlas V 411 for the ASRG concept, with a cruise time of 10 years. The REP trajectory option allowed the full payload to be carried on an Atlas V 431 with a cruise time of 8 years. Both concepts achieved the science objectives at a primary target asteroid with one or more flybys prior to the rendezvous. While specific flyby targets were not defined, both the ballistic and electric propulsion trajectory designs allowed for sufficient time in the "Trojan cloud" prior to the primary rendezvous to be statistically confident one or more flybys are achievable. Both the chemical ASRG concept and REP concept enabled potential secondary science objectives such as landing. The REP concept could possibly support advancing to a second asteroid rendezvous; an identified second target was achievable with typical resource margins (>30%), but not within the study mandated margins (≥43%). The chemical ASRG concept was selected by the panel as the point design to present in detail and cost, since it met all of the study objectives while minimizing risk and technical complexity. There is no guarantee that this mission or any of the other missions studied will appear in the decadal survey's final list of priorities. The study was conducted by a team led by Mike Brown with members of the Primitive Bodies Panel working with the APL Space Department as the design center. NASA Glenn Research Center's COMPASS team made significant contributions as part of the design team in the areas of Mission Design, REP concept development, and ASRG performance.

## Joint Radioisotope Electric Propulsion Studies – Neptune System Explorer

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**Abstract.** The Neptune System Explorer (NSE) mission concept study assessed opportunities to conduct Cassini-like science at Neptune with a radioisotope electric propulsion (REP) based spacecraft. REP is based on powering an electric propulsion (EP) engine with a radioisotope power source (RPS). The NSE study was commissioned under the Joint Radioisotope Electric Propulsion Studies (JREPS) project, which sought to determine the technical feasibility of flagship class REP applications. Within JREPS, special emphasis was given toward identifying tall technology tent poles, as well as recommending any new RPS technology developments that would be required for complicated REP missions. Based on the goals of JREPS, multiple RPS (e.g. thermoelectric and Stirling based RPS) and EP (e.g. Hall and ion engines) technology combinations were traded during the NSE study to determine the most favorable REP design architecture. Among the findings from the study was the need for >400W<sub>e</sub> RPS systems, which was driven by EP operating powers and the requirement for a long-lived mission in the deep solar system. Additionally multiple development and implementation risks were identified for the NSE concept, as well as REP missions in general. Among the strengths of the NSE mission would be the benefits associated with RPS and EP use, such as long-term power (~2-3kW) at Neptune and flexible trajectory options for achieving orbit or tours of the Neptune system. Although there are still multiple issues to mitigate, the NSE concept demonstrated distinct advantages associated with using REP for deep space flagship-class missions.

## Uranus Mission Concept Options

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**Abstract.** As one of several studies commissioned by the National Research Council's Planetary Decadal Survey to explore the technical readiness, feasibility and affordability of scientifically promising mission scenarios, JHU/APL helped to develop several Uranus Mission concepts. This study defined a preferred approach within the risk/cost trade space for a Uranus Mission to be launched in 2020–2023 within a cost range of \$1.5B–\$1.9B in FY15\$. Initial energy trades identified Uranus as a more accessible target and a lower risk ice giant mission option than Neptune within the specified launch time frame. A low-thrust solar electric propulsion trajectory option was developed to Uranus based on a single Earth gravity assist that could be repeated every year with a 21-day launch window. Launching on an Atlas V 531 and allowing a 13-year cruise time, a mission concept was developed that could accommodate both the floor and enhanced orbiter payload, perform atmospheric science with a fully equipped shallow entry probe, and perform multiple targeted flybys of each of the five Uranian satellites. No new technology is required with the exception of continued development of large parasol solar arrays (similar to those being developed for Orion) to power the solar electric propulsion stage, and the completion of the development of the Advanced Stirling Radioisotope Generator. Overall, the study has developed a concept that can achieve very robust science at Uranus at a cost below flagship mission levels and with minimal required technology development. Significant descope options are available to ensure that the mission is affordable. The study was conducted by a team directed by Dr. William Hubbard with members of both the Giant Planets and Satellites Panels working with the JHU/APL Space Department as the design center. Other team members included NASA Glenn Research Center's COMPASS team for the cruise portion of mission design and the solar electric propulsion stage concept; NASA Langley Research Center for entry probe descent trajectory analysis; and Georgia Institute of Technology for Uranus satellite tour trajectory development.

## Kuiper Belt Object Orbiter Using Advanced Radioisotope Power Sources and Electric Propulsion

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**Abstract.** A joint NASA GRC / JPL design study was performed for the NASA Radioisotope Power Systems Office to explore the use of radioisotope electric propulsion for flagship class missions. The Kuiper Belt Object Orbiter is a flagship class mission concept projected for launch in the 2030 timeframe. Due to the large size of a flagship class science mission larger radioisotope power system 'building blocks' were conceptualized to provide the roughly 4 kW of power needed by the NEXT ion propulsion system and the spacecraft. Using REP the spacecraft is able to rendezvous with and orbit a Kuiper Belt object in 16 years using either eleven 420 W advanced RTGs or nine (includes a spare) 550W advanced Stirling Radioisotope systems. The design study evaluated integrating either system and estimated impacts on cost as well as required General Purpose Heat Source requirements.

# Hyperthermal Environments Simulator for Nuclear Rocket Engine Development

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**Abstract.** An arc-heater driven hyperthermal convective environments simulator was recently developed and commissioned for long duration hot hydrogen exposure of nuclear thermal rocket materials. This newly established non-nuclear testing capability uses a high-power, multi-gas, wall-stabilized constricted arc-heater to produce high-temperature pressurized hydrogen flows representative of nuclear reactor core environments, excepting radiation effects, and is intended to serve as a low-cost facility for supporting non-nuclear developmental testing of high-temperature fissile fuels and structural materials. The resulting reactor environments simulator represents a valuable addition to the available inventory of non-nuclear test facilities and is uniquely capable of investigating and characterizing candidate fuel/structural materials, improving associated processing/fabrication techniques, and simulating reactor thermal hydraulics. This paper summarizes facility design and engineering development efforts and reports baseline operational characteristics as determined from a series of performance mapping and long duration capability demonstration tests. Potential follow-on developmental strategies are also suggested in view of the technical and policy challenges ahead.



## **An Overview of Facilities and Capabilities to Support the Development of Nuclear Thermal Propulsion**

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**Abstract.** The future of American space exploration depends on the ability to rapidly and economically access locations of interest throughout the solar system. There is a large body of work (both in the U.S. and the Soviet Union) that show that Nuclear Thermal Propulsion (NTP) is the most technically mature, advanced propulsion system that can enable this rapid and economical access by its ability to provide a step increase above what is feasible using a traditional chemical rocket system. For an NTP system to be deployed, the earlier measurements and recent predictions of the performance of the fuel and the reactor system need to be confirmed experimentally prior to launch. Major fuel and reactor system issues to be addressed include fuel performance at temperature, hydrogen compatibility, fission product retention, and restart capability. The prime issue to be addressed for reactor system performance testing involves finding an affordable and environmentally acceptable method to test a range of engine sizes using a combination of nuclear and non-nuclear test facilities. This paper provides an assessment of some of the capabilities and facilities that are available or will be needed to develop and test the nuclear fuel and reactor components. It will also address briefly options to take advantage of the great improvement in computation/simulation and materials processing capabilities that would contribute to making the development of an NTP system more affordable.

## NERVA-Derived and CERMET Concepts for a Bimodal Nuclear Thermal Rocket - An Update

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**Abstract.** The Nuclear Thermal Rocket (NTR) is an enabling technology for space exploration missions. The “bimodal” NTR (BNTR) provides a novel approach to meeting both propulsion and power requirements of future manned and robotic missions. The purpose of this paper is to provide information on in-core cooling path configurations for power generation, BNTR performance, Brayton cycle description, and Liquid Oxygen (LOX)-Augmented BNTR (LAB NTR) capability to arrive at state-of-the-art BNTR configurations for subsequent system definition.

**Laser Simulated Re-entry Oxidation Experiments on Possible Replacement  
Materials for FWPF in  $^{238}\text{PuO}_2$  Fueled Space Power Systems**

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**Abstract.** Deep space planetary exploration missions (i.e. Galileo/Jupiter, Cassini/Saturn, New Horizons/Pluto) rely on thermal to electrical conversion power systems built by the DOE and employed by NASA. These power systems utilize the heat released from the decay of the radioisotope plutonium-238 to generate all of the electrical power for the spacecraft. The encapsulated plutonium-238 dioxide fuel pellets are encased within several layers; with the outer layer being a carbon based Fine Weave Pierced Fabric (FWPF) aeroshell that is designed to thermally ablate and partially protect the encapsulated fuel in the event of an inadvertent launch abort or accident scenario. Several candidate materials have been identified as possible replacements for the baseline FWPF material. First-order high-temperature reentry oxidation simulation experiments have been initiated employing high power lasers at the Air Force's Laser Hardened Materials Evaluation Laboratory (LHMEL). Comparison of the simulated reentry oxidation characteristics of the new materials directly with FWPF on a first-order basis has been obtained and the results of the evaluations will be discussed.

## Alternative Radioisotopes for Heat and Power Sources

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**Abstract.** Production of  $^{238}\text{Pu}$  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. There are many alternative radioisotopes that exist but few that satisfy the criteria of performance, availability and cost to produce. Any alternative to  $^{238}\text{Pu}$  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.

This paper will focus on the preferred European alternative of  $^{241}\text{Am}$ , and the issues that will need to be addressed.

## Tritium Based Radioisotopic Thermoelectric Generators

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**Abstract.** The Tritium Thermoelectric Generator, currently under development at Sandia National Laboratories, provides a compact non-<sup>238</sup>Pu long life, milliwatt power source to our customers. The tritium, used as the heat source, is stored in a stable titanium solid bed contained within a thin walled vessel. In order to minimize volume, a low emissivity vacuum jacket was developed to operate efficiently with minimal conductive heat loss. Additionally, a vacuum compatible thermoelectric module was fabricated that resides within the vacuum to minimize parasitic heat loss. A high efficiency voltage converter was developed to boost the output voltage to 3.3V. Subcomponents of the vacuum isolation, thermoelectric module, upconverter, and the tritium heat source have been fabricated and tested. Additionally, FEM analysis of the design was performed for both thermal transport and mechanical response and validated against measured performance on assembled prototypical systems.

# Performance of a Kilowatt-Class Stirling Power Conversion System in a Thermodynamically Coupled Configuration

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**Abstract.** A pair of 1-kWe free-piston Stirling power convertors has been modified into a thermodynamically coupled configuration, and performance map testing has been completed. This is the same configuration planned for the full-scale 12-kWe power conversion unit (PCU) that will be used in the Fission Power System Technology Demonstration Unit (TDU). The 1-kWe convertors were operated over a range of conditions to evaluate the effects of thermodynamic coupling on convertor performance and to identify any possible control challenges. The thermodynamically coupled convertor showed no measureable difference in performance from the baseline data collected when the engines were separate, and no major control issues were encountered during operation. The results of this test are guiding controller development and instrumentation selection for the TDU.

## Transient Response to Rapid Cooling of a Stainless Steel Sodium Heat Pipe

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**Abstract.** Compact fission power systems are under consideration for use in long duration space exploration missions. Power demands on the order of 500 W<sub>e</sub> to 5 kW<sub>e</sub> will be required for up to 15 years of continuous service. One candidate small reactor design consists of a fast spectrum reactor cooled with an array of in-core alkali metal heat pipes coupled to thermoelectric or Stirling power conversion systems. Heat pipe advantageous attributes include a simplistic design, lack of moving parts, and well understood behavior. Concerns over reactor transients induced by heat pipe instability as a function of extreme thermal transients require experimental investigation. One particular concern is rapid cooling of the heat pipe condenser that would propagate to cool the evaporator. Rapid cooling of the reactor core beyond acceptable design limits could possibly induce unintended reactor control issues. This paper discusses a series of experimental demonstrations where a heat pipe operating at near prototypic space reactor conditions experienced rapid cooling of the condenser. The condenser section of a stainless steel sodium heat pipe was enclosed within a heat exchanger. The heat pipe – heat exchanger assembly was housed within a vacuum chamber held at a pressure of 50 Torr of helium. The heat pipe was brought to steady-state operating conditions using graphite resistance heaters then cooled by a high flow of gaseous nitrogen through the heat exchanger. Subsequent thermal transient behavior was characterized by performing an energy balance using temperature, pressure and flow rate data obtained throughout the tests. Results indicate the degree of temperature change that results from a rapid cooling scenario will not significantly influence thermal stability of an operating heat pipe, even under extreme condenser cooling conditions.

## Experimental Studies of NaK in a Simulated Space Environment

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**Abstract.** Space fission power systems are being developed at the National Aeronautics and Space Administration (NASA) and Department of Energy (DOE) with a short term goal of building a full scale, non-nuclear, Technology Demonstration Unit (TDU) test at NASA's Glenn Research Center. Due to the geometric constraints, mass restrictions, and fairly high temperatures associated with space reactors, liquid metals are typically used as the primary coolant. A eutectic mixture of sodium (22 percent) and potassium (78 percent), or NaK, has been chosen as the coolant for the TDU with a total system capacity of approximately 55L. NaK, like all alkali metals, is very reactive, and warrants certain safety considerations. To adequately examine the risk associated with the personnel, facility, and test hardware during a potential NaK leak in the large scale TDU test, a small scale experiment was performed in which NaK was released in a thermal vacuum chamber under controlled conditions. The study focused on detecting NaK leaks in the vacuum environment as well as the molecular flow of the NaK vapor. This paper reflects the work completed during the NaK experiment and provides results and discussion relative to the findings.



## Design and Test Plans for a Non-Nuclear Fission Power System Technology Demonstration Unit

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**Abstract.** A joint National Aeronautics and Space Administration (NASA) and Department of Energy (DOE) team is developing concepts and technologies for affordable nuclear Fission Power Systems (FPSs) to support future exploration missions. A key deliverable is the Technology Demonstration Unit (TDU). The TDU will assemble the major elements of a notional FPS with a non-nuclear reactor simulator (Rx Sim) and demonstrate system-level performance in thermal vacuum. The Rx Sim includes an electrical resistance heat source and a liquid metal heat transport loop that simulates the reactor thermal interface and expected dynamic response. A power conversion unit (PCU) generates electric power utilizing the liquid metal heat source and rejects waste heat to a heat rejection system (HRS). The HRS includes a pumped water heat removal loop coupled to radiator panels suspended in the thermal-vacuum facility. The basic test plan is to subject the system to realistic operating conditions and gather data to evaluate performance sensitivity, control stability, and response characteristics. Upon completion of the testing, the technology is expected to satisfy the requirements for Technology Readiness Level 6 (System Demonstration in an Operational and Relevant Environment) based on the use of high-fidelity hardware and prototypic software tested under realistic conditions and correlated with analytical predictions.

## Feasibility Study of a Three-Stage Radioisotope-Powered Mars Ascent Vehicle

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**Abstract.** To date, analysis of Martian samples has been limited to on-location testing due to the high cost of delivering mass to Mars and the lack of sufficiently efficient return vehicles. In order to make sample return missions feasible and enable more in-depth, adaptive analysis it is paramount that lightweight, efficient transfer vehicles be developed. Recent advancements in methods of housing radioisotopes at the Center for Space Nuclear Research have led to the concept of a radioisotope thermal rocket—a rocket powered by the accumulated heat of radioisotope decay. Heat energy from the decay can be accumulated over long periods of time in a material of high heat capacity to create a thermal capacitor. The capacitor can then be discharged at such a rate as to provide high power for short periods of time; in this case, the heat is transferred to a gas propellant. This paper explores the feasibility of using a radioisotope thermal rocket with in-situ atmospheric CO<sub>2</sub> propellant to deliver a 10 kg payload from the Martian surface to a 200 km circular orbit about Mars. Models of heat transfer, gas dynamics, and ascent mechanics are constructed to test performance of different core materials and geometries. Of the configurations tested, the best simulation results fail to meet the altitude and velocity requirements by 12 km and 50 m/s respectively. The proximity to success indicates that the given models are capable of reaching orbital parameters if optimization algorithms and closed-loop guidance methods are employed. It is believed, however, that the current models underestimate expansion losses to the degree that if more realistic and computationally-intensive models are incorporated, the effect will definitively disprove the concept with currently available technology. Based on this preliminary research, radioisotope thermal rockets utilizing current technology are not capable of serving as Mars ascent vehicles.

# Preliminary Mission Architecture for Mars Sample Return Utilizing Nuclear Thermal Rockets

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**Abstract.** A Mars Sample Return mission could serve the dual purpose of providing invaluable information about the Martian environment and the possibility of life while also flight testing propulsion technology that has been deemed ‘enabling’ for future manned missions. This paper poses a mission architecture that utilizes nuclear thermal rockets to retrieve Martian samples. The proposed craft could be used in conjunction with the Mars Hopper platform being developed by the Center for Space Nuclear Research. The use of in-situ propellants reduces the mass needed in LEO to a level at which a single Atlas V HLV could perform the launch of the entire craft. This study proposes a basic craft design, mission timeline, and mass budget for a craft that would be capable of returning 100kg of Martian samples to Earth.

## In-Situ Missions for the Exploration of Titan's Lakes

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**Abstract.** The lakes of Titan represent an increasingly tantalizing target for future exploration. As Cassini continues to reveal more details the lakes appear to offer a particularly rich reservoir of knowledge that could provide insights to Titan's formation and evolution, as well as an ideal location to explore Titan's potential for pre-biotic chemistry. A recent study of Titan Lake Probe missions was undertaken as one of several dozen studies commissioned by the National Research Council (NRC) Planetary Decadal Survey to explore the technical readiness, feasibility and affordability of scientifically promising mission scenarios. This in-depth study focused on an in-situ examination of a hydrocarbon lake on the Saturnian moon Titan—a target that presents unique scientific opportunities as well as several unique engineering challenges (e.g., submersion systems and cryogenic sampling) to enable those measurements. Per direction from the NRC Planetary Decadal Survey Satellites Panel, and after an initial trade-space examination, study architectures focused on three possible New Frontiers-class missions and a more ambitious Flagship-class lander intended as the in-situ portion of a larger collaborative mission. Detailed point designs were developed to explore these four potential mission options, including consideration of flight system and mission designs, as well as operations on and under the lake's surface and scenarios for data return. In this paper we present an overview of the science objectives of the missions, the mission architecture and surface element trades, and the detailed point designs chosen for in-depth analysis.

## Fusion Power Sources for Mars Exploration

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**Abstract.** A fundamental need for Mars colonization is an abundant source of energy for local utilities, manufacturing, waste treatment and terraforming. Two fusion nuclear power units, the Inertial Electrostatic Confinement (IEC) fusion torch and small Low Energy Nuclear Reaction (LENR) power units, have unique capabilities for such use. Most of the resources that are needed by these two power units exist on Mars. This allows construction and operation of these units directly on Mars, greatly reducing transportation costs. The IEC device would provide a central unit in 500 kWe - 1 MWe size; LENR units would serve as portable sources ranging from Ws to kW. To start colonization, an IEC fusion torch would produce super greenhouse gases to warm up the planet, plus producing oxygen and nitrogen for breathable air, by decomposing and recombining materials in the ultra hot IEC fusion torch plasma. The first IEC power plant, LENR power unit and some robotics would be brought from earth. Robots powered by LENR units would perform iron mining for use by an IEC plasma torch in steel making and carrying out self-reproducing production of more power plants.

# Thermal-hydraulics analysis of a radioisotope-powered Mars Hopper propulsion system

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**Abstract.** *Thermal-hydraulics analyses results produced using a combined suite of computational design and analysis codes are presented for the preliminary design of a concept Radioisotope Thermal Rocket (RTR) propulsion system. Modeling of the transient heating and steady state temperatures of the system is presented. Simulation results for propellant blow down during impulsive operation are also presented. The results from this study validate the feasibility of a practical thermally capacitive RTR propulsion system.*

# Exergy Analysis of Two Proposed Mars Hopper Propulsion Configurations

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**Abstract.** Exergy analysis, or availability, is a way to measure the usefulness of the energy within a system. This paper presents an exergy analysis of two proposed Mars Hopper designs. The Mars Hopper needs to compress the Martian atmospheric gases (primarily carbon dioxide) into a storage tank, and at a later time, release the stored fluid through a nozzle in order to “hop” to a new location on the planet. A radioisotopic heater provides a heat addition to the captured fluid as well as powers the on-board instrumentation using a power cycle. The first model examines the Mars Hopper designed with the heater external to the carbon dioxide storage tank. The compressed two-phase carbon dioxide flows from the storage tank, through the radioisotopic heater, into a plenum and out the nozzle. The second model analyzes the Mars Hopper designed with the same heater inside the carbon dioxide storage tank. The heater remains inside the pressure tank, which keeps the carbon dioxide completely in its gaseous phase, and the gaseous carbon dioxide then exits the pressure tank directly into the nozzle. In both systems, the same amount of carbon dioxide is compressed from atmospheric conditions to a maximum pressure before its release through the nozzle. This analysis shows the second model uses energy from the radioisotopic heater more efficiently.

## **The Mars Hopper: a radioisotope powered, impulse driven, long-range, long-lived mobile platform for exploration of Mars**

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**Abstract.** Planetary exploration mission requirements are becoming more demanding. Due to the increasing cost, the missions that provide mobile platforms that can acquire data at multiple locations are becoming more attractive. Wheeled vehicles such as the MER rovers have proven extremely capable but have very limited range and cannot traverse rugged terrain. Flying vehicles such as balloons and airplanes have been proposed but are problematic due to the very thin atmospheric pressure and the strong, dusty winds present on Mars. The Center for Space Nuclear Research has designed an instrumented platform that can acquire detailed data at hundreds of locations during its lifetime - a Mars Hopper. The Mars Hopper concept utilizes energy from radioisotopic decay in a manner different from any existing radioisotopic power sources—as a thermal capacitor. By accumulating the heat from radioisotopic decay for long periods, the power of the source can be dramatically increased for short periods. The platform will be able to “hop” from one location to the next every 5-7 days with a separation of 5-10 km per hop. Preliminary designs show a platform that weighs around 52 kgs unfueled which is the condition at deployment. Consequently, several platforms may be deployed on a single launch from Earth. With sufficient lifetime, the entire surface of Mars can be mapped in detail by a couple dozen platforms. In addition, Hoppers can collect samples from all over the planet, including gorges, mountains and crevasses, and deliver them to a central location for eventual pick-up by a Mars Sample Return mission. The status of the Mars Hopper development project at the CSNR will be discussed.



# A Small Fission Power System With Stirling Power Conversion for NASA Science Missions

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**Abstract.** In early 2010, a joint National Aeronautics and Space Administration (NASA) and Department of Energy (DOE) study team developed a concept for a 1 kWe Fission Power System with a 15-year design life that could be available for a 2020 launch to support future NASA science missions. The baseline concept included a solid block uranium-molybdenum reactor core with embedded heat pipes and distributed thermoelectric converters directly coupled to aluminum radiator fins. A short follow-on study was conducted at NASA Glenn Research Center (GRC) to evaluate an alternative power conversion approach. The GRC study considered the use of free-piston Stirling power conversion as a substitution to the thermoelectric converters. The resulting concept enables a power increase to 3 kWe with the same reactor design and scalability to 10 kW without changing the reactor technology. This paper presents the configuration layout, system performance, mass summary, and heat transfer analysis resulting from the study.

## Space Nuclear Power & Propulsion Heritage

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**Abstract.** Rocketdyne has a rich heritage in the development of space nuclear fission power and propulsion technologies through its involvement in most of the past U.S. space nuclear power reactor development programs such as SNAP 10A, SP-100, Multi-MegaWatt, S-PRIME thermionic, Prometheus, JIMO, Fission Surface power systems and more recent work in the Sub-kilowatt Reactor EPS. Hamilton Sundstrand-Rocketdyne's involvement in radioisotope power system (RPS) began with the development of the Dynamic Isotope Power System (DIPS) program in 1988 and continued on with the Advanced Stirling Converter development, Multi-Mission RTG development and Advanced RTG studies for the ATEC program. This experience spans more than 50 years in the design, system engineering integration and testing of the space nuclear electrical power systems. In addition, Pratt & Whitney Rocketdyne designed the Phoebus nozzles and LH2 feed systems for the Rover and Nuclear Engine for Rocket Vehicle Application (NERVA) Programs which demonstrated Nuclear Thermal Rocket (NTR) technologies. In the 1990s, Pratt & Whitney Rocketdyne, working with NASA, developed designs for a Bimodal Nuclear Thermal Propulsion (NTP) unit for the joint production of electrical power and thrust from the single reactor unit.

## Sub-Kilowatt Class Fission Heat Source Thermoelectric Power Study

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**Abstract.** Two fission heat-source thermoelectric power system concepts were developed based on a heat pipe-cooled solid core reactor (HPCR) concept and a liquid metal-cooled reactor (LMCR) concept. Thermoelectric (TE) materials, developed under the Advanced Thermoelectric Converter (ATEC) program at the Jet Propulsion Laboratory, were used to evaluate each thermoelectric converter concept for performance at a nominal 1.0 kW power level. A comparative analysis was performed of the two system concepts based on the assumption that some of the required attenuation of the neutron and gamma dose at the payload dose plan would be provided by the power systems' primary shield assembly and the remainder would be provided by the mass structure and chemical propulsion propellant tanks of the spacecraft. Based on this scenario, the specific power of the HPCR system was estimated to be 1.44 W/kg versus the LMCR system result of 1.76 W/kg. The LMCR TE power system concept was evaluated for its system mass over the 0.5 kW to 5 kW range. These values were then used in a comparison of the radioisotope power system (or RPS) mass estimates for a typical mission such as the Jupiter Europa Orbiter (JEO). A 600 W beginning-of-mission power supply was used as the basis in the comparison of spacecraft mass impacts for switching to a fission heat-source thermoelectric power supply. The best estimate of spacecraft mass impact was roughly a 400 kg mass increase to replace the radioisotope power system with a fission heat source power supply.

However, if high-efficiency electric thrusters using xenon propellants, and powered by a 5 kW fission heat-source power supply, were substituted for a storable chemical propulsion system and the RPS, then a ten-to-fifteen percent reduction in spacecraft mass could be achieved on a JEO-type orbiter mission to the outer planets. These very preliminary results suggest that a nuclear electric propulsion and power supply (NEP&PS) unit may be a viable option for this type of NASA mission.

# The Design and Development of a 12 kW<sub>e</sub> Stirling Power Conversion Unit for Fission Power Technology Demonstration

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**Abstract.** This paper describes the design and development status of 12 kW<sub>e</sub> opposed Stirling Power Conversion Unit (PCU) for potential use in a fission power technology demonstration. The design is based on a mechanically simple and proven engine arrangement. Heating is provided by a pumped NaK loop and the unit utilizes a stainless steel heater head. Heat rejection is to a pumped water loop. Efficiency (AC out/ heat in) is projected at 27% for the convertor which operates at a temperature ratio of 2.3.

# Self-Fueling Fusion Hybrid Reactor For Space Power and Propulsion

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**Abstract.** A fusion hybrid reactor whose fusion component is the Gravitational Dynamic Mirror (GDM) is presented as a potential energy source for utilization in space exploration. Such a reactor will consist of a fusion component whose primary function is to supply neutrons to a surrounding blanket containing fertile material where they will breed fissile material and simultaneously burn it to produce power. Since the primary function of the fusion component is to supply high energy neutrons, it can operate at or near “breakeven” condition, a much less stringent condition than that required for a pure fusion power reactor. Since the GDM is a linear, cylindrically symmetric plasma confinement device that can operate in steady state, we find it particularly suitable for utilization as the fusion component of the proposed hybrid reactor. Moreover, a large aspect ratio GDM is desirable from the standpoint of MHD stability and that in turn allows us to treat the system as semi-infinite, and to employ two, one-dimensional equations to assess the power producing capability of the system: one that describes the time evolution of the density of uranium-233 that is being bred and burned in a thorium-232 blanket, and another that describes the transport of the 14.1 MeV neutrons generated by DT reactions in the GDM and radially impinging on the thorium blanket. We find that for a reasonable design, such a reactor can produce several gigawatts of power per cm “safely” since it will operate as a “subcritical” system. When utilized for propulsion applications we find that it can generate a specific impulse of about 17,000 seconds at a thrust of about 29 meganewtons: a propulsion capability that can readily open the solar system to human exploration.

## Fusion Space Propulsion using Fast-Ignition Inertial Confinement Fusion (FI-ICF)

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**Abstract.** Use of laser-driven Inertial Confinement Fusion (ICF) for space propulsion has been examined in several earlier conceptual design studies. However, these designs used older ICF target technology. Important new directions opened following the development of “chirped” lasers capable of ultra-short ps pulses with powers of PWs. This allows fast ignition (FI) for high energy gain ICF power plants. The FI approach uses a conventional laser to pre-compress the target to high density followed by a PW laser pulse to heat a hot spot that ignites the burn. In the deuteron beam version, the PW laser is fired on a converter plate in front of the ICF target, creating an intense deuteron ion beam that ignites the fusion burn in a central core of the target. It is estimated that using a 10 TW-ps laser for FI can achieve fusion energy gains  $>10^3$ . Application of deuteron beam fast ignition to the earlier VISTA design for ICF space propulsion unit is considered here.

# A Method For Improving The Efficiency Of Energy Amplifiers With Multiple Subcritical Cores

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**Abstract.** A new method for increasing the power generating efficiency of Energy Amplifiers (EA's) is investigated. It was found that an EA with multiple cores each acting as the neutron source for the next will provide much greater power output than a single core for a given source.

Calculations showed that a reactor with two sub-critical cores in such an arrangement greatly increased the number of fissions per injected neutron without risking criticality or upsetting breeding equilibrium. This could make EA's more feasible with smaller proton accelerators, and possibly make them practical for other uses such as spacecraft power.

# Advanced Stirling Convertor (ASC) Technology Maturation in Preparation for Flight

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**Abstract.** The Advanced Stirling Convertor (ASC) is being developed by an integrated team of Sunpower and NASA's Glenn Research Center (GRC). The ASC development, funded by NASA's Science Mission Directorate, started as a technology development effort in 2003 and has since evolved through progressive convertor builds and successful testing to demonstrate high conversion efficiency, low mass, and capability to meet Long-life Radioisotope Power System (RPS) requirements. The technology has been adopted by the Department of Energy (DOE) and Lockheed Martin Space Systems Company's Advanced Stirling Radioisotope Generator (ASRG) which has been selected for potential flight demonstration on Discover 12. This paper provides an overview of the status of ASC development including the most recent ASC-E2 convertors that have been delivered to GRC, and an introduction to the ASC-E3 and ASC-Flight convertors that Sunpower will build next. The paper also describes the technology maturation and support tasks being conducted at GRC to support ASC and ASRG development in the areas of convertor and generator extended operation, high temperature materials, heater head life assessment, organics, non-destructive inspection, spring fatigue testing, and others.



## Advanced Stirling Convertor (ASC-E2) Performance Testing at NASA Glenn Research Center

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**Abstract.** NASA Glenn Research Center has been supporting development of the Advanced Stirling Radioisotope Generator (ASRG) since 2006. A key element of the ASRG Project is providing life, reliability and performance testing of the Advanced Stirling Convertor (ASC). For this purpose, four pairs of ASC's capable of operating to 850 °C and designated with the model number ASC-E2, were delivered by Sunpower of Athens, OH to GRC in 2010. These convertors were fabricated under Sunpower's new quality assurance program, and were built and maintained under configuration control. The ASC-E2's underwent a series of tests that included workmanship vibration testing, performance mapping, and extended operation. Workmanship vibration testing was performed following fabrication of each convertor to verify proper hardware build. Performance mapping consisted of operating each convertor at various conditions to simulate those expected during a mission. Included were conditions representing beginning-of-mission, end-of-mission, and fueling. This same series of tests was performed by Sunpower prior to ASC-E2 delivery. The data generated during the GRC test were used to compare performance before and after delivery. The performance map test data were also used to compare convertor operation to the product specification. Extended operation consisted of a 500-hour period of operation with conditions maintained at the beginning-of-mission point. This was performed to demonstrate steady convertor performance following performance mapping. Following this initial 500-hour period, the ASC E2s will continue extended operation, controller development and special durability testing, during which the goal is to accumulate 10's of thousands of hours of operation. Data collected during extended operation will support reliability analysis. Performance data from these tests is summarized in this paper.

## Stirling Convertor Dynamic Analysis Using Phasor Diagrams

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**Abstract.** With the development of Advanced Stirling Convertors (ASCs) for use as power conversion systems in space missions, it is increasingly important to understand the interactions between each component of the system and how they perform relative to each other. A convenient and revealing way of performing this analysis is by using phasor diagrams to represent the forces and voltages acting on the mechanical and electrical components, respectively. The phasors act as vector representations of the forces and voltages. Phasor diagrams were generated from simulation results using the Stirling convertor System Dynamic Model. Nominal values were set for five parameters including AC bus voltage, tuning capacitance, bounce space temperature, mean pressure, and operating frequency. As these parameters were individually varied the relationship between phasor magnitude and phase angle for each variation was analyzed and conclusions were drawn from the results. A comparison with test results from operating frequency variation with an ASC-E2 convertor further illustrates use of the technique.

# Natural Convection Cooling of the Advanced Stirling Radioisotope Generator Engineering Unit

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**Abstract.** After fueling and prior to launch, the Advanced Stirling Radioisotope Generator (ASRG) will be stored for a period of time then moved to the launch pad for integration with the space probe and mounting on the launch vehicle. During this time, which could be as long as three years, the ASRG will operate continuously with heat rejected from the housing and fins. Typically the generator will be cooled by forced convection using fans. During some of the ground operations, maintaining forced convection may add significant complexity, so allowing natural convection may simplify operations. A test was conducted on the ASRG Engineering Unit (EU) to quantify temperatures and operating parameters with natural convection only and determine if the EU could be safely operated in such an environment. The results show that with natural convection cooling the ASRG EU Stirling convertor pressure vessel temperatures and other parameters had significant margins while the EU was operated for several days in this configuration. Additionally, an update is provided on ASRG EU testing at NASA Glenn Research Center, where the ASRG EU has operated for over 16,000 hours and undergone extensive testing.

# Advanced Stirling Radioisotope Generator Flight Design Overview

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**Abstract.** Under the joint sponsorship of the Department of Energy (DOE) and National Aeronautics and Space Administration (NASA), a radioisotope power system utilizing Stirling energy conversion technology is being developed for potential use on future space missions. The higher conversion efficiency of the Stirling-based system compared with that of Radioisotope Thermoelectric Generators (RTG) used in previous missions (Viking, Pioneer, Voyager, Galileo, Ulysses, Cassini, Pluto New Horizons) and soon to be used on the Mars Science Lab offers the advantage of a four-fold reduction in PuO<sub>2</sub> fuel, thereby minimizing the need for this scarce resource, saving cost and reducing radiation exposure to support personnel. With the advancement of state-of-the-art Stirling technology development under the NASA Research Announcement (NRA) project, the Stirling Radioisotope Generator project has evolved to incorporate the Advanced Stirling Converter (ASC), provided by Sunpower, into an Advanced Stirling Radioisotope Generator (ASRG) Engineering Unit (EU), built and tested in 2008, as well as eight flight pathfinder ASC units in 2010.

The first potential mission to utilize ASRG is Discovery 12. In November 2009, Lockheed Martin began the study of incorporating Discovery-based new requirements to enhance the ASRG EU design. These requirements include Electra EMI compatibility, the ability of ASRG to provide restoring power to a potentially shorted host satellite bus, the ability to change electrical controller and harnesses during fueled ground operations and the remote mounting of the controller from the generator on the host spacecraft.

This paper provides a summary of the updated flight design as covered in the recent August 2010 system-level ASRG Preliminary Design Review.

## The Four-GPHS Stirling Generator: XP300

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**Abstract.** The Advanced Stirling Radioisotope Generator (ASRG) Engineering Unit (EU), having two General Purpose Heat Source (GPHS) modules, one for each Advanced Stirling Converter (ASC), provides a nominal output of 140 W. Higher power generators are derived from the basic ASRG design by increasing the number of GPHS modules in steps of two and by scaling the converter to the higher power level. With two GPHS per converter, the nominal power output of an extended performance ASRG is 285 W<sub>dc</sub>. The specific power is calculated to be 8.6 W/kg based mainly on measured and geometrically scaled mass of the ASRG EU. The results of the thermal analyses and the recommended hardware modifications to achieve these results are presented and discussed. The XP300 with a specific power greater than 8 W/kg can enable and meet the requirements of power-hungry missions to the outer planets, radioisotope electric propulsion, and lunar rovers with 4.5 times the plutonium fuel efficiency and 1.7 times the specific power as the venerable GPHS-RTG.

# Modeling Impact-Induced Reactivity Changes Using DAG-MCNP

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**Abstract.** There is a long literature studying the criticality of space reactors immersed in water/sand after a launch accident; however most of these studies evaluate nominal or uniformly compacted system configurations. There is less research on the reactivity consequences of impact, which can cause large structural deformation of reactor components that can result in changes in the reactivity of the system. Predicting these changes is an important component of launch safety analysis. This paper describes new features added to the DAG-MCNP5 neutronics code that allow the criticality analysis of deformed geometries. A CAD-based solid model of the reactor geometry is used to generate an initial mesh for a structural mechanics impact calculation using the PRONTO3D/PRESTO continuum mechanics codes. Boundary conditions and material specifications for the reactivity analysis are attached to the solid model that is then associated with the initial mesh representation. This geometry is then updated with the deformed finite element mesh to perturb node coordinates. DAG-MCNP5 was extended to accommodate two consequences of the large structural deformations: dead elements representing fracture, and small overlaps between adjacent volumes. The dead elements are removed during geometry initialization and adjustments are made to conserve mass. More challenging, small overlaps where adjacent mesh elements contact cause the geometric queries to become unreliable. A new point membership test was developed that is tolerant of self-intersecting volumes, and the particle tracking algorithm was adjusted to enable transport through small overlaps. These new features enable DAG-MCNP5 to perform particle transport and criticality eigenvalue calculations on both deformed mesh geometry and CAD geometry with small geometric defects. Detailed impact simulations were performed on an 85-pin space reactor model. In the most realistic model that included NaK coolant and water in the impact simulation, the eigenvalue was determined to increase 2.7% due to impact.

## Experimental Correlation of an RPCSIM Model

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**Abstract.** This paper describes the process of assembling and correlating the latest version of a Reactor, Power, and Control Simulation model (RPCSIM), developed at Sandia National Laboratories, to an experimental test setup of a representative liquid metal cooled reactor (LMCR). This experimental setup was used at Marshall Space Flight Center (MSFC) during the summer of 2009 to test equipment and balance-of-plant transients of a LMCR to inform the design of a Fission Surface Power Technology Demonstration Unit (FSPS-TDU). Test data was used to control inputs to the RPCSIM model, and simulations of individual components provided correlation coefficients to refine the accuracy of friction factor and Nusselt number correlations. The original tests were not intended to be used to validate a computer simulation, so some data had to be estimated and some modeled components could not be correlated directly with data. After correlation, the model showed less than 10% error with most of the test data, and ran faster than the experiments. This result is promising as it will guide further improvement of RPCSIM to quickly develop systems and simulate system transients with moderate fidelity, including the FSPS TDU, using components modeled from first-principles and data tables to model complicated physical processes.

## Operation of a Closed Brayton Cycle Using Simulated Reactivity Feedback

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**Abstract.** *This paper describes the modeling and initial operations of a reactivity feedback control system for an electric heater operating within a low pressure closed Brayton cycle. Modeling was carried out using Simulink, converted to a dynamic-linked library in RealTime Workshop, and interfaces with the Brayton cycle hardware through an 800MHz CompactRIO controller and its custom LabView set-up. Experimentally measured temperatures of the operating Brayton loop are used by the model to calculate average fuel and coolant temperatures for a simulated reactor core, which in turn govern feedback to electrical heating elements within the loop. Coupled with the reactivity controller, this laboratory-scale Brayton system operates with a heat source that has the feedback characteristics of a nuclear reactor core. This capability is being developed for space reactor transient analysis in support of NASA's FSP (Fission Surface Power) technology.*



# Implementation of a Sage-Based Stirling Model Into a System-Level Numerical Model of the Fission Power System Technology Demonstration Unit

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**Abstract.** The Fission Power System (FPS) project is developing a Technology Demonstration Unit (TDU) to verify the performance and functionality of a subscale version of the FPS reference concept in a relevant environment and to verify component and system models. As hardware is developed for the TDU, component and system models must be refined to include the details of specific component designs. This paper describes the development of a Sage-based pseudo-steady-state Stirling convertor model and its implementation into a system-level model of the TDU.

## **Mechanical Properties of Advanced Thermoelectric materials and Thermo-Mechanical Modeling Of High Efficiency Thermoelectric Couples**

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**Abstract.** Radioisotope Thermoelectric Generators (RTGs) have been successfully demonstrated in several deep space missions. Several innovations in materials selection and design have been deployed in the development of advanced versions of these devices. The successful development of these devices can be assisted greatly by the use of computer assisted thermo-mechanical modeling. Typically such models are continuum-based and require the input of several crucial mechanical properties. Thermoelectric materials tend to be quite brittle and pose special challenges in test specimen fabrication and test methodologies. An overview of the thermo-mechanical modeling and implications will be discussed. Experimental issues involved in mechanical property measurements will be illustrated through an example thermoelectric material.

## High Thermoelectric Figure of Merit in Heavy-hole Dominated PbTe

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**Abstract.** Pristine p-PbTe thermoelectric materials typified by Na-doping was successfully used for power generation on the earliest NASA missions about 60 years ago, yet the thermoelectric performance of this material was underestimated due to the difficulties on accurate estimation of the thermal conductivity and achieving optimum sodium doping at that time. Reinvestigation of this simple material reveals that with heavy doping the system actually shows a thermoelectric figure of merit,  $zT$ , as high as  $\sim 1.4$  (twice that previously believed) because of the complex band structure. This  $zT$  is comparable with the recently discovered PbTe:TI with resonant state enhancement of the Seebeck effect, and similar results with nanostructures, providing an additional explanation (and simple, less toxic solution) for high  $zT$  in PbTe-based thermoelectrics

## Variable Conductance Heat Pipes for Long-Lived Venus Landers

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**Abstract.** Long-lived Venus Landers require cooling, which can be provided with a radioisotope power converter and cooling system. Heat from a stack of General Purpose Heat Source (GPHS) modules must be delivered to the Stirling convertor with minimal  $\Delta T$ . In addition, the cooling system must be shut OFF during transit to Venus without overheating the GPHS modules. The bypass heat can be removed by an alkali metal Variable Conductance Heat Pipe (VCHP) integrated with a two-phase heat collection/transport package from the GPHS stack to the Stirling convertor. The VCHP will allow the cooling system to: 1) rest during transit at a lower temperature than the nominal one; 2) pre-cool the modules to an even lower temperature before the re-entry in Venus atmosphere; 3) work at nominal temperature on Venus surface; 4) briefly stop multiple times on the Venus surface to allow scientific measurements. In addition, the VCHP will continuously reject the excess heat if short-lived isotopes are used. This thermal management system will also improve the Stirling convertor efficiency by decreasing the temperature non-uniformities at the interface with the hot end of the heater head. A proof of concept of this thermal management system was recently completed. A five-feature flat front theory based VCHP model was developed and a four-feature proof of concept VCHP was designed, built and successfully tested. The five-feature VCHP model predicts that the Stirling convertor can: 1) rest during transit at  $\sim 100^\circ\text{C}$  lower temperature than the nominal one ( $\sim 1200^\circ\text{C}$ ); 2) pre-cool the modules, lowering the temperature by another  $\sim 85^\circ\text{C}$ ; 3) work at nominal temperature of  $\sim 1200^\circ\text{C}$  on Venus surface; 4) stop working (for short periods of time on Venus surface with a relatively small vapor temperature increase of  $\sim 6\text{-}9^\circ\text{C}$  and 5) reject excess heat during the entire mission if short-lived isotopes are used. The four-feature proof of concept test setup was a sodium-stainless steel VCHP. The experimental data fully validated the model.

## **Practical Small Satellite RTG Power Sources, To Include A 5 kW<sub>e</sub> Pulsed (2% Duty Cycle) RTG Power Source For ESPA-Class And Similar Small Satellite Space Applications**

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**Abstract.** A feasibility study on the design of radioisotope thermoelectric generators (RTGs) for small satellites, to include ESPA-class satellites, made of “off the shelf” components was performed. While using previous space flight qualified approaches would make such small RTGs impractical, new advances in material properties have made such systems possible. System materials include a tungsten cermet to contain the radioisotope; Li-900 (space shuttle tiling) insulation, a beryllium heat capacitor, and heat sinks designed with a variety of materials to include lithium, water, sodium, phosphorous, and pure radiation cooling. Free-piston stirling engines are the primary means of thermal to eclectic energy conversion (30-36% efficiency). This paper focuses on three system designs: 1.) a 5 kW electric, 2.13% duty cycle, pulsed-power system, 2.) a 1kW electric, 1.06% duty cycle pulsed-power system, and 3.) a 200 W electric continuous power system. System analysis focuses on mass budgets and thermal analysis, however radiation shielding and material handling issues are also addressed.

# HTGR Power System Technology for Space Exploration Missions

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**Abstract.** Nuclear fission power is best suited to NASA surface and flight missions requiring continuously reliable power in difficult environments where sunlight is limited, thus making solar power less than ideal. This paper outlines a new concept that is based on a semi-mature, terrestrial reactor design of a prismatic High-Temperature Gas-Cooled Reactor (HTGR) concept utilizing cylindrical fuel pellets filled with TRISO particles. Highly enriched uranium (HEU) is placed at the core of each fuel block and is used as the main driver fuel, while thorium rods are placed near the outside and act as breeder fuel for U-233. In each fuel assembly, the fuel rods are arranged within either a graphite or beryllium oxide matrix, depending on the desired neutronic characteristics. Sensitivity studies were performed on a variety of core configurations by varying fuel packing fractions in order to maximize fuel cycle length while minimizing reactivity swings. Temperature effects due to the Doppler broadening of the resonance region were also studied. Preliminary analysis suggests that the addition of thorium to the fuel cycle can result in fuel cycle lengths of 25-30+ years of continuous operation with minimal reactivity swings using HEU driver fuel. In order maintain such long operation; it was found that a fertile-to-driver fuel weight ratio of greater than 9:1 was needed in order to achieve prolonged operation (Worrall and Shayer, 2010). The power that can be extracted from the proposed system can range from 100 KWe up to 1 MWe.

## Basic Research and Development Effort to Design a Micro Nuclear Power Plant for Brazilian Space Application

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**Abstract.** For some years the Nuclear Energy Division of the Institute for Advanced Studies is conducting the TERRA (Portuguese abbreviation for advanced fast reactor technology) project. This project aims at research and development of the key issues related with nuclear energy applied to space technology. The purpose of this development is to allow future Brazilian space explorers the access of a good and reliable heat, power and/or propulsion system based on nuclear energy. Efforts are being made in fuel and nuclear core design, designing and building a closed Brayton cycle loop for energy conversion, heat pipe systems research for passive space heat rejection, developing computational programs for thermal loop safety analysis and other technology that may be used to improve efficiency and operation. Currently there is no specific mission that requires these technology development efforts; therefore, there is a certain degree of freedom in the organization and development efforts. This paper will present what has been achieved so far, what is the current development status, where efforts are heading and a proposed time table to meet development objectives.

## Space Molten Salt Reactor Concept for Nuclear Electric Propulsion and Surface Power

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**Abstract.** Students at The Ohio State University working under the NASA Steckler Grant sought to investigate how molten salt reactors with fissile material dissolved in a liquid fuel medium can be applied space applications. Molten salt reactors of this kind, built for non-space applications, have demonstrated high power densities, high temperature operation without pressurization, high fuel burn up and other characteristics that are ideal for space fission systems. However, little research has been published on the application of molten salt reactor technology to space fission systems. This paper presents a conceptual design of the Space Molten Salt Reactor (SMSR), which utilizes molten salt reactor technology for Nuclear Electric Propulsion (NEP) and surface power at the 100 kWe to 15 MWe level. Central to the SMSR design is a liquid mixture of LiF, BeF<sub>2</sub> and highly enriched U<sub>235</sub>F<sub>4</sub> that acts as both fuel and core coolant. In brief, some of the positive characteristics of the SMSR are compact size, simplified core design, high burn up percentages, proliferation resistant features, passive safety mechanisms, a considerable body of previous research, and the possibility for flexible mission architecture.



# Design of a Low Specific Mass 10 kWe Nuclear Reactor for Space Propulsion

Hoifeldt, Nic; Ferrulli, Regal; Sudderth, Laura; Deason, Wesley; Gupta, Mahima; Reneau, Jarred; Howe, Steven D<sup>1</sup>.

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**Abstract.** With an increasing demand for long-duration and energy intensive missions in space, alternatives to radioisotope power systems are being explored. Nuclear fission reactors can provide sufficient power while maintaining a low specific mass comparable to radioisotope power systems. One of the projects focused on designing a small scale nuclear reactor with a low specific mass for use on a fourteen year unmanned mission. The results show a craft can be made that requires no internal pumps or electrical input to run the power conversion system. The power conversion system selected consisted of free-piston Stirling engines. The core design is based upon a heat pipe thermal transport system using a U10Mo Core, while a liquid bath controls thermal conditions around the power conversion systems. The radiators are also designed with carbon composite materials. Results of this paper show a reduction in specific mass of the system.

# Advanced Materials and Optimisation of a Radioisotope Thermal Rocket Motor for a Mars Hopper

Hugo R. Williams<sup>1a</sup>, Richard M. Ambrosi<sup>1</sup>, Nigel P. Bannister<sup>1</sup>, Marie-Claire Perkinson<sup>2</sup>, Jaime Reed<sup>2</sup>, Steven D. Howe<sup>3</sup> and Robert C. O'Brien<sup>3</sup>.

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**Abstract.** Rocket propelled vehicles capable of travelling a kilometre or more in a ballistic ‘hop’ have been proposed by several authors to offer significantly enhanced mobility compared to conventional rovers. This opens new opportunities for planetary investigation and enhanced science return. Mars is an attractive candidate for such a vehicle due to the availability of carbon dioxide as an in-situ propellant resource. A radioisotope is an attractive heat source to power both the propellant compression system and charge a ‘heat capacitor’ consisting of a material of high specific heat capacity and melting point. Thermal energy stored in this core material is transferred to the pure CO<sub>2</sub> propellant to provide sufficient specific impulse for a useful hopping range.

Feasibility studies (reported to-date) have covered a variety of topics via experiment and analysis. In this paper simple analytical relations are used to guide selection of the ‘heat capacitor’ or ‘core’ material via material selection charts and preliminary estimates of the effect of thermal conductivity. Advanced engineering ceramics (e.g. boron carbide, silicon carbide) and beryllium alloys appear the most promising candidate materials. Significant potential for composite or functional materials exists.

## Development of a propulsion system and component test facility for advanced radioisotope powered Mars Hopper platforms

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**Abstract.** *Verification and validation of design and modeling activities for radioisotope powered Mars Hopper platforms undertaken at the Center for Space Nuclear Research is essential for proof of concept. Previous research at the center has driven the selection of advanced material combinations; some of which require specialized handling capabilities. The development of a closed and contained test facility to forward this research is discussed within this paper.*

# Collection and Utilization of In-Situ Propellant for Europa Hopper

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**Abstract.** As the exploration of the solar system expands outwards, the opportunity for life finding missions becomes an ever growing possibility. One of these possibilities for life is found on Jupiter's moon Europa, which is believed to have a liquid ocean beneath its icy surface. Similar to earth, hydrothermal vents may allow a diverse biological community to thrive without sunlight. The best chance of finding indications of life is located at upwellings, which are created from the subsurface ocean pushing water and possibly organic material up through cracks in the ice. The problem arises with how to transport a vehicle from one upwelling to the next. With the goal to use in-situ resources further questions arise about what fuel should be used and how the fuel should be collected. Due to the abundance of ice located on the surface of Europa, the possibility of using in-situ propellants becomes a viable option for exploration missions. To determine the feasibility of using European ice as an in-situ propellant a fundamental understanding of ice at cryogenic temperatures was investigated. Afterwards a trade study was conducted of the feasibility of current technologies with considerations to make such systems effective. The results of the investigation led to the conclusion that the best method for ice collection on Europa would be thermal drilling with a model based upon the Subsurface Ice Probe. The energy for thermal drilling is an overall magnitude greater than electro-mechanical drilling. Due to difficulties in ice core handling and the mission longevity, however thermal drilling was chosen. The results of this investigation provide the motivation to support and further technology advancements in thermal drilling, specifically for application on planetary polar regions. Assuming water vapor has been collected the best propellant was determined based on propellant mass and the energy requirements for obtaining needed mass. Three types of propellants were considered: superheated steam, hydrogen, and oxygen. An analytical model was created to calculate the delta-v requirement for traversing the icy surface. This provided propellant mass, which was compared to the energy needed to obtain each propellant. The process of electrolysis requires  $44.5 \text{ kW} \cdot \text{hr}_{\text{elc}}$  per kg of hydrogen and  $5.97 \text{ kW} \cdot \text{hr}_{\text{elc}}$  per kg of oxygen. Based upon the large power requirements for hydrogen and oxygen, the possibility of using them compared to water is undesirable. Collecting and using water as a propellant for icy planet exploration is a feasible option.

## Life Testing of $\text{Yb}_{14}\text{MnSb}_{11}$ for High Performance Thermoelectric Couples

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**Abstract.** The goal of this study is to verify the long term stability of  $\text{Yb}_{14}\text{MnSb}_{11}$  for high performance thermoelectric (TE) couples. Three main requirements need to be satisfied to ensure the long term stability of thermoelectric couples: 1) stable thermoelectric properties, 2) stable bonding interfaces, and 3) adequate sublimation suppression. The efficiency of the couple is primarily based on the thermoelectric properties of the materials selected for the couple. Therefore, these TE properties should exhibit minimal degradation during the operating period of the thermoelectric couples. The stability of the bonding is quantified by low contact resistances of the couple interfaces. In order to ensure high efficiency, the contact resistances of the bonding interfaces should be negligible. Sublimation suppression is important because the majority of thermoelectric materials used for power generation have peak figures of merit at temperatures where sublimation rates are high. Controlling sublimation is also essential to preserve the efficiency of the couple. During the course of this research, three different life tests were performed with  $\text{Yb}_{14}\text{MnSb}_{11}$  coupons. TE properties of  $\text{Yb}_{14}\text{MnSb}_{11}$  exhibited no degradation after 6 months of aging at 1273K, and the electrical contact resistance between a thin metallization layer and the  $\text{Yb}_{14}\text{MnSb}_{11}$  remained negligible after 1500hr aging at 1273K. A sublimation suppression layer for  $\text{Yb}_{14}\text{MnSb}_{11}$  was developed and demonstrated for more than 18 months with coupon testing at 1273K. These life test data indicate that thermoelectric elements based on  $\text{Yb}_{14}\text{MnSb}_{11}$  are a promising technology for use in future high performance thermoelectric power generating couples.

## Highly Integrated Quality Assurance – An Empirical Case

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**Abstract.** The Radioisotope Power Systems Program of the Idaho National Laboratory makes an empirical case for a highly integrated quality assurance function pertaining to the preparation, assembly, testing, storage and transportation of <sup>238</sup>Pu fueled radioisotope thermoelectric generators. Case data represents multiple campaigns including the Pluto/New Horizons mission, the Mars Science Laboratory mission in progress, and other related projects. Applicability of this case extends to any high-value, long-term project where traceability and accountability are determining factors.

## 10 kW Radioisotope Powered Pulsed Brayton Cycle For Space Applications

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**Abstract.** This paper studies the feasibility of a 10 kW<sub>e</sub> radioisotope-powered closed Brayton cycle for pulsed power station keeping applications. The study evaluates the specific power of the proposed system compared to current solar-photovoltaic systems. To achieve a high power pulse from a continuous low power input, a boron thermal capacitor surrounds a tungsten cermet matrix containing a radioisotope heat source which gradually adds heat to the thermal capacitor. During a power pulse this heat is removed by a HeXe coolant which expands through a closed Brayton conversion cycle to produce electric power for the spacecraft's ion thrusters. Since real time heat rejection is not necessary for a pulsed power system, a lithium thermal capacitor absorbs waste heat for the duration of the pulse, and radiates that heat to space between pulses.

## Material Studies Related to the Use of NaK Heat Exchangers Coupled to Stirling Heater Heads

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**Abstract.** NASA has been supporting design studies and technology development that could provide power to an outpost on the moon, Mars, or an asteroid. Technology development efforts have included fabrication and evaluation of components used in a Stirling engine power conversion system. Destructive material evaluation was performed on a NaK shell heat exchanger that was developed by the NASA Glenn Research Center and integrated with a commercial 1kWe Stirling convertor from Sunpower Incorporated. The NaK Stirling test demonstrated Stirling convertor electrical power generation using a pumped liquid metal heat source under thermal conditions that represent the heat exchanger liquid metal loop in a Fission Power Systems (FPS) reactor. The convertors were operated for a total test time of 66 hours at a maximum temperature of 823 K. After the test was completed and NaK removed, the heat exchanger assembly was sectioned to evaluate any material interactions with the flowing liquid metal. Several dissimilar-metal braze joint options, crucial for the heat exchanger transfer path, were also investigated. A comprehensive investigation was completed and lessons learned for future heat exchanger development efforts are discussed.



## SNAP 10A Safety Test Program

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**Abstract:** The Systems for Nuclear Auxiliary Power (SNAP) program was sponsored by the Atomic Energy Commission (AEC), now DOE, from 1956 to 1973. Both radioisotope and nuclear reactor heat sources were developed during this program to support nuclear electric power sources for remote terrestrial and in-space power applications. Projects using radioisotope heat sources were odd-numbered (i.e., SNAP 3, SNAP 9, etc.), while projects using fission reactor heat sources were even numbered (i.e., SNAP 2, SNAP 4, SNAP 10A). Each type of nuclear heat source had its own radiological safety program to support the development of the power unit. The SNAP 10A nuclear power unit (or NPU) was a 500 W, 1-year life, spacecraft power source which used a nuclear reactor heat source with a silicon-germanium (SiGe) thermoelectric power converter module. An on-board shunt regulator controlled output voltage level to the spacecraft bus. Because the SNAP 10A NPU would be the first nuclear reactor to be launched into orbit by the United States, a comprehensive set of tests were devised and performed to establish the safety criteria and validate the design in various hazardous environments it could be exposed to throughout its mission profile. These tests, along with their results, and their impact on changes to the U.S. space nuclear safety criteria, employed for today's launches of nuclear power sources, will be reviewed. The factory-to-flight sequence, as envisioned during the SNAP 10A program, will be reviewed with respect to the safety approach at each step of the NPU preparation for its flight test.

## Radiation Specifications for Fission Power Conversion Component Materials

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**Abstract.** NASA has been supporting design studies and technology development that could provide power to an outpost on the moon, Mars, or an asteroid. One power-generation system that is independent of sunlight or power-storage limitations is a fission-based power plant. There is a wealth of terrestrial system heritage that can be transferred to the design and fabrication of a fission power system for space missions, but there are certain design aspects that require qualification. The radiation tolerance of the power conversion system requires scrutiny because the compact nature of a space power plant restricts the dose reduction methodologies compared to those used in terrestrial systems. An integrated research program has been conducted to establish the radiation tolerance of power conversion system-component materials. The radiation limit specifications proposed for a Fission Power System power convertor is 10 Mrad ionizing dose and  $5 \times 10^{14}$  neutron/cm<sup>2</sup> fluence for a convertor operating at 150 °C. Specific component materials and their radiation tolerances are discussed. This assessment is for the power convertor hardware; electronic components are not covered here.

# Post Test Analysis of a Ten Year Sodium Heat Pipe Life Test

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**Abstract.** High temperature heat pipes are being evaluated for use in energy conversion applications such as fuel cells, gas turbine re-combustors, Stirling cycle heat sources; and with the resurgence of space nuclear power both as reactor heat removal elements and as radiator elements. Long operating life and reliable performance are critical requirements for these applications. Accordingly long-term materials compatibility is being evaluated through the use of high temperature life test heat pipes. Thermacore, Inc. has carried out a ten year sodium heat pipe life test to establish long term operating reliability. Sodium heat pipes have demonstrated favorable materials compatibility and heat transport characteristics at high operating temperatures in air over long time periods. A representative one-tenth segment Stirling Space Power Converter heat pipe with an Inconel 718 envelope and a stainless steel screen wick has operated for over 87,000 hours (ten years) at nearly 700 °C. These life test results have demonstrated the potential for high temperature heat pipes to serve as reliable energy conversion system components for power applications that require long operating lifetime with high reliability. Detailed design specifications, operating history, and post-test analysis of the heat pipe and sodium working fluid are described. Lessons learned and future life test plans are also discussed.

# Multi-MW Closed Cycle MHD Nuclear Space Power Via Nonequilibrium He/Xe Working Plasma

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**Abstract.** Prospects for a low specific mass multi-megawatt nuclear space power plant were examined assuming closed cycle coupling of a high-temperature fission reactor with magnetohydrodynamic (MHD) energy conversion and utilization of a nonequilibrium helium/xenon frozen inert plasma (FIP). Critical evaluation of performance attributes and specific mass characteristics was based on a comprehensive systems analysis assuming a reactor operating temperature of 1800 K for a range of subsystem mass properties. Total plant efficiency was expected to be as high as 55.2% including plasma pre-ionization power, and the effects of compressor stage number, regenerator efficiency and radiation cooler temperature on plant efficiency were assessed. Optimal specific mass characteristics were found to be dependent on overall power plant scale with 3 kg/kW<sub>e</sub> being potentially achievable at a net electrical power output of 1-MW<sub>e</sub>. This figure drops to less than 2 kg/kW<sub>e</sub> when power output exceeds 3 MW<sub>e</sub>. Key technical issues include identification of effective methods for non-equilibrium pre-ionization and achievement of frozen inert plasma conditions within the MHD generator channel. A three-phase research and development strategy is proposed encompassing Phase-I Proof of Principle Experiments, a Phase-II Subscale Power Generation Experiment, and a Phase-III Closed-Loop Prototypical Laboratory Demonstration Test.

## Trade Study of a 20 Megawatt Electric Low Specific Mass Nuclear Power System for Space Propulsion

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**Abstract.** Low specific mass systems are increasingly being researched to develop exploratory missions to Mars, as well as other large masses within our solar system. Nuclear power systems possess the potential to meet the requirements by providing higher power output at a much lower system mass when compared to traditional chemical combustion technologies. At the Center for Space Nuclear Research, methods were developed to outline the design of such a system by comparing the most efficient options. The system requirement was to design a 20 Mega-Watt Electric (MWe) nuclear reactor coupled with a power conversion system to power an electric propulsion unit for a two-year lifetime. The final two designs discussed here are a Super Rankine system using Lithium as a coolant and Potassium or Sodium as a working fluid with U-233 Cermet core while the competing system utilized a Magnetohydrodynamic (MHD) power conversion system using Lithium as the working fluid and the nuclear reactor coolant powered by a 61% enriched U-235 Cermet nuclear reactor core. In both cases, radiators are designed with carbon composite materials for high emissivity and low mass. Shielding and magnet cooling systems are also discussed. The result of this paper show final specific masses ( $\alpha$  in kg/kW) for these competing systems.

# A Conceptual Multi-Megawatt System Based on a Tungsten CERMET Reactor

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**Abstract.** *A conceptual reactor system to support Multi-Megawatt Nuclear Electric Propulsion is investigated within this paper. The reactor system consists of a helium cooled Tungsten-UN fission core, surrounded by a beryllium neutron reflector and 13 B<sub>4</sub>C control drums coupled to a high temperature Brayton power conversion system. Excess heat is rejected via carbon reinforced heat pipe radiators and the gamma and neutron flux is attenuated via segmented shielding consisting of lithium hydride and tungsten layers. Turbine inlet temperatures ranging from 1300 K to 1500 K are investigated for their effects on specific powers and net electrical outputs ranging from 1 MW to 100 MW. The reactor system is estimated to have a mass, which ranges from 15 Mt at 1 MW<sub>e</sub> and a turbine inlet temperature of 1500 K to 1200 Mt at 100 MW<sub>e</sub> and a turbine temperature of 1300 K. The reactor systems specific mass ranges from 32 kg/kW<sub>e</sub> at a turbine inlet temperature of 1300 K and a power of 1 MW<sub>e</sub> to 9.5 kg/kW at a turbine temperature of 1500 K and a power of 100 MW<sub>e</sub>.*

# COMPARISONS OF PLANETARY SPACE RADIATION ENVIRONMENTS AND EFFECTS—A REVIEW

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**Abstract.** In addition to the nuclear-induced radiation environments intrinsic to radioactive power sources, the in-situ natural radiation environment itself poses a potential threat to the practical utilization of these systems for spacecraft missions. These environments range from the ubiquitous Galactic Cosmic Ray background to trapped radiation belts, Solar Energetic Particle Events, and secondary particle emissions from planetary surfaces. These environments in turn can negatively impact control electronics, material properties, and sensor/monitor backgrounds. This paper will review and compare the most severe of the natural radiation environments relevant to nuclear spacecraft power systems, their impacts, and common methods for mitigating the worst of their effects. The objective of the review will be to provide spacecraft designers and engineers with tools for the preliminary assessment and mitigation of the common radiation concerns to be expected by missions utilizing radioactive power sources.

## A Hypothesis on Biological Protection from Space Radiation Through the Use of New Therapeutic Gases

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**Abstract.** Radiation exposure to astronauts could be a significant obstacle for long duration manned space exploration because of current uncertainties regarding the extent of biological effects. Furthermore, concepts for protective shielding also pose a technically challenging issue due to the nature of cosmic radiation and current mass and power constraints with modern exploration technology. The concern regarding exposure to cosmic radiation is the biological damage it induces. As damage is associated with increased oxidative stress, it is important and would be enabling to mitigate and/or prevent oxidative stress prior to the development of clinical symptoms and disease. This paper hypothesizes a “systems biology” approach in which a combination of chemical and biological mitigation techniques are used conjunctively. It proposes using new, therapeutic, medical gases as both chemical radioprotectors for radical scavenging and biological signaling molecules for management of the body’s response to exposure. From reviewing radiochemistry of water, biological effects of CO, H<sub>2</sub>, NO, and H<sub>2</sub>S gas, and mechanisms of radiation biology, it is concluded that this approach may have great therapeutic potential for radiation exposure. Furthermore, it also appears to have similar potential for curtailing the pathogenesis of other diseases in which oxidative stress has been implicated including cardiovascular disease, cancer, chronic inflammatory disease, hypertension, ischemia/reperfusion injury, acute respiratory distress syndrome, Parkinson’s and Alzheimer’s disease, cataracts, and aging.



# Optimization Of Interplanetary Transfers Of Space Vehicles With Nuclear Thermal Rocket Engine

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**Abstract.** In this article we consider of optimization of finite-thrust interplanetary transfer of a space vehicle with nuclear thermal rocket (NTR) engine. It was assumed that the trajectory contains one finite-thrust arc during escape and one arc during capture maneuvers. The modified method of spheres of influence (MMSI) is used to reduce the problem to the external (heliocentric) and the internal (planet-centric) parts. The internal part, which is equal to the problem optimizing a finite-thrust maneuver between near-earth elliptic and escape hyperbolic orbits, is studied closely. The model of NTR thrust controlling was developed. The NTR engine's thrust value control is accomplished by the regulation of reactor thermal power and propellant mass flow rate. Thereby we propose an approximate method of coupled optimization of the thrust control and the trajectory path during the burn period. The method is based on quadrature solution of the correspondent two-point boundary problem in a central uniform gravity field. As well, the method can be used to obtain the initial guess for the solution of the problem stated using a central Newtonian gravity field.

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NETS 2011 At A Glance

Time	Monday, Feb 7, 2011			
	Registration	EH*	Carlsbad	Salon E/F
0700-0800	Registration & Help Desk Open	Continental Breakfast		
0800-1000		Exhibit Hall Open	Spouse/ Guest Hospitality Room Open	Opening Plenary: Welcome & Keynote Speakers
1000-1030				Break
1030-1230				Plenary II: Science Missions Enabled by Nuclear Power and Propulsion
1230-1400				Lunch (on your own)
1400-1700				Plenary: The Non-Technical Challenges of Developing Space Nuclear Technology: Navigating the World of Politics and Policy
1900-2100	Opening Reception/Dinner (Grand Ballroom). Keynote Speaker: Dr. Glen Schmidt (ret.), former test engineer for SNAP 10a Program			

Time	Tuesday, Feb 8, 2011						
	Registration	EH*	Carlsbad	Salon A/B	Salon C/D	Salon G/H	Salon I/J
0730-0830	Registration & Help Desk Open	Cont'l Breakfast					
0830-1000		Exhibit Hall Open	Spouse/ Guest Hospitality Room Open	Track 2 Reactor Design	No Session	No Session	Track 3 Panel Session: Pu-238 Supply/ Production
1000-1030				Break			
1030-1200				Track 2 Liquid Metal Technology	No Session	Track 4 Fuels Development	Track 3 Panel Session: (Cont'd)
1200-1330				Lunch (on your own)			
1330-1500				Track 2 Heat Rejection Technology	Track 1 Mission Applications for Fission Power Systems	No Session	Track 3 RPS Thermo-electric Components & Systems
1500-1530				Break			
1530-1700				Track 2 Reactor Simulation	Track 1 Nuclear-Enabled Deep Space Missions	Track 4 Testing	Track 3 Isotope Heat Sources

\*EH = Exhibit Hall (Pecos, Acoma, Sandia)

## NETS 2011 At A Glance

Time	Wednesday, Feb 9, 2011						
	Registration	EH*	Carlsbad	Salon A/B	Salon C/D	Salon G/H	Salon I/J
0730-0830	Registration & Help Desk Open	Cont'l Breakfast					
0830-1000		Exhibit Hall Open	Spouse/ Guest Hospitality Room Open	Track 2 Testing & Validation 1	Track 1 Mars Sample Return/ Advanced Concepts	Track 4 Systems Performance	No Session
1000-1030				Break			
1030-1200				Track 2 System Concepts 1	Track 5 Advanced Nuclear Sys. Concepts	No Session	Track 3 Stirling Components & Modeling
1200-1330				Lunch (on your own)			
1330-1500				No Session	Track 2 <b>Panel:</b> Path Forward for Fission Power Systems	No Session	Track 3 Stirling Systems
1500-1530				Break			
1530-1700				Track 2 Tools & Modeling	Track 2 Panel Session Continued (if needed)	No Session	W-4d-3e RPS Mech., Thermal & Elect. Integration
1900 -	Banquet Dinner at Nat'l Museum of Nuclear Science & History. Keynote Address: Dr. Harrison "Jack" Schmitt, Apollo 17 Astronaut, former US Senator from NM						

Time	Thursday, Feb 10, 2011							
	Registration	EH*	Carlsbad	Salon A/B	Salon C/D	Salon G/H	Salon I/J	
0730-0830	Registration/ Help Desk Open	Continental Breakfast						
0830-1000		Exhibit Hall Closed	Spouse/ Guest Hosp. Room Open	Track 2 System Concepts 2	Track 1 Radio- isotope Thermal Propulsion Mission Applications	No Session	Track 3 RPS Testing, Validation & Adv. Pwr Conversion	
1000-1030				Break				
1030-1200				Track 2 Testing & Validation 2	Track 5 Multi- megawatt Fission Reactor Concepts	No Session	Track 1 Space Radiation: Effects & Mitigation	
1200-1300								
1300-1700		Lunch (on your own)						
	Technical Tours: Sandia National Laboratories							





## Meeting Space Diagram:

