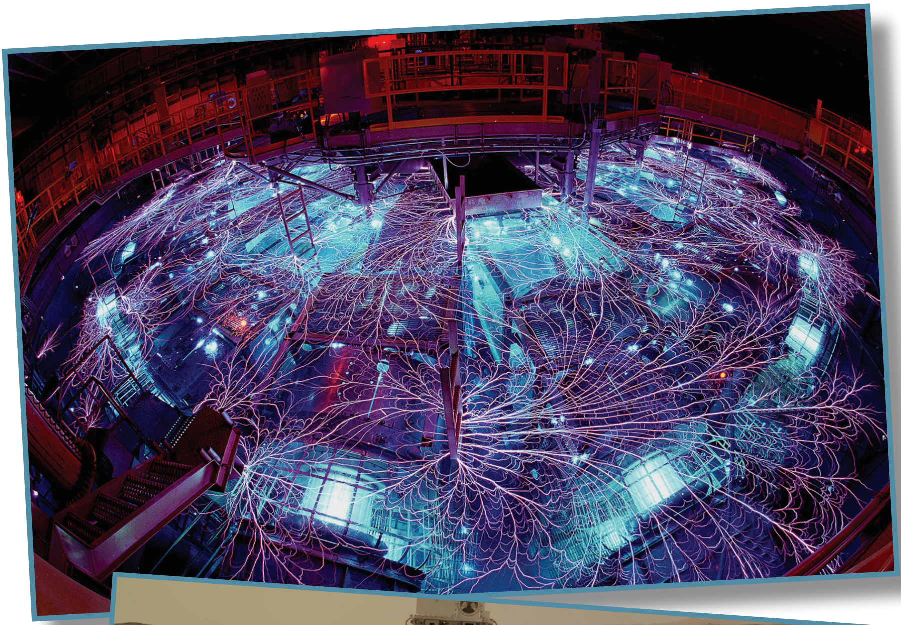
Program Book

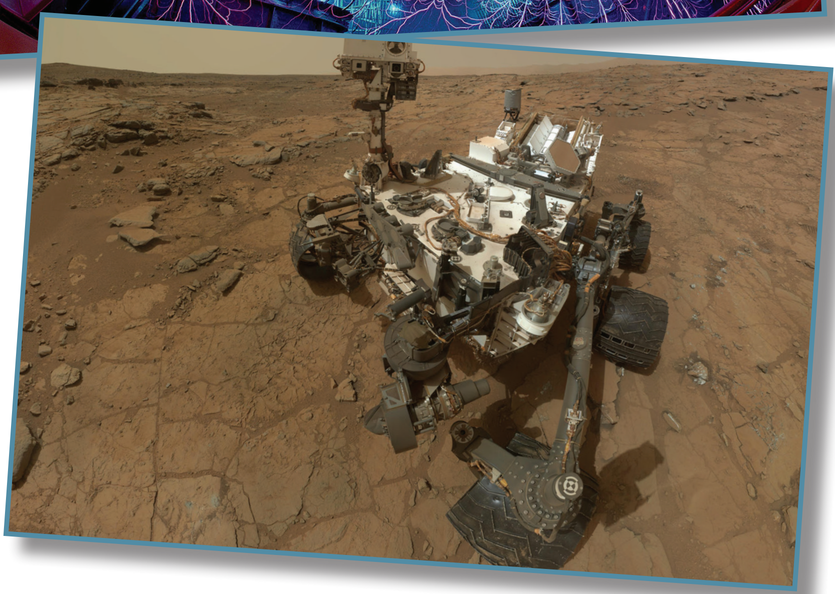
NETS-2015

Nuclear and Emerging Technologies for Space

Sponsored by
ANS Aerospace Nuclear Science and Technology Division
Universities Space Research Association
NASA

Full proceedings on jump drive/
memory stick





About the Meeting

In February 2015, the Aerospace Nuclear Science and Technology Division (ANSTD) of the American Nuclear Society (ANS) will hold the 2015 Nuclear and Emerging Technologies for Space (NETS 2015) topical meeting at the Albuquerque Marriott in Albuquerque, NM. NETS 2015 is the premier conference for landed and in-space applications in 2015.

With authors from universities, national laboratories, NASA facilities and industry, NETS 2015 will provide an excellent communication network and forum for information exchange.

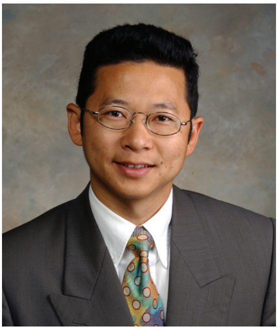
Topic Areas

NASA is currently considering capabilities for robotic and crewed missions to the Moon, Mars, and beyond. Strategies that implement advanced power and propulsion technologies, as well as radiation protection, will be important in accomplishing these missions in the future. NETS serves as a major communications network and forum for professionals and students working in the area of space nuclear technology. Every year it facilitates the exchange of information among research and management personnel from international government, industry, academia, and the national laboratory systems. To this end, the NETS 2015 meeting will address topics ranging from overviews of current programs to methods of meeting the challenges of future space endeavors.

John Bess, Ph.D.
General Chair
Idaho National Laboratory

Alice Caponiti
General Chair
U.S. Department of Energy

Pete Worden, Ph.D.
General Chair
NASA Ames Research Center



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Track I: Radioisotope Power Systems

Track Chair: Kelly Lively, Idaho National Laboratory

Dr. Richard Ambrosi	University of Leicester
Ms. Rebecca Onuschak	DOE-Office of Nuclear Energy
Dr. Stephen Johnson	Idaho National Laboratory
Ms. June Zakrajsek	NASA-Glenn Research Center
Ms. Young Lee	Jet Propulsion Laboratory
Mr. Dirk Cairns-Gallimore	DOE-NE75
Dr. Robert Wham	Oak Ridge National Laboratory
Mr. Thomas Sutliff	NASA-Glenn Research Center
Dr. Jean-Pierre	Fleurial Jet Propulsion Laboratory
Dr. Daniel Kramer	University of Dayton Research Institute

Track II: Fission Power and Electric Propulsion

Track Chair: Patrick McClure, Los Alamos National Laboratory

Dr. D.V. Rao	Los Alamos National Laboratory
Dr. John Bess	Idaho National Laboratory
Dr. David Poston	Los Alamos National Laboratory
Mr. Don Palac	NASA-Glenn Research Center

Track III: Nuclear Thermal Propulsion

Track Chair: Omar Mireles, NASA MSFC

Dr. Omar Mireles	NASA-Marshall Space Flight Center
Mr. Jarvis Caffrey	NASA-Marshall Space Flight Center
Dr. Omar Mireles	NASA-Marshall Space Flight Center
Ms. Kelsa Benensky	Penn State University
Dr. Michael Houts	NASA-Marshall Space Flight Center
Dr. Omar Mireles	NASA-Marshall Space Flight Center
Mr. Wesley Deason	Center for Space Nuclear Research
Mr. Michael Eades	Center for Space Nuclear Research
Mr. Daniel Cavender	NASA-Marshall Space Flight Center
Mr. Leroy Hardin	Nuclear Regulatory Commission

Track IV: Advanced Concepts

Track Chair: John Scott, NASA JSC

Mr. Ardash Rajguru	Center for Space Nuclear Research
Mr. John Scott	NASA-Johnson Space Center
Mr. Matthew Lund	University of Utah
Mr. John Scott	NASA-Johnson Space Center
Dr. Alfonso Tarditi	Electric Power Research Institute
Mr. John Scott	NASA-Johnson Space Center

Aerojet Rocketdyne is a world-recognized aerospace and defense leader providing propulsion and energetics to the domestic and international space, missile defense and strategic systems, tactical systems and armaments areas, and transformational energy technology solutions to address the world's energy needs. GenCorp is a diversified company providing innovative solutions to its customers in the aerospace and defense, energy and real estate markets.

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The UK's National Nuclear Laboratory (NNL) offers an unrivalled breadth of technical products and services to our customers across the whole nuclear industry.

Covering the complete nuclear fuel cycle from fuel manufacture and power generation, through to reprocessing, waste treatment and disposal and including defence, new nuclear build and Homeland Security. NNL provides these services supported by an impressive range of facilities and links with international research organisations, academia and other national laboratories. NNL's facilities are second to none. The Central Laboratory at Sellafield is the most modern nuclear research facility in the world. The Windscale Laboratory provides Post-Irradiation Examination (PIE) and other services critical to plant life extension. At Workington NNL operates a non-radioactive test rig facility and at Preston NNL operates a uranium active chemistry laboratory. NNL also has staff at the Risley, Stonehouse and Harwell sites providing Head Office functions, graphite technology, radiation chemistry and modelling/simulation.

Appointed by the European Space Agency (ESA), NNL's role has been to find a sustainable power source in batteries to power future European space missions beyond Mars. After finding that americium was the ideal power source, NNL then started examining the logistical and chemical issues involved in the separation of americium from plutonium. NNL is now a key player in a European wide space programme.

Monday February 23, 2015		
7:00 am - 8:00 am	**Registration**	Registration Desk
	Session Preparation	Exhibitition Hall (Acoma)
8:00 am - 10:00 am	**Opening Plenary**	Pecos/Sandia
	Welcome and Q&A • David Schurr, NASA HQ • Scott Seymour, Aerojet Rocketdyne • John Kelly, DOE-NE	
10:00 am - 10:30 am	Refreshments	Exhibition Hall (Acoma)
10:30 am - 12:30 pm	**Plenary**	Pecos/Sandia
	• Pete Worden, NASA ARC • Alice Caponiti, DOE-NE • John Bess, Idaho National Laboratory	
12:30 pm - 1:30 pm	Lunch Break	On your own
1:30 pm - 4:00 pm	**Technical Sessions**	Salons A, B, C, D
4:00 pm - 4:30 pm	Refreshments	Exhibition Hall
4:30 pm - 6:00 pm	**Technical Sessions**	Salons A, B, C, D
6:00 pm - 9:00 pm	Opening Tapas Reception	National Museum of Nuclear Science & History *Sponsored by National Nuclear Lab*

Tuesday February 24, 2015		
8:00 am - 10:00 am	**Technical Sessions**	Salons A, B, C, D
10:00 am - 10:30 am	Refreshments	Exhibition Hall
10:30 am - 12:30 pm	**Technical Sessions**	Salons A, B, C, D
12:30 pm - 1:30 pm	Lunch Break	On your own
1:30 pm - 3:00 pm	**Technical Sessions**	Salons A, B, C, D
3:00 pm - 3:30 pm	Refreshments	Exhibition Hall
3:30 pm - 5:00 pm	**Technical Sessions**	Salons A, B, C, D

Evening	Dinner	On your own

Wednesday February 25, 2015		
8:00 am - 10:00 am	**Technical Sessions**	Salons A, B, C, D
10:00 am - 10:30 am	Refreshments	Exhibition Hall
10:30 am - 12:30 pm	**Technical Sessions**	Salons A, B, C, D
12:30 pm - 1:30 pm	Lunch	On your own
1:30 pm - 3:30 pm	**Technical Sessions**	Salons A, B, C, D
3:30 pm - 4:00 pm	Refreshments	Exhibition Hall
4:00 pm - 6:00 pm	**Technical Sessions**	Salons A, B, C, D
7:00 pm - 9:00 pm	**Dinner Banquet**	Marriott Ballroom *Sponsored by Aerojet-Rocketdyne* *Speaker: Bill Gerstenmaier, NASA HQ*

Thursday February 26, 2015		
Morning	Tour	Sandia National Lab

Monday February 24, 2014

Track I: Radioisotope Power Systems
Nuclear Power Assessment Studies

1:30 pm - 4:00 pm — Salon A

The Nuclear Power Assessment Study, *R.L. McNutt (John Hopkins University), S.M. Aleman (NASA HQ), M.J., Amato (NASA GFC), W. Carroll (DOE), L. Dudzinski (NASA HWQ, J. McKamy (DOE), C. Moore (NASA HQ), C. Reed (John Hopkins University), K.R. Reh (Jet Propulsion Lab), J.A. Sholtis (Sholtis Engineering and Safety Consulting), R.A. Stephan (NASA HQ)*

The 2014 NASA Nuclear Power Assessment Study: Mission Study Results Investigating Advanced Radioisotope Systems and Fission Power Systems, *Y.H. Young, B.K. Bairstow (JPL), R. Cataldo (NASA GRC), R. Anderson (Applied Physics Lab), S, Oleson (NASA GRC), S.G. Johnson (Idaho National Lab)*

The 2014 NASA Nuclear Power Assessment Study: Assembly, Test and Launch Operations Comparisons between Notional 1kWe Fission Power System and Conventional Radioisotope Power System, *S. G. Johnson (Idaho National Lab), R. Cataldo (NASA GRC), S. Vernon (Applied Physics Lav), C. Tatro (NASA JSC), G. English, R. Cook (Idaho National Lab), R. Langevin (NASA JSC), Y.H. Young (Jet Propulsion Lab)*

The 2014 NASA Nuclear Power Assessment Study: Safety, Environmental Impact, and Launch Approval Considerations and Findings, *J.A. Sholtis Jr (Sholtis Engineering and Safety Consulting), R.D. Bechtel (DOE NE-75), P.K. Van Damme, J. M. Phillips (Jet Propulsion Lab), R.J. Lipinski (Sandia National Lab)*

Reference Power System Options for the Nuclear Power Assessment Study, *L.S. Mason, J.G. Schreiber, P.C. Schmitz (NASA GRC), J.P. Fleurial, D.F Woerner (Jet Propulsion Lab), D. Cairns-Gallimore, A. Belvin (DOE), P.R. McClure, D.I. Poston (Los Alamos National Lab), S.G. Johnson, J.S. Herring (Idaho National Lab), C.R. Robinson, J.T. Creasy (Y-12 Security Complex), M.E. Fraeman (John Hopkins University)*

Track I: Radioisotope Power Systems
Radioactive Studies: Part A

4:30 pm - 6:00 pm — Salon A

Toward Certified Pu-238 Purification Laboratory, *A. Zeytun, D. Spengler, A.D. Mclaughlin, J. Brown, J. Gower, A.E. Enriquez (Nuclear Los Alamos National Lab)*

Kinetics of the High Temperature Oxygen Exchange Reaction on 238PuO2 Powder, *C.E. Whiting (University of Dayton), M. Du), L.K. Felker, R.M. Wham (Oak Ridge National Lab, C.D. Barklay, D.P. Kramer (University of Dayton)*

Chemical Separations of Pu-238 from Irradiated Neptunium Targets, *L.K. Felker , D.E. Benker, D.W. DePaoli (Oak Ridge National Lab)*

	Track II: Fission Power and Electric Propulsion NEP Space Nuclear Power Programs	
2:00 pm - 6:00 pm	**MEGAHIT: Conclusion of the Development of the Advanced Propulsion Roadmap for HORIZON202,** *T. Tinsley (National Nuclear Lab), F. Mason (CNES), E. Detsis (European Space Foundation), E. Gaia (Thales Alenia Space Italia), Z. Hodgson (National Nuclear Lab), F. Jansen (Institute of Aerospace Systems), A. Semenkin (Keldysh Research Center), J. Ruault (CNES), J. Worms (European Space Foundation)*	Salon D
	Democritos: Preparing Demonstrators for High Power Nuclear Electric Space Propulsion, *F. Masson, J.M Ruault (CNES), D. Worms, E. Detsis (European Space Foundation) A. Beaurin, F. Lassoudiere (Sneema) E. Gaia, M.C. Tosi (Thales Alenia Space Italia) F. Jansen, W. Bauer (DLR), A. Semenkin (Keldysh Research Center), T. Tinsley, Z. Hodgson (National Nuclear Lab)*	
	Nuclear Systems Kilopower Project Overview, *D.T. Palac , M.A. Gibson, L.S. Mason (NASA GRC), P. McClure (Los Alamos National Lab), R.C. Robinson (Y-12 Security Complex)*	
	Integrated Surface Power Strategy for Mars, *M.A. Rucker*	
	Status Update on the Fission Surface Power Technology Demonstration Unit, *B.H. Briggs, M.A. Gibson (NASA GRC)*	
	Nuclear Technologies for Space Applications: Past, Present, and Future, *L.K. Sudderth (Texas A&M University)*	
	Track III: Thermal Nuclear Propulsion NTP Project and Mission Architecture	
2:30 pm - 5:30 pm	**Iridium Welding Process Improvement,** *S. Pierce, P. Moniz (Los Alamos National Lab)*	Salon C
	Nuclear Thermal Propulsion: Considerations for Affordable Development Strategies, *G.E. Goughty (NASA MSFC)*	
	Determining an Affordable Mars Mission Capable NTP Thrust Size, *C.R Joyner II, J.H Levack, J. Crowley (Aerojet Rocketdyne)*	
	Affordable Development and Demonstration of a Small NTR Engine and Stage: A Preliminary NASA, DOE and Industry Assessment, *S.K. Borowski, R.J. Sefcik (NASA GRC), J.E. Fittje (Vantage Partners), A.L. Qualls, B.G. Schnitzler (Oak Ridge National Lab), A. Weitzberg (DOE Consultant), C.R. Joyner (Aerojet Rocketdyne)*	
	Revised Point-of-Departure Design Options for the Nuclear Thermal Propulsion, *J.E. Fittje (Vantage Partners), B.G. Schnitzler (Oak Ridge National Lab), S.K. Borowski (NASA GRC)*	

2:30 pm - 6:00 pm	**Track IV: Advanced Concepts** Advanced Nuclear Safety and Radiation Detection	Salon B
	An Analysis of Projected Risks from Abnormal Occurrences During Ground Based Testing and Development of Space Nuclear Systems, *L.A. Hardin Jr. (Nuclear Regulatory Commission)*	
	Space Nuclear System Development Process Risk Mitigation, *L.A. Hardin Jr. (Nuclear Regulatory Commission)*	
	Potential Regulatory Processes and Frameworks to Support Space Nuclear Development, *L.A. Hardin Jr. (Nuclear Regulatory Commission)*	
	GEANT4 Based Assessment of the Cosmic Radiation Transport in Space: Examples of International Space Station and Apollo, *M. Lund, T. Jevremovic (University of Utah)*	
	Microstructured Semiconductor Neutron Detectors (MSNDs), D.S. McGregor (Kansas State University), *S.L.Bellinger (Radiation Detection Technologies), R.G. Fronk, L.C. Henson, T.R. Ochs, J.K. Shultis, T.J. Sobering (Kansas State University)*	
	Mechanical Properties and Sublimation Studies of Composited High Temperature Thermoelectric Lanthanum Telluride, La3-xTe4, and 14-1-1 Zintls, Yb14MnSb11, *J. Ni, T. Caillat, S. Firdosy, J. Paik, J. Ma (Jet Propulsion Lab)*	

Tuesday February 24, 2015

8:00 am - 9:30 am	**Track I: Radioisotope Power Systems** Radioactive Isotope Studies: Part A Cont'd	Salon A
	Personnel Dose Cost Considerations for Pu-238 Heat-Source Production, *D.E. Kornreich, A.C. Davis (Los Alamos National Lab)*	
	Feasibility Study of Polonium Isotopes as Radioisotopes Fuel for Space Nuclear Power, *J. NIshiyama (Tokyo Institute of Technology)*	
	Compatibility of Tantalum Coated Stainless Steel with Compounds of 238Pu, *D. Spengler, M. Stoll, M.A. Reimus (Los Alamos National Lab)*	

Track I: Radioisotope Power Systems
CeO2 as a Fuel Simulant

9:30 am - 12:30 pm — Salon A

Dilatometry Characterization of CeO2 Ceramic Discs as a Function of Temperature and Atmosphere, *D.P. Kramer, S.M. Goodrich, C.D. Barklay, C.E. Whiting (University of Dayton Research Institute)*

Development of Cerium-Neodymium Oxide Surrogates for Americium Oxieds, *E.J. Watkinson (University of Leicester), M.J. Sarsfield (National Nuclear Lab), R.M. Ambrosi, H.R. Williams, D. Weston, N. Marsh, C. Haidon (University of Leicester), K. Stephenson (European Space Agency), T. Tinsley (National Nuclear Lab)*

Sintering Trials of Ceria as an Analogue of Americium-241, *E.J. Watkinson (University of Leicester), C.E. Whiting, C.D. Barklay (University of Dayton Research Institute), R.M. Ambrosi, H.R. Williams (University of Leicester), M. Reece, H. Ning (Queen Mary University of London), D. Weston (University of Leicester), M. Sarsfield, T. Tinsley (Natoinal Nuclear Lab), D. Kramer (University of Dayton Research Institute)*

Hot Pressing of CeO2 Ceramic Pellets, *D.P. Kramer, T.M. Pierson, C.O, Sjöblom, S.M. Goodrich, C.D. Barklay, C.E. Whiting (University of Dayton Research Institute)*

Reduction of CeO2, a PuO2 Surrogate, Via Gas Phase Interaction with Graphite, *H. Knachel, C.E. Whiting, C.D. Barklay, D.P. Kramer (University of Dayton Research Institute)*

Track I: Radioisotope Power Systems
Power Conversion Technologies: Part A

8:30 am - 12:00 pm — Salon B

Manufacturability Demonstration and Assessment of Aerogel Applicability as an Insulation Replacement for eMMRTG Flight Module, *Y. Song, J. Wojcik, T.C. Holgate, G. Gaines, R. Utz, M. Nicolau, R. Bennett, T. Hammel, S. Keyser (Teledyne Energy Solutions), J. Paik, S. Jones, T. Caillat (Jet Propulsion Lab)*

Skutterudites for Space Power – Developing Flight Capable Thermoelectric Modules, *R. Bennett, J. Wojcik, Y. Song, G. Gaines, R. Utz, T.C. Holgate, S. Keyser, T. Hammel, M. NIcolau (Teledyne Energy Systems), T. Caillat (Jet Propulsion Lab)*

Stutterudite-Based Advanced Thermoelectric Technology for Potential Integration into an Enhanced MMRTG, *T. Caiiat, I. Chi, S. Firdosy, C.-K. Huang, K. Smith, J. Paik, J.-P. Feurial (Jet Propulsion Lab), R. Bennett, S. Keyser (Teledyne Energy Systems)*

Thermoelectric Module Mechanical Performance Effects in Am-241 Radioisotope Thermoelectric Generators, *H.R. Williams, R.M. Ambrosi, K. Chen, U. Fiedman (University of Leicester), H. Ning, M.J. Reece (Queen Mary University of London), M.C. Robbins, K. Simpson (European Thermodynamics), K. Stephenson (European Space Agency)*

Enhancing the Performance of Zintl Phases via Defect Chemistry, *S.K. Bux, A. Zevalkink, D. Uhl, F. Drymiotis, D. Neff, W. Zeier, E. Cheng, J. Snyder, P.V. Allmen, J-P. Fleurial (Jet Propulsion Lab)*

Direct Energy Conversion Radioisotopes Based Battery, *L. Popa-Simil (Los Alamos Academy of Sciences)*

Track III: Nuclear Thermal Propulsion
NTP Reactor Design & Modeling

8:00 am - 12:30 pm

Salon C

Exploring the Design Space of CERMET LEU ZrH1.8 Moderated Nuclear Thermal Propulsion Systems, *W.R. Deason (Center for Space Nuclear Research), M.J. Eades (The Ohio State University/CSNR), P.J. Husemeyer (University of Cambridge/CSNR), V.K. Patel (Texas A&M University/CSNR)*

Full Submersion Criticality Accident Mitigation in the Carbide LEU-NTR, *P. Venneri, Y. Kim (Korea Advanced Institute of Science and Technology)*

Time Dependence of Fission Energy Deposition in Nuclear Thermal Rockets, *M.J. Eades (The Ohio State University), J.A. Caffrey (Oregon State University)*

Reactor Design Comparison of 25-klb Composite and Cermet Fueled NTRs, *D. Poston (Los Alamos National Lab)*

Thermal Rocket Nuclear Design Evaluation and Control System Modification Using MCNP, *J.B. McCallum (Idaho State University)*

CSNR Space Propulsion Optimization Code: SPOC, P.J. Husemeyer (University of Cambridge/CSNR), *V. Patel (Texas A&M University/CSNR), P.F. Venneri (Korea Advanced Institute of Science and Technology/CSNR), W.R. Deason (Center for Space Nuclear Research), M.J. Eades (The Ohio State University/CSNR), S.D. Howe (Center for Space Nuclear Research)*

Preliminary Design Study of an Innovative High-Performance Nuclear Thermal Rocket Utilizing LEU Fuel, *S.H. Nam, P.F. Venneri, J.Y. Choi, Y.H. Jeong (Korea Advanced Institute of Technology), S.H. Chang (Handong Global University)*

An Arcjet Augmented Nuclear Thermal Rocket for Interplanetary Exploration, *C.G. Rosaire IV (Texas A&M University)*

8:30 am - 12:00 pm	Track IV: Advanced Concepts Advanced Nuclear Mission Design	Salon D
	Engineering Space Nuclear Power Systems Using a System of Systems Perspective, *R. Onuschak (DOE), C. E. Sandifer II (NASA GRC)*	
	One Bit, One Joule: Data Return, Science Value and Power on Deep-Space Missions, *R.D. Lorenz (Johns Hopkins University)*	
	Limits of the Advanced Nuclear Power Systems for Space Exploration, *L. Popa-Simil (Los Alamos Academy of Science)*	
	Radioisotope-Based Propulsion System Enabling Exploration with Small Payloads, *N.D. Jerred, T.M. Howe (Center for Space Nuclear Research), A. Rajguru (University of Southern California, S.D. Howe (Center for Space Nuclear Research*	
	Storing Water Propellant Mined from Asteroids, *A. Rajguru), J. Nieminen (University of Southern California/CSNR , N. Nadupalli (University of Michigan/CSNR), J. Weatherford (George Fox University/CSNR), J. Santora (University of Utah/CSNR)*	
	Detection and Extraction of Water from Hydrated C-Class Asteroids in the Main Asteroid Belt, *A. Rajguru), J. Nieminen (University of Southern California/CSNR , N. Nadupalli (University of Michigan/CSNR), J. Weatherford (George Fox University/CSNR), J. Santora (University of Utah/CSNR)*	
	Development of Modeling Approaches for Nuclear Thermal Propulsion Test Facilities, *D. R. Jones, D. C. Allgood, and K. Nguyen (NASA-JSC)*	

1:30 pm - 5:00 pm	Track I: Radioisotope Power Systems Radioactive Isotope Studies: Part B	Salon A
	Optimisation to TRL4 241Am Separations to be Used in Radioisotope Power Systems, *M.J. Sarsfield, M.J Carrott, C.C. Maher, C. Mason, C. Cambell, J. Holt, T. Griffiths, C. Gregson, T. Tinsley (National Nuclear Lab), K. Stephenson (European Space Agency)*	
	Post-Irradiation Examiniation of 237Np Targets for 238Pu Production, *R.N. Morris, C.A. Baldwin, R.W. Hobbs, J.E. Schmidlin (Oak Ridge National Lab)*	
	Current Status of the Plutonium-238 Production Project, *R. M. Wham (Oak Ridge National Lab)*	
	Characterization of Pu-238 Heat Source Granule Containment, *P.D. Richardson, J. Sanchez, A.D. Neuman, R. Chavarria (Los Alamos National Lab)*	
	Modleing the Substoichiometric Behavior of 238PuO2 and 241AmO2 in the Low Oxygen Potential Environments Found in Radioisotope Power Systems, *C.E Whiting (University of Dayton Research Institute), E.J. Watkinson (University of Leicester), C.D. Barklay, D.P. Kramer (University of Dayton Research Institute), H.R. Williams, R.M. Ambrosi (University of Leicester)*	
	Neutronics Simulations of 237Np Targets to Support Safety-Basis and 238Pu Production Assessment Efforts at the High Flux Isotope Reactor, *D. Chandler (Oak Ridge National Lab)*	

	Track I: Radioisotope Power Systems Power Conversion Technologies: Part B		
1:30 pm - 5:00 pm	**Mechanical Properties and Sublimation Studies of Composited High Temperature Thermoelectric Lanthanum Telluride, La3-xTe4, and 14-1-11 Zintls, Yb14MnSb11,** *J. Ni, T. Caillat, S.A. Firdosy, J-A. Pail, J. Ma (Jet Propulsion Lab)*	Salon B
	The Segmented Thermoelectric Module: A Common Converter Building Block for Future Radioisotope and Fission Thermoelectric Generators, *J-P. Fleurial, S. Firdosy, B.C-Y. Li, K. Smith, (Jet Propulsion Lab)*	
	Zintl Thermoelectrics for Power Generation in Space, *U. Aydemir (California Institute of Technology), A. Zevalkink (Jet Propulsion Lab), A. Ormeci (Max Planck Institute for Chemical Physics of Solids), S. Bux (Jet Propulsion Lab), G.J Snyder (California Institute of Technology)*	
	Lanthanum Telluried-Nickel Thermoelectric Composites with Enhanced Mechanical Strength and Toughness, *J. M. Ma, J.P. Niroula, J-P. Fleurial, S.K. Bux (Jet Propulsion Lab)*	
	Development of Ambiently Dried Aerogels for Thermoelectric Power Generators, *J-A. Paik, S.M. Jones, T. Caillat, J-P. Fleurial (Jet Propulsion Lab)*	
	Development of High Temperature Device Technologies for the Advanced Thermoelectric Couple Project (ATEC), *S. Firdosy, T. Caillat, B. C-Y. Li, C.K. Huang, V. Ravi, J. Pail. D. Uhl, S. Bux, J. Ni, K. Smith, G. Nakatsukasa, J-P. Fleurial (Jet Propulsion Lab)*	
	Track II: Fission Power and Electric Propulstion NEP Reactor Physics and Fuel	
1:30 pm - 4:30 pm	**Initial Characterization of the Advanced Stirling Radioisotope Generator EU2,** *E.J. Lewandowski, S.M. Oriti (NASA GRC)*	Salon D
	Benchmark Experiment for Fast Neutron Spectrum Potassium Worth Validation in Space Power Reactor Design, *J. Bess (Idaho National Lab)*	
	The Performance of an Acciedent-Tolerant Control Drum System for HEU-Fueled Space Reactors, *H.C. Lee, T.Y Han, H.S. Lim, J.M. Noh (Korea Atomic Energy Research Institute)*	
	Solid Matrix Fuels for Space Power Reactors, *C.G. Morrison, W. Ji (Rensselaer Polytechnic Institute)*	
	Thermal Power Scaling of the Kilopower Reactor Concept, *D.I. Poston, P.R. McClure (Los Alamos National Lab)*	

1:30 pm - 5:00 pm	**Track III: Nuclear Thermal Propulsion** NTP Engine and Component Development	Salon C
	Nuclear Thermal Propulsion Component Development, *O.R. Mireles, D.P. Cavender, C. Garcia, C. Gomez (NASA MSFC), W. Deason (Center for Space Nuclear Research), T. Goode (University of Alabama), D. Konyndyk (Oregon State University)*	
	Temperature Profile in Fuel and Tie-Tubes for Nuclear Thermal Propulsion Systems, *V. Patel (Texas A&M University/CSNR)*	
	Development of a Prototypic Tie-Tube for Low-Enriched Uranium Nuclear Thermal Propulsion, *K.M. Benensky (The Pennsylvania State University), J.W. Harry (Iowa State University), J.T. Clemens (Texas A&M University), O.R. Mireles (NASA MSFC)*	
	Reflector and Control Drum Design for a Nuclear Thermal Rocket, *T. Goode (NASA MSFC/University of Alabama), J. Clemens (NASA MSFC/Texas A&M University), M. Eades (The Ohio State University/CSNR), J.B. Pearson (NASA MSFC)*	
	Shielding Development for Nuclear Thermal Propulsion, *J.A. Caffrey (Oregon State University/NASA MSFC), C.F. Gomez, L.L. Scharber (NASA MSFC)*	

Wednesday February 25, 2015

Track I: Radioisotope Power Systems
Material or System Testing

8:00 am - 12:30 pm

Salon A

High-Temperature Mechanical Properties of a DOP-26 Iridium Alloy Under Impact Loading, *B. Song, K. Nelson, R. Lipinksi, J. Bignell (Sandia National Lab), G.B. Ulrich, E.P. George (Oak Ridge National Lab)*

Design of a Flight Demonstration Experiment for Radioisotope Thermophotovoltaic (RTPV) Power System, *A. Goel (Stanford University), B. Franz (University of Southern California), K.J. Schillo (University of Alabama-Huntsville), S. Reddy (University of Southern California), S. Howe (Center for Space Nuclear Research)*

Safety Analysis Models for the Irradiation of 237N Targets at the High Flux Isotope Reactor, *C.J. Hurt (University of Tennessee), J.D. Freels, F.P. Griffin, D. Chandler, R.W. Hobbs, R.M. Wham (Oak Ridge National Lab)*

Demonstration of Sol-Gel Techniques for Dust-Free Plutonium-238 Heat Source Fabrication, *J.A. Katalenich (Pacific Northwest National Lab/University of Michigan)*

High-Rate Starin Testing on High-Strength Graphite as a Simulant for Fine Weave Pierced Fabric (FWPF) Aeroshell Material, *D.P. Kramer, S.I. Hill, J Chumack, S.M. Goodrich, C.D. Barklay, C.E. Whiting (University of Dayton Research Institute)*

Summary of the Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement, *D.J. Clayton, J. Bignell, C.A. Jones, D.P. Rohe, G.J. Flores, T.J. Bartel, F. Gelbard, S. Le, C.W. Morrow, D.L. Potter, L.W. Young, N.E. Bixler, R.J. Lipinksi (Sandia National Lab)*

Lifecycle Testing of the EU/QU MMRTG, *C.D. Barklay, B.A. Tolson, C.W. Sjöblom, R.J. Harris (University of Dayton Research Institute*

Sublimation Suppression Coating for Thermoelectric Materials, *C.D. Barklay, D.P. Kramer (University of Dayton Research Institute), P.R. Lichty, D.M. King (PneumaticCoat Technologies), T.M. Wittberg (Mound Technical Solutions)*

8:00 am - 12:30 pm | Salon B

Track I: Radioisotope Power Systems
Power System Technology: Part A

Chassis Short Mitigation and Characterization Techinique for the Multi-Mission Radioisotope Thermoelectric Generator, *G. Bolotin, N. Keyawa (Jet Propulsion Lab)*

The eMMRTG – To Europa, Titan or Mars, *T. Hammel (Teledyne Energy Solutions), B. Otting (Aerojet Rocketdyne), R. Bennett, B. Sievers (Teledyne Energy Solutions)*

Radioisotope Thermoelectric Generators Based on Americieum-241, R.M. Ambrosi, *H.R. Williams (University of Leicester), M. Robbins (European Thermodynamcis Ltd), H. Ning, M. Reece (Queen Mary University of London), K. Simpson (European Thermodynamics Ltd), P. Samara-Ratna (University of Leicester), M-C. Perkinson, K. Tomkins (Airbus Defense and Space), K. Stephenson (European Space Agency), N.P. Bannister, T. Crawford, D. Vernon, E.J. Watkinson (University of Leicester)*

RTG Degradation Primer and Application of the MMRTG, *T. Hammel (Teledyne Energy Solutions), B. Otting (Aerojet Rocketdyne), R. Bennett, B. Sievers (Teledyne Energy Solutions)*

Beta Voltaic Power Source Design Using an Electron Emitting Radioisotope Source for a Pinger Device to be Dropped on a Hydrated C-Class Asteroid, *A. Rajguru, J. Nieminen (University of Southern California/CSNR), N. Nadupalli (University of Michigan/CSNR), J. Weatherford (George Fox University/CSNR), J. Santora (University of Utah/CSNR)*

Advanced Stirling Radioisotope Generator Engineering Unit 2 Final Assembly, *S.M. Oriti (NASA GRC)*

A History, the Development and Potential Mission Uses for a 40mW Radioisotope Power System, *F.A. Leavitt (Hi-Z Technology), B.J. Nesmith (Jet Propulsion Lab), J.C. Bass, C. Brown (Hi-Z Technolgoy)*

Track II: Fission Power and Electric Propulsion
NEP Power Conversion and Associated Technologies

Turbo-Brayton Power Converter for Spaceflight Applications, *J. Breedlove, T.M. Conboy, D. Deserranno, M.V. Zagarolo (Creare)*

Thermodynamic Analysis and Radiator Design of a Pulsed Bi-modal Radioisotope Propulsion System, *A. Rajguru, J. Nieminen (University of Southern California/CSNR), N. Nadupalli (University of Michigan/CSNR), J. Weatherford (George Fox University/CSNR), J. Santora (University of Utah/CSNR)*

Trade Study on Thermodynamic Architectures for Low Specific Mass Electric Space Power Systems, *C.G. Morrison, W. Ji (Rensselaer Polytechnic Institute)*

Preliminary Desing of an Ultra-High Temperature Reactor Using MHD Power Conversion for Mars Exploration, *W. An, J. Song, G. Hu, J. Xie, S. Zhao, A. Sun (China Institute of Atomic Energy)*

High Temperature Water-Titanium Heat Pipes for Spacecraft Fission Power, *W.G. Anderson, R. Hay (Advanced Cooling Technologies)*

	Track III: Nuclear Thermal Propulsion NTP Fuel Development	
8:00 am - 12:00 pm	**A Historical Review of Cermet Fuel Development and the Engine Performance Implications,** *M.E. Steward (VPL)*	Salon C
	Hot Isostatic Pressing (HIP) of W-UO2 CERMETS for Nuclear Thermal Propulsion, *R. Hickman, G> Belancik, M. Barnes, D. Tucker, R. Waelchli (NASA MSFC)*	
	CSNR-Aerojet Rocketdyne Cermet Fuels Research: Summary and Status, *R.C. O'Brien, L.A. Hone, S.D. Howe (Center for Space Nuclear Research), C.R. Joyner, R. Meyers (Aerojet Rocketdyne)*	
	Optimization of a WCl6CVD System to Coat UO2 Powder with Tungsten, *G.A. Belancik, M.W. Barnes, O. Mireles, R. Hickman (NASA MSFC)*	
	Methodology for Producing a Uniform Distribution of UO2 in a Tungsten Matrix, *D.S. Tucker (NASA MSFC), A. O'Conner (Purdue University), R. Hickman, J. Broadway, G. Belancik (NASA MSFC)*	
	Development of Advanced Coatings for NERVA-Type Fuel Elements, *S.V. Raj, J.A. Nesbitt (NASA GRC)*	
	CrYOgenic to High TEmperature (CYOHTE) Test Train for Transient Reactor Testing Fuels, *R.C. O'Brien (Center for Space Nuclear Reseach), N.E. Woolstenhulme (Idaho National Lab)*	
	Track I: Radioisotope Power Systems Material or System Testing Cont'd	
1:30 pm -2:30 pm	**Pyroschock Induced Loads Driving Electrical, Thermal, and Structural Impacts in Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs),** *A. Derkevorkian, A.R. Kolaini, N.R. Keyawa, D.J. Neff, B.J. Nesmith, T.J. Hendricks (Jet Propulsion Lab)*	Salon A
	New Horizons NEPA/LA Lessons Learned, *Y. Chang (John Hopkins University)*	

	Track I: Radioisotope Power Systems RPS Infrastructure and Capabilities	
2:30 pm - 6:00 pm	**Heat Source Compenent Manufacturing Qualifications for Radioisotope Power Systems at Oak Ridge National Lab,** *G.B Ulrich, G.R. Romanoski, C.I. Contescu, E.K. Ohriner, B.R. Friske, R.G. Miller, K.R. Veach Jr. (Oak Ridge National Lab)*	Salon A
	DOE Radioisotope Power Systems Infrastructure, Technical and Regulatory Challenges, Approaches and Successful Outcomes: How We Got to Where We Are, *S.G. Johnson, K.L. Lively (Idaho National Lab)*	
	Idaho National Laboratory Recent Equipment Development for Fueling and Testing Radioisotope Power Systems, *K.L. Lively, J.C. Birch, S.E. Davis, C.E. Dees, G.A. Hula, K.R. Munns, S.G. Johnson (Idaho National Lab)*	
	Refurbishment of LANL's Heat Source Manufacturing Infrastructure to Meet Future Mission Needs, A.D. McLaughlin, *D.E. Kornreich, R.M. Burnside (Los Alamos National Lab)*	
	Iridium Welding Process Improvement, *S.W. Pierce, P.F. Moniz (Los Alamos National Lab)*	
	Modernizing Welding Capability, *P.F. Moniz, S. Pierce, J.N. Martinez, J.L. Brown, E.M. Serrano, A. Hoff, A. Thronas, B. Rose (Los Alamos National Lab)*	
	Track I: Radioisotope Power Systems Power System Technologies: Part B	
1:30 pm - 6:00 pm	**Radioisotope Power System Pool Concept,** *J.J. Rusick (NASA GRC), G.S. Bolotin (Jet Propulsion Lab)*	Salon B
	Optimized Backup Cooling System for the Advanced Stirling Radioisotope Generator, *C.L. Schwendeman, C. Tarau (Advanced Cooling Technologies), N.A. Schifer (NASA GRC), J.Polak, W.G. Anderson (Advanced Cooling Technologies)*	
	Initial Characterization of the Advanced Stirling Radioisotope Generator EU2, *E.J. Lesandowski, S.M. Oriti (NASA GRC)*	
	Real-Time Electrical Advanced Stirling Convertor Simulator, *D.P. Frankford, H.H. Ambrose, D.J. Duven, A. Shamkovich, M.E. Fraeman, D. Adams (Applied Physics Lab)*	
	Advanced Radioisotope Thermoelectric Generators (ARTGs) that Leverage Segmented Thermoelectric Technology, *B. Otting (Aerojet Rocketdyne), T. Hammel (Teledyne Energy Solutions), D. Woerner, J-P. Fleurial (Jet Propulsion Lab)*	
	Stirling Technology Research Overview, *S.D. Wilson (NASA GRC)*	
	Advanced Stirling Convertor Technology Development, *W.A. Wong (NASA GRC)*	
	Radioisotope Fueld Thermophotovoltaic Power Systems for Space Applications, *J. Strauch, A. Klein, P. Charles (General Atomics), C. Murray (3-L Communications), M. Du (Oak Ridge National Lab)*	

	Track II: Fission Power and Electric Propulsion NEP Reactor Analytical Studies	
1:30 pm - 3:30 pm	**Low-Cost Radiator for Fission Power Thermal Control,** *T. Maxwell, C. Tarau, W.G. Anderson (Advanced Cooling Technologies, M. Wrosch (Vanguard Space Technologies), M.H. Briggs (NASA GRC)*	Salon D
	Radiation Guiding in Active Nano-Structures for Shielding and Nuclear Reaction Control Systems, *L. Popa-Simil (Los Alamos Academy of Sciences)*	
	Liquid Metal Thermo-magnetic Systems for Space, Nuclear, and Industrial Applications, *C. Maidana (Maidana Research)*	
	Computational Predications of the Reactor Simulator Subsystem at NASA GRC, *T.V. Reid (NASA GRC)*	
	Low-Cost Radiator for Fission Power Thermal Control, *T. Maxwell, C. Tarau, W.G. Anderson (Advanced Cooling Technologies, M. Wrosch (Vanguard Space Technologies), M.H. Briggs (NASA GRC)*	
	Track III: Nuclear Thermal Propulsion NTP Test Facility & Regulatory Considerations	
1:30 pm - 3:30 pm	**Assessment of Space Nuclear Thermal Propulsion Facility and Capability Needs,** *J. Werner (Idaho National Lab)*	Salon C
	Review of Nuclear Thermal Propulsion Engine Ground Test Options, *D. Coote (NASA JSC)*	
	Nuclear Thermal Propulsion Development Risks, *T. Kim (NASA MSFC)*	
	Initial Operation of the Nuclear Thermal Rocket Element Environmental Simulator, *W.J. Emrich Jr, J.B. Pearson, M.P. Schoenfeld (NASA MSFC)*	
	Fusion and Transmutation Energy Sources, *L. Popa-Simil (Los Alamos Academy of Sciences)*	
	Progress in Development of an LENR Power Cell for Space, *G.H. Miley, K-J. Kim, E. Ziehm, T. Patel, B. Stunkard (University of Illinois)*	
	The Magneto-Confined Fusion Ion Thruster, *S. Lakshminarayana (Rajasthan Institute of Engineering and Technology)*	
	Magnetic Collector for Traveling Wave Direct Energy Conversion of Fission Reaction Fragments, *A.G. Tarditi (Electric Power Research Institute), J.H. Scott (NASA JSC)*	
	Track IV: Advanced Concepts NTP Test Facility & Regulatory Considerations	
4:30 pm - 6:00 pm	**Fusion and Transmutation Energy Sources,** *L. Popa-Simil (Los Alamos Academy of Sciences)*	Salon C
	Progress in Development of an LENR Power Cell for Space, *G.H. Miley, K-J. Kim, E. Ziehm, T. Patel, B. Stundark (University of Illinois)*	
	The Magneto-Confined Fusion Ion Thruster, *S. Lakshminarayana (Rajasthan Institute of Engineering and Technology)*	
	Magnetic Collector for Traveling Wave Direct Energy Conversion of Fission Reaction Fragments*, A.G. Tarditi (Electric Power Research Institute), J.H. Scott (NASA JSC)*	

John D. Bess, PhD
R&D Nuclear Engineer
Chair of International Benchmarking Programs
Nuclear Systems Design and Analysis
Idaho National Laboratory

John Bess is a research and development nuclear engineer in the Nuclear Systems Design and Analysis Department at the Idaho National Laboratory. In this capacity, he performs physics analyses and benchmark evaluation to support computational validation, experiment design, and refinement of integral nuclear data. His activities include significant involvement with the International Reactor Physics Experiment Evaluation Project (IRPhEP) and the International Criticality Safety Benchmark Experiment Project (ICSBEP), organized under the auspices of the OECD NEA; he currently serves as the Chair for both projects. Reactor physics modeling and simulation activities include fast reactor analysis of FFTF and ASTRID, graphite-reactor analysis of HTTR and HTR-PROTEUS, and reactor physics support for research reactors such as NRAD and TREAT. Dr. Bess also provides support for space nuclear applications and mentorship of participants in the benchmark projects.

Prior to joining the Idaho National Laboratory in 2008, Dr. Bess worked for the Center for Space Nuclear Research. He also currently serves as the Chair of the Aerospace Nuclear Science and Technology Division (ANSTD) of the American Nuclear Society.

Dr. Bess earned his B.S. degree in chemical and fuels engineering in 2003, M.S. degree in nuclear engineering in 2005, and Ph.D. in nuclear engineering in 2008 from the University of Utah.

Alice K. Caponiti
Director
Office of Space and Defense Power Systems
Office of Nuclear Energy
U.S. Department of Energy

Alice Caponiti is the Director of Department of Energy's Office of Space and Defense Power Systems. Her office designs, builds, tests, and delivers safe and reliable nuclear power systems for space exploration and national security applications and performs detailed safety analyses for each mission. Ms. Caponiti is working to reestablish a reliable domestic supply of plutonium-238 – the nuclear material used in radioisotope power systems that provide reliable, long duration power for space exploration missions. She served as the as the technical advisor to the Department of State and a United Nations working group on space nuclear power sources, as well as a risk communications spokesperson for the New Horizons mission to Pluto and the Mars Science Laboratory mission that delivered the Curiosity rover to the surface of Mars. Ms. Caponiti also serves on the Generation IV International Forum Experts Group that advises on research and development needed to establish the feasibility and performance capabilities of the next generation nuclear energy systems.

Prior to joining the Department's space and defense power systems program in 2002, Ms. Caponiti worked on a nonproliferation program dealing with the other plutonium – Pu-239 – on a program to reduce stockpiles of excess Russian weapons plutonium.

Ms. Caponiti earned her B.S. degree in civil engineering from the University of Maryland in 1991 and M.S. degrees in nuclear engineering and the Technology and Policy Program from the Massachusetts Institute of Technology in 1995.

William H. Gerstenmaier
Associate Administrator for Human Exploration and Operations
NASA Headquarters

William H. Gerstenmaier is the associate administrator for the Human Exploration and Operations Directorate at NASA Headquarters in Washington, DC. In this position, Gerstenmaier provides strategic direction for all aspects of NASA's human exploration of space and cross-agency space support functions of space communications and space launch vehicles. He provides programmatic direction for the continued operation and utilization of the International Space Station, development of the Space Launch System and Orion spacecraft, and is providing strategic guidance and direction for the commercial crew and cargo programs that will provide logistics and crew transportation for the International Space Station.

Gerstenmaier began his NASA career in 1977 at the then Lewis Research Center in Cleveland, Ohio, performing aeronautical research. He was involved with the wind tunnel tests that were used to develop the calibration curves for the air data probes used during entry on the Space Shuttle.

Beginning in 1988, Gerstenmaier headed the Orbital Maneuvering Vehicle (OMV) Operations Office, Systems Division at the Johnson Space Center. He was responsible for all aspects of OMV operations at Johnson, including development of a ground control center and training facility for OMV, operations support to vehicle development, and personnel and procedures development to support OMV operations. Subsequently he headed the Space Shuttle/Space Station Freedom Assembly Operations Office, Operations Division. He was responsible for resolving technical assembly issues and developing assembly strategies.

Gerstenmaier also served as Shuttle/Mir Program operations manager. In this role, he was the primary interface to the Russian Space Agency for operational issues, negotiating all protocols used in support of operations during the Shuttle/Mir missions. In addition, he supported NASA 2 operations in Russia, from January through September 1996 including responsibility for daily activities, as well as the health and safety of the NASA crewmember on space station Mir. He scheduled science activities, public affairs activities, monitored Mir systems, and communicated with the NASA astronaut on Mir.

In 1998, Gerstenmaier was named manager, Space Shuttle Program Integration, responsible for the overall management, integration, and operations of the Space Shuttle Program. This included development and operations of all Space Shuttle elements, including the orbiter, external tank, solid rocket boosters, and Space Shuttle main engines, as well as the facilities required to support ground processing and flight operations.

In December 2000, Gerstenmaier was named deputy manager, International Space Station Program and two years later became manager. He was responsibility for the day-to-day management, development, integration, and operation of the International Space Station. This included the design, manufacture, testing, and delivery of complex space flight hardware and software, and for its integration with the elements from the International Partners into a fully functional and operating International Space Station.

Named associate administrator for the Space Operations Directorate in 2005, Gerstenmaier directed the safe completion of the last 21 Space Shuttle missions that witnessed assembly complete of the International Space Station. During this time, he provided programmatic direction for the integration and operation of the International Space Station, space communications, and space launch vehicles.

Gerstenmaier received a bachelor of science in aeronautical engineering from Purdue University in 1977 and a master of science degree in mechanical engineering from the University of Toledo in 1981. In 1992 and 1993, he completed course work for a doctorate in dynamics and control with emphasis in propulsion at Purdue University.

Gerstenmaier is the recipient of numerous awards, including three NASA Certificates of Commendation, two NASA Exceptional Service Medals, a Senior NASA Outstanding Leadership Medal, the Meritorious Executive Presidential Rank Award, and Distinguish Executive Presidential Rank Award. He also was honored with an Outstanding Aerospace Engineer Award from Purdue University. Additionally, he was twice honored by Aviation Week and Space Technology for outstanding achievement in the field of space. His other awards include: the AIAA International Cooperation Award; the National Space Club Astronautics Engineer Award; National Space Club Von Braun Award; the Federation of Galaxy Explorers Space Leadership Award; AIAA International Award; the AIAA Fellow; Purdue University Distinguished Alumni Award; and Honored at Purdue as an Old Master in the Old Masters Program; recipient of the Rotary National Award for Space Achievement's National Space Trophy; Space Transportation Leadership Award; the AIAA von Braun Award for Excellence in Space Program Management; and the AIAA von Karman Lectureship in Astronautics.

He is married to the former Marsha Ann Johnson. They have two children.

Dr.John E. Kelly, PhD
Deputy Assistant Secretary for Nuclear Reactor Technologies, Office of Nuclear Energy

Dr. John E. Kelly is the Deputy Assistant Secretary for Nuclear Reactor Technologies in the Office of Nuclear Energy. His office is responsible for the Department of Energy (DOE) civilian nuclear reactor research and development portfolio, which includes DOE's programs on Small Modular Reactors, Light Water Reactor sustainability, and Generation IV reactors. His office is also responsible for the design, development, and production of radioisotope power systems, principally for NASA missions. In the international arena, Dr. Kelly chairs the Generation IV International Forum and the International Atomic Energy Agency's Standing Advisory Group on Nuclear Energy.

Prior to joining the Department of Energy, Dr. Kelly spent 30 years at Sandia National Laboratories where he was engaged in a broad spectrum of research programs in nuclear reactor safety, advanced nuclear energy technology, and national security.

Dr. Kelly received his B.S. in nuclear engineering from the University of Michigan in 1976 and his Ph.D. in nuclear engineering from the Massachusetts Institute of Technology in 1980.

David C. Schurr
Deputy Director of Planetary Science Division, NASA's Science Mission Directorate

David C. Schurr is the Deputy Director of the Planetary Science Division of NASA's Science Mission Directorate, and is the Director of Solar System Exploration Programs. Schurr oversees a $1 billion in annual development, operations, and research for missions exploring all aspects of the solar system.

Formerly, Schurr was the NASA Comptroller. In this position, Schurr directed NASA's budget formulation, advocacy and execution processes for the Agency's institutions, programs and projects.

In 1982, Schurr began his career at the Johnson Space Center in Houston Texas, as a Shuttle flight controller in mission control. He was responsible for various defense and interplanetary satellites deployed using the Space Shuttle.

Beginning in 1993, Schurr was responsible for managing the integration of the Japanese Laboratory into the International Space Station. Subsequently, he managed development of the Italian-built logistics and habitation modules for the International Space Station.

Schurr managed the Prime development contract for the International Space Station and became deputy business manager of the International Space Station Program in 2001, responsible for program control and budget processes.

Schurr has been at NASA headquarters since 2003.

Schurr received a Bachelor of Science degree in aerospace engineering from the University of Notre Dame in 1982, a master of science degree in process control from the University of Houston in 1987, and a master of business administration degree from the University of Houston in 1996.

He is married to the former Catherine Ramsay Morgan. They have four children.

Scott J. Seymour
GenCorp President and Chief Executive Officer

Scott Seymour's career in the aerospace and defense industry spans five decades and he currently serves as GenCorp President and CEO, including the company's subsidiaries, Aerojet Rocketdyne, Inc., Energetic Technology Solutions, LLC, and Easton Development Company, LLC. He joined GenCorp in January 2010 and also held the position of Aerojet President through August 2012.

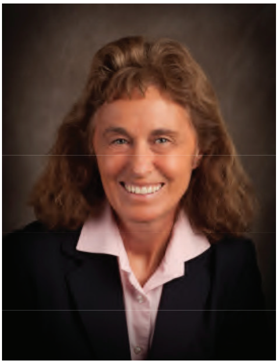
Aerojet Rocketdyne is a world-recognized aerospace and defense rocket propulsion engineering and manufacturing company providing propulsion and energetics systems to the space, missile defense, strategic, tactical missile and armaments areas in support of domestic and international markets. Energetics Technology Solutions is an energy business which applies rocket propulsion science to solve complex energy challenges. Easton is a real estate business which is currently engaged in the entitlement and development of approximately 6,000 acres of the company's excess Sacramento-area land.

Prior to joining GenCorp, Mr. Seymour served in a number of senior leadership positions at Northrop Grumman, including corporate vice president and president of Integrated Systems, vice president of Air Combat Systems, and vice president and B-2 program manager.

While serving as president of the Integrated Systems sector, the portfolio Mr. Seymour managed included the B-2 Stealth Bomber, Unmanned Combat Air System (N-UCAS), RG-4A Global Hawk, Broad Area Maritime Surveillance (BAMS), RQ-8A Firescout, E-8 Joint STARS and the E-2D Advanced Hawkeye. He also led the company's efforts on the F/A-18E/F Super Hornet, EA-18G Growler and F-35 programs. Prior to joining Northrop Grumman, Mr. Seymour was involved in the manufacture and flight testing of the F-14A, EF-111A and the F/A-18A aircraft for Grumman Aerospace and McDonnell Douglas.

A United States Marine Corps veteran, Mr. Seymour holds a Bachelor of Science in Electrical Engineering from Polytechnic University in Brooklyn, N.Y., and received his Juris Doctorate from Western State University College of Law. Mr. Seymour is a member of the Florida Institute of Technology board of trustees; the board of managers of the U.S.A.F. National Museum; the Air Warrior Courage Foundation board and the Astronauts Memorial Foundation board.

Mr. Seymour is married and has four children.



Julie A. Van Kleeck
Vice President
Advanced Space and Launch Business Unit

Julie Van Kleeck is Vice President of the Advanced Space and Launch Business Unit for Aerojet Rocketdyne. In this position, she is responsible for space and launch propulsion research, technology development and product development programs.

Ms. Van Kleeck joined Aerojet in 1981 and was appointed to her present position in June 2013. Prior to this assignment, she was the vice president of the Space and Launch Business Unit and the Space Programs organization for Aerojet. From 2004-2005, she was the executive director for Atlas programs.

From 2001-2004, she served as executive director, Space Systems Business Development, responsible for the strategic direction, investments and growth of Aerojet's space propulsion business. From mid-1999 to October 2001, Ms. Van Kleeck managed a multi-national commercial launch vehicle project,during which she interfaced extensively with foreign launch vehicle companies and affiliated governmental agencies.

Prior to these appointments, Ms. Van Kleeck held numerous technical and management assignments at Aerojet where she focused on rocket propulsion research and development for defense, civil andcommercial markets. She has been instrumental in the development of leading-edge rocket propulsiontechnology and products for Aerojet Rocketdyne. She has been responsible for critical productadvancements in divert and attitude propulsion for kill vehicle applications and integrated propulsionsystems for space exploration, which are among Aerojet Rocketdyne's most important business focus areas. In addition, as evidenced by the Atlas V solid rocket motors, Ms. Van Kleeck led the adaptation of strategic propulsion products to the commercial market place.

Ms. Van Kleeck earned her Bachelor of Science degrees in Mechanical and Aeronautical Engineering from the University of California and has extensive "hands-on" experience in fundamental rocket combustion research and development, systems engineering and liquid rocket engine and system design, development and testing. She has received numerous technical awards from Aerojet Rocketdyne, GenCorp and outside organizations. Throughout the last decade, she has participated on many senior management review teams, external to Aerojet Rocketdyne, that have addressed a broad range of space and launch subjects. She is also chairperson of the European Space Propulsion board of directors.

Ms. Van Kleeck resides in Folsom, Calif. with her husband and extended family. She is an avid skier and runner.

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

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

The National Aeronautics and Space Administration (NASA) missions, programs and projects are ensuring the United States will remain the world's leader in space exploration and scientific discovery for years to come, while making critical advances in aerospace, technology development and aeronautics. The United States has been developing and utilizing space nuclear systems for over 50 years, and remains an international leader in that area. Space nuclear systems have supported missions ranging from the Apollo moon landings to the Mars Science Laboratory to outer planet probes. Future space nuclear power and propulsion systems may enable even more exciting missions within our solar system and beyond.

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

The UK's National Nuclear Laboratory (NNL) offers an unrivalled breadth of technical products and services to our customers across the whole nuclear industry.

Covering the complete nuclear fuel cycle from fuel manufacture and power generation, through to reprocessing, waste treatment and disposal and including defence, new nuclear build and Homeland Security. NNL provides these services supported by an impressive range of facilities and links with international research organisations, academia and other national laboratories. NNL's facilities are second to none. The Central Laboratory at Sellafield is the most modern nuclear research facility in the world. The Windscale Laboratory provides Post-Irradiation Examination (PIE) and other services critical to plant life extension. At Workington NNL operates a non-radioactive test rig facility and at Preston NNL operates a uranium active chemistry laboratory. NNL also has staff at the Risley, Stonehouse and Harwell sites providing Head Office functions, graphite technology, radiation chemistry and modelling/simulation.

Aerojet Rocketdyne is a world-recognized aerospace and defense leader providing propulsion and energetics to the domestic and international space, missile defense and strategic systems, tactical systems and armaments areas, and transformational energy technology solutions to address the world's energy needs. GenCorp is a diversified company providing innovative solutions to its customers in the aerospace and defense, energy and real estate markets.

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

Abstract Number	Abstract Title	Authors	First Author Affiliation
5001	High-temperature Mechanical Properties of a DOP-26 Iridium Alloy under Impact Loading	B. Song, K. Nelson, R. Lipinski, J. Bignell, G. B. Ulrich, E. P. George	Sandia National Laboratories
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High-temperature Mechanical Properties of a DOP-26 Iridium Alloy under Impact Loading

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Abstract. Iridium alloys have been utilized as structural materials for certain high-temperature applications due to their superior strength and ductility at elevated temperatures. In some applications, the iridium alloys may be subjected to extreme environments that include a combination of high temperature and high-speed impact. Thus, the high-temperature high-strain-rate mechanical properties of the iridium alloys must be fully characterized to understand the mechanical response of the components in these severe applications. Kolsky bars (also called split Hopkinson bars) have been employed for high-strain-rate characterization of materials in compression or tension at room temperature. It has been challenging to directly apply the Kolsky bars for dynamic measurements at high temperatures even in compression, let alone in tension, which is significantly more difficult. In this study, we modified the conventional room-temperature Kolsky compression and tension bars for dynamic high-temperature compressive and tensile characterization of iridium alloys. DOP-26 iridium alloy blanks with a thickness of 0.65 mm were made into disc specimens with a diameter of 3 mm for compression tests and dog-bone-shape sheet specimens with a gage section of 2.54 mm (width) by 6.35 mm (length) for tensile tests. The stress-strain curves of the DOP-26 iridium alloy were obtained in compression at four different strain rates (~300, 1000, 3000, and 10000 s^{-1}), in tension at two different strain rates (~1000 and 3000 s^{-1}), and in both cases at two different temperatures (750 and 1030°C). Both compressive and tensile stress-strain curves of the DOP-26 iridium alloy showed significant strain-rate and temperature effects. At certain strains, the flow stresses significantly increase with increasing strain rates but decrease when temperature increases. The dynamic tensile stress-strain curves also demonstrated high ductility of the DOP-26 iridium alloy at high strain rates and elevated temperatures. The dynamic tensile stress-strain curves were also compared with the compressive stress-strain curves at similar strain-rate and temperature conditions. Uncertainties in the dynamic high-temperature compression and tensile tests are discussed.

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Keywords: Iridium alloy, Kolsky bar, Stress-strain curve, High strain rate, Elevated temperature

Design of a Flight Demonstration Experiment for Radioisotope Thermophotovoltaic (RTPV) Power System

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Abstract. Radioisotopes have been used as the power source for many unmanned missions throughout the solar system. In most cases, the power system used has been the radioisotope thermoelectric generator (RTG) with plutonium-238 dioxide (PuO_2) serving as the radioisotope of choice. Despite their proven flight heritage, RTGs have low power conversion efficiencies, on the order of 6-8%. By contrast, a radioisotope thermophotovoltaic (RTPV) system can offer efficiencies above 15%. In addition to this, the shortage of plutonium has made americium an attractive alternative. In this paper, we describe the design of an RTPV flight demonstration experiment using americium 241 as the radioactive thermal source.

Due to the regulations associated with launching radioisotopes in space, we choose the Payload Orbital Delivery System from Space Systems Loral to host our experiment on a geostationary satellite. With analysis done using Monte Carlo N-Particle code, we find that while pure americium dioxide poses challenges in terms of source preparation and handling, a couple of millimeters of tungsten shielding is enough to reduce the radioactivity levels to almost zero. Static and vibrational loading analysis coupled with the thermal radiation modeling leads to the choice of six, 3mm diameter Incoloy 903 rods for mounting. Based on the analysis of the power conversion efficiency, roughened tantalum emerges as the best option for selective emitter. The overall system efficiency is estimated to be around 6-8% and a sensitivity analysis reveals that this value is highly sensitive to the reflectivity profile of the filters used on the PV cells. Our algorithm also shows that by going to larger sizes or by switching to Plutonium dioxide, we can achieve efficiencies close to 15%. Finally, we discuss the changes in shielding requirements and temperatures if the system were to use plutonium instead of americium.

Keywords: radioisotope, thermophotovoltaic, americium, plutonium, thermal efficiency

Optimisation to TRL4 for ^{241}Am separations to be used in radioisotope power systems

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Abstract. Electrical power sources used in outer planet missions are a key enabling technology for data acquisition and communications. Power sources generate electricity from the thermal energy from alpha decay of the radioisotope ^{238}Pu via thermo-electric conversion. Production of ^{238}Pu requires specialist facilities including a nuclear reactor and reprocessing plants that are expensive to build and operate, so naturally, a more economical alternative is attractive to the industry. Within Europe ^{241}Am is a feasible alternative to ^{238}Pu that can provide a heat source for radioisotope thermoelectric generators (RTGs) and radioisotope heating units (RHUs). As a daughter product of ^{241}Pu decay, ^{241}Am is present at 1000s kg levels within the UK civil plutonium stockpile.

A chemical separation process is required to extract the ^{241}Am in a pure form and the process to achieve this has been presented previously but only on a 0.5g ^{241}Am scale and with lower concentrations of ^{241}Am in the feed. This paper presents the results of increasing the americium levels to full scale process concentrations. A number of improvements to the process have been made that result in a >99% pure product with > 99% recovery. This level of recovery is important when minimising the amount of radioactivity sent to waste streams and the level of impurities found in the final product.

The paper will discuss the improvements to the flowsheet, how they have been successful and comment on americium oxide pellet pressing which is the next stage in the process.

Keywords: Americium, heat source, solvent extraction, impurity analysis.

Radioisotope Power System Pool Concept

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Abstract. Advanced Radioisotope Power Systems (RPS) for NASA deep space science missions have historically used static thermoelectric-based designs because they are highly reliable, and their radioisotope heat sources can be passively cooled throughout the mission life cycle. Recently, a significant effort to develop a dynamic RPS, the Advanced Stirling Radioisotope Generator (ASRG), was conducted by NASA and the Department of Energy, because Stirling based designs offer energy conversion efficiencies four times higher than heritage thermoelectric designs; and the efficiency would proportionately reduce the amount of radioisotope fuel needed for the same power output. However, the long term reliability of a Stirling based design is a concern compared to thermoelectric designs, because for certain Stirling system architectures the radioisotope heat sources must be actively cooled via the dynamic operation of Stirling converters throughout the mission life cycle. To address this reliability concern, a new dynamic Stirling cycle RPS architecture is proposed called the RPS Pool Concept. This system, if developed further, could provide the following capabilities:

1. Passive cooling of radioisotope heat sources throughout the mission life cycle.
2. A single modular design that uses a small Stirling converter building block approach to support potential future missions between 100 to 1000 Watts.
3. High system reliability via Stirling converter redundancy.
4. Cold sparing of Stirling converters.
5. Ability to turn all Stirling converters on or off during storage, spacecraft integration, or on-orbit operations (safe mode during cruise).
6. Power cycling and/or reset of Stirling converter controller cards to clear single event upsets.
7. Excess radioisotope heat available for spacecraft thermal control.

The key design elements of the Pool Concept that will be described in the NETS presentation are:

- Overall Pool Concept size and configuration – Watts/kg
- (N) Advanced Stirling Converters (ASCs) which produce AC power
- Advanced Controller Unit (ACU) that can run (N) ASCs and produces DC power
- General Purpose Heat Source (GPHS) modules
- Low-temperature space radiator for Stirling converter heat rejection
- High-temperature radiator to radiate GPHS heat directly to space
- Thermal shadow shield that would fail “open” to provide fail-safe cooling of all GPHS modules, or would partially open when some ASCs are running and cooling the GPHS modules
- A low-pressure NaK pool
- Electric motor-driven NaK mixers to minimize temperature gradients in the NaK pool
- A passive damper system to isolate ASC vibrations from the spacecraft

Keywords: Radioisotope, Stirling, GPHS, Controller, Converter, Sodium

Post-Irradiation Examination of ^{237}Np Targets for ^{238}Pu Production

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Abstract. Oak Ridge National Laboratory is recovering the US ^{238}Pu production capability and the first step in the process has been to evaluate the performance of a ^{237}Np target cermet pellet encased in an aluminum clad. The process proceeded in 3 steps; the first step was to irradiate capsules of single pellets composed of NpO_2 and aluminum power to examine their shrinkage and gas release. These pellets were formed by compressing sintered NpO_2 and aluminum powder in a die at high pressure followed by sintering in a vacuum furnace. Three temperatures were chosen for sintering the solution precipitated NpO_2 power used for pellet fabrication. The second step was to irradiate partial targets composed of 8 pellets in a semi-prototypical arrangement at the two best performing sintering temperatures to determine which temperature gave a pellet that performed the best under the actual planned irradiation conditions. The third step was to irradiate ~50 pellets in an actual target configuration at design irradiation conditions to assess pellet shrinkage and gas release, target heat transfer, and dimensional stability. The higher sintering temperature appeared to offer the best performance after one cycle of irradiation by having the least shrinkage, thus keeping the heat transfer gap between the pellets and clad small minimizing the pellet operating temperature. The final result of the testing was a target that can meet the initial production goals, satisfy the reactor safety requirements, and can be fabricated in production quantities. The current focus of the program is to verify that the target can be remotely dissembled, the pellets dissolved, and the ^{238}Pu recovered. Tests are being conducted to examine these concerns and to compare results to code predictions. Once the performance of the full length targets has been quantified, the pellet ^{237}Np loading will be revisited to determine if it can be increased to increase ^{238}Pu production.

Keywords: Post-Irradiation, ^{237}Np target, ^{238}Pu, cermet pellet

Safety Analysis Models for the Irradiation of ^{237}Np Targets at the High Flux Isotope Reactor

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Abstract. A campaign is underway to provide a new domestic supply of plutonium-238 using existing nuclear research reactors at the Oak Ridge National Laboratory (ORNL) and Idaho National Laboratory (INL) and existing chemical recovery facilities at ORNL. Validation and testing activities for new irradiation target designs have been conducted in three phases over a 2 year period to provide data to support an increased throughput toward a continuous production phase. Design, qualification and fabrication of "fully loaded" targets of NpO_2/Al pellets have been completed at ORNL and target irradiation is ongoing at the High Flux Isotope Reactor (HFIR) at ORNL. In order to qualify experiments for irradiation at HFIR, bounding accident conditions established in the HFIR safety analysis report (SAR) must be analyzed. Target design drawings, pellet fabrication data and post-irradiation examination (PIE) measurements are input to computational safety analyses that calculate conservative parameters of interest in the target including maximum internal temperatures, coolant surface temperatures and structural stress/strain maxima. Heat generation and decay rates in the target are analyzed using the neutronics codes MCNP, SCALE, and VESTA. Steady-state thermal-structural analysis of the target is performed in COMSOL Multiphysics, and transient thermal hydraulic analysis is performed in RELAP5. The primary physics phenomena explored include heat conduction, structural mechanics, thermal hydraulics, neutron transport, and isotopic transmutation with specific challenges in gas-gap/contact conductance, coupled thermal-structural responses and pellet irradiation behavior.

Keywords: hfir, pu-238, thermal, Np-237, ornl.

Development of a Prototypic Tie-Tube for Low-Enriched Uranium Nuclear Thermal Propulsion

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Abstract. Nuclear thermal propulsion (NTP) is under consideration for future human missions to deep space destinations such as Mars. NTP will be capable of providing a specific impulse (I_{sp}) nearly double that of the highest performing chemical engines, which significantly reduces the amount of propellant required for to complete a mission and with reduced transit time. NASA in collaboration with external partners is investigating development a low enriched uranium (LEU) engine concepts for future mission needs. The current point design calls for an array of in-core tie-tube elements, which function in part to pre-heat the hydrogen propellant that will drive the turbo-pump and house the zirconium hydride ($ZrH_{1.8}$) moderator to thermalize the neutron spectrum. A small development team was tasked to mature a tie tube concept by considering detailed mechanical design and materials selection based upon specific design constraints. The material and thermo-mechanical response of the system was evaluated through the construction of a sub-scale tie-tube test rig. An experimental test apparatus was developed in order to determine temperature gradients across the tie-tube, variations in inlet and outlet pressure, and potential material degradation. Nitrogen, argon, and hydrogen was used over a range of mass flow rates and furnace temperatures (-200 - 500^{o}C). The project culminated in the construction and preliminary testing of the test rig in addition to the creation and quantification of ZrH samples. Future work aims to scale the test rig to effectively test full-length tie-tube elements.

Keywords: Nuclear Thermal Propulsion, Tie-Tube, Low Enriched Uranium, Zirconium Hydride

Neutronics Simulations of ^{237}Np Targets to Support Safety-Basis and ^{238}Pu Production Assessment Efforts at the High Flux Isotope Reactor

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Abstract. Fueled by two highly enriched uranium-bearing fuel elements surrounded by a large concentric ring of beryllium reflector, the High Flux Isotope Reactor (HFIR) provides one of the highest neutron fluxes in the world that is used to produce unique isotopes like plutonium-238. As part of the US Department of Energy's task to re-establish the domestic production of ^{238}Pu to power deep-space missions for the National Aeronautics and Space Administration, a technology demonstration sub-project has been initiated using HFIR at the Oak Ridge National Laboratory (ORNL), the Advanced Test Reactor at Idaho National Laboratory and the chemical recovery facilities at ORNL to develop and implement the technology required to establish a new ^{238}Pu supply chain.

The "fully loaded" ^{238}Pu production target design consists of an aluminum cladding tube loaded with a stack of cermet pellets composed of neptunium-dioxide blended with aluminum powder (NpO_2/Al). Neutron capture on ^{237}Np produces ^{238}Np, which beta-decays into ^{238}Pu. Irradiations in HFIR's permanent beryllium reflector (PB), which is penetrated by 22 vertical experiment facilities (VXF), are being assessed. The neutronics toolkit being used includes the MCNP, VESTA and SCALE codes that are maintained and developed at Los Alamos National Laboratory, Institut de Radioprotection et de Sûreté Nucléaire (France) and ORNL, respectively.

Safety-basis neutronics calculations are performed to ensure the target irradiations have no adverse impacts on reactor performance such as power tilts that are greater than those previously evaluated in the HFIR safety analysis report, as well as to calculate data required as input to follow-on analyses. Fission product gas inventories, fission densities, nuclear heat generation rates and decay heat data are calculated and provided to thermal-structural and thermal-hydraulic specialists who perform follow-on safety-basis analyses to demonstrate the pellets' melting temperature would not be exceeded if subjected to bounding conditions and to study other parameters of interest. Post-shutdown radionuclide inventories are calculated to support post-irradiation examination, transportation, storage and dose consequence analyses.

Assuming HFIR operates for 6–7 cycles per year, it is estimated that a total of 0.96–1.12 kg ^{238}Pu (~1.28–1.49 kg PuO_2 at 85% ^{238}Pu/Pu purity) could be produced per year in the PB. However, it is important to note that other irradiation facilities exist in HFIR for potential ^{238}Pu production, some PB facilities may need to be reserved for other users and a few facilities may need to be left unoccupied if it is determined that they adversely affect other HFIR scientific missions like neutron scattering when loaded with ^{238}Pu targets. Comparisons of post-irradiation isotopic measurements to calculated inventories will serve to validate the neutronics methods.

Keywords: plutonium-238, HFIR, isotope, depletion, neutronics.

Demonstration of Sol-Gel Techniques for Dust-Free Plutonium-238 Heat Source Fabrication

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Abstract. Sol-gel methods are being developed to produce oxide microspheres of materials as surrogates for plutonium-238 (Pu-238). Aqueous-based fuel fabrication techniques such as the internal gelation sol-gel process are of interest for Pu-238 heat source production as a means to prevent the generation of corrosive, radioactive fines currently produced by ball-milling steps in the traditional powder-based flowsheet. However, sol-gel methods must be developed and demonstrated for Pu-238 heat source production to ensure that the process is viable and yields an equivalent product. Due to the hazardous nature of Pu-238, sol-gel demonstration work is being performed using a stepped approach with increasingly relevant surrogate materials. Initial work at the University of Michigan included the design and construction of a lab-scale device capable of producing 10 grams per day of monodisperse, non-radioactive cerium oxide microspheres with diameters near 100 µm. Analysis of cerium oxide microspheres has indicated that the desired sizes can be produced with very low impurity levels. Density and specific surface area measurements on cerium oxide microspheres also suggest that spheres could be pressed into oxide pellets with the desired coarse porosity. Based on results with cerium oxide, additional work with neptunium and plutonium-239 surrogates is planned at the Pacific Northwest National Laboratory as a part of a postdoctoral fellowship. A modified sol-gel apparatus is being designed for use in a glovebox to refine the process chemistry and production parameters to produce neptunium oxide, and subsequently plutonium oxide, microspheres for further analysis. Based on results with neptunium and plutonium surrogates, further investigations to explore the effects of radiolysis and heat generation from Pu-238 will be considered.

Keywords: sol-gel, microspheres, plutonium-238, radioisotope power

MEGAHIT: Conclusion of the development of the advanced propulsion roadmap for HORIZON2020

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Abstract. A significant number of exploration missions require nuclear propulsion for which power sources are essential and enabling key assets. Associated technological developments however require important financial efforts that can probably only take place in the frame of an international collaboration, sharing the efforts as this has been the case for the International Space Station. MEGAHIT, funded by the European Commission under the 7th Framework Programme for Research and Technological Development, was a supporting action aiming at building a European roadmap for Megawatt level nuclear electric propulsion, in preparation of the Horizon 2020 programme. It concluded in September 2014. MEGAHIT was driven by a consortium coordinated by the European Science Foundation and included CNES, DLR, Keldysh Research Center, the National Nuclear Laboratory from U.K. and Thales Alenia Space Italia. The consortium favoured an open and participative approach in order that all interested stakeholders - research centers, agencies and industry- within consortium or not, can establish common research objectives and initiate research alliances. This approach allowed the building of a scientific and technical community on the topic in Europe and Russia. Potential collaboration opportunities at international level with other space fairing nations were also explored.

Megahit adopted an approach in 4 phases.

- **Phase 1: High level requirements.** Collected inputs from space agencies and research centers on mission-related high level requirements.

- **Phase 2: Reference vision.** Built a reference vision of what system we aim at, and what would be the best technological options.

- **Phase 3: Technological plans.** The rationale was that the best people for establishing technological plans are the stakeholders identified as being able to carry out the development. These stakeholders were associated through discussions and workshops on technologies they have expertise in. Main workshop was held in Brussels on December 2013 and was attended by about a hundred specialists.

- **Phase 4: Road-maps.** Aims at a synthesis of the three previous phases, translating into consistent roadmaps what has been established in terms of key technologies and technological plans.

The paper and presentation will provide a summary of the project and conclusions on the progress made. The follow on project named DEMOCRITIOS will be discussed in a separate paper.

Keywords: MEGAHIT, electrical propulsion, reactor.

Preliminary Design Study of an Innovative High-Performance Nuclear Thermal Rocket Utilizing LEU Fuel

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Abstract. A Nuclear Thermal Rocket (NTR) is a viable and efficient option for manned deep-space missions such as to Mars and beyond. The NTR technology has already been developed and successfully tested for over 50 years since the 1950s by the United States (US) and Russia. The representative US NERVA type reactors traditionally load hexagonal shaped fuel elements utilizing High Enriched Uranium (HEU) due to the imperative of making a high power reactor with a minimum size. This state-of-the-art NTR technology could be applicable with contemporary space vehicles. However, even though the NTR designs utilizing HEU is the best choice in terms of rocket performance and technical maturity, they inevitably arouse nuclear proliferation obstacles on all Research and Development (R&D) activities by civilians and non-nuclear weapon states, and its eventual commercialization. To cope with the security issue to use HEU, the innovative future NTR engine concept utilizing Low Enriched Uranium (LEU) fuel is proposed in this paper. The Korea Advanced NUclear Thermal Engine Rocket utilizing LEU (KANUTER-LEU) is currently being designed at Korea Advanced Institute of Science and Technology (KAIST). The major design requirement is to make use of LEU fuel for its compact reactor, but does not sacrifice the rocket performance relative to the traditional NTRs utilizing HEU. The KANUTER-LEU mainly consists of a 250 MW_{th} moderated Extremely High Temperature Gas cooled Reactor (EHTGR) utilizing H_2 propellant, a propulsion system housing a Propellant Feeding System (PFS), a Nozzle Assembly, etc., and an optional Electricity Generation System (EGS) as a bimodal engine. To implement LEU fuel for the EHTGR, the KANUTER adopts W-UO_2 CERMET fuel to increase uranium density drastically and metal hydride moderators to thermalize neutrons in the core consequentially having a high neutron economy. The moderator and structural material selections also consider neutronic and thermo-physical characteristics to reduce non-fission neutron loss and reactor weight. The geometry design of fuel element and reactor focuses on protective cooling capability, fabricability and compactness. This paper mainly presents the preliminary design study of the KANUTER-LEU focusing on the neutronic and thermohydraulic features. The result shows comparable characteristics of high efficiency, and compact and lightweight system despite the heavier LEU fuel utilization. The reference performance is theoretically estimated at a thrust of 51.4 kN, a thrust to weight ratio of 5.5 and a specific impulse of 916 s.

Keywords: nuclear propulsion, nuclear thermal rocket, innovative space reactor, low enriched uranium

Current Status of the Plutonium-238 Production Project

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Abstract. Since 2012, the Oak Ridge National Laboratory has been working on the plutonium-238 (Pu-238) production project to re-establish the capability to produce ~ 1.5 kg/yr. of plutonium oxide (PuO_2). Early target design tests started with targets containing a single pellet of neptunium oxide/aluminum NpO_2/Al. After target irradiation, fission gases were sampled and analyzed to determine release fraction. The pellets were cut out of the targets for dimensional measurements. Review of post irradiation examination data allowed the design to scale up rapidly from single pellets to partially loaded targets. Kilogram quantities of neptunium oxide have been irradiated to make ~ 100 gm of Pu for use in chemical processing tests to validate product purity, as well as validate the efficiency of the chemical process steps. Chemical processing steps will be conducted to first dissolve the aluminum and actinides. The next step will be solvent extraction to separate and dispose of fission products as well as partition the Pu and Np. Once Pu has been separated, it will be purified using anion exchange then converted to a solid oxide via oxalate precipitation/calcination. The product PuO_2 will be shipped to Los Alamos National Laboratory. Neptunium will be recovered and recycled back to target fabrication. The current status of process tests, as well as a limited set of results will be presented.

Keywords: RPS; plutonium-238; chemical processing; target irradiation

The 2014 NASA Nuclear Power Assessment Study: Mission Study Results Investigating Advanced Radioisotope Power Systems and Fission Power Systems

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Abstract. The 2008 Titan Saturn System Mission (TSSM) and 2010 Uranus Orbiter and Probe (UOP) studies were used as Design Reference Missions (DRMs) during the recent NASA Nuclear Power Assessment Study (NPAS). The TSSM concept required a total power of 540 W_e at end of mission (EOM) using 2008 Advanced Stirling Radioisotope Generators (ASRGs) producing 135 W_e EOM each, has high priority for the "next" decade, and is a complex mission concept with technology challenges for *in situ* elements. The UOP concept required a total power of 368 W_e at EOM using 2010 ASRGs producing 122.5 W_e EOM each, and was ranked third by the decadal survey for the next Flagship mission concept. Each DRM was studied: by replacing the ASRGs with higher-powered Radioisotope Power Systems (RPS) and Fission Power Systems (FPS), and by investigating the necessary accommodations required and their resulting impacts on the mission.

The TSSM RPS and FPS studies by NPAS explored the utility of increasing mission power from 500 W_e to 1,000 W_e. The UOP RPS study investigated new RPS at the 300-400 W_e power level. Variable unit sizing of power system levels was also examined: the revised TSSM concept utilized a Stirling Radioisotope Generator (SRG) concept with six General Purpose Heat Source (GPHS) modules or an Advanced Radioisotope Thermal Generator (ARTG) concept with 16-GPHS to achieve a 1,000 W_e power level. In contrast, the revised UOP concept utilized 4-GPHS SRG or 9-GPHS ARTG concepts to achieve 370 W_e EOM power while meeting mission's tight mass and configuration constraints. Based on these two study results, the redundancy policy for missions was noted to be a major driver to differentiate RPS options when considering future implementation.

NPAS also assessed the impact on science instrument design and measurements arising from utilizing RPS or FPS on a spacecraft. The impact of radiation, gamma rays, and neutrons on science instruments must be taken into account for FPS-enabled missions, in particular, for instruments with optical detectors and instruments that require high-voltage electronics. Total radiation dose could be mitigated with shield design, boom length, reactor operation duration, spot shielding, and instrument robustness. Thermal, vibration, EMI, and other effects are expected to be resolvable with standard spacecraft engineering approaches.

NPAS performed a broader assessment of future power needs and applicable power unit size. Human missions and science missions would have a variety of power needs that could be met by a combination of FPS and RPS. Potential human exploration mission power needs tend to be much higher than potential robotic science needs, and move into the tens of kW_e range. Based on the science mission-class power needs assessment results, future NASA Discovery, New Frontiers, and Flagship missions could all be supported by an RPS unit size of ~300 W_e at EOM.

The power level of the transition point between RPS and FPS is subjective and mission dependent. NPAS identified and discussed three major discriminators: plutonium fuel availability, power system mass, and power system cost impact. NPAS analyses using those discriminators found a prudent general transition point around 1 kW_e.

Keywords: RPS, FPS, Mission Study

The 2014 NASA Nuclear Power Assessment Study: Assembly, Test and Launch Operations Comparisons between a Notional 1 kWe Fission Power System and a Conventional Radioisotope Power System

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Abstract. The current notional FPS would be a compact reactor that would generate approximately 1 kWe of usable power. Although a small FPS shares some common features with with previous RPS, the use of this type of system would pose specific challenges in the area of assembly, test and launch operations (ATLO) of a FPS-powered mission. The intent of ATLO is to start with the various components required of the specific NASA mission (instrumentation packages, spacecraft, rocket fairing, nuclear power system, etc.) and, by the conclusion of operations, have a fully prepared rocket with mission-specific payload hardware on the launch pad tested and ready for launch. The current ATLO heritage based concept of operations explored to support a nuclear-powered mission involves a specific subset of existing buildings at KSC and Cape Canaveral Air Force Station (CCAFS): the Radioisotope Thermoelectric Generator Facility (RTGF), the Payload Hazardous Storage Facility (PHSF), and the Atlas Vertical Integration Facility (VIF) at Space Launch Complex-41 (SLC-41), and any connecting roadways between these structures that the nuclear materials would travel upon. The ATLO operations at KSC typically transpire over a six-month period immediately prior to launch. However, the preparations for these operations start approximately five years prior to launch. A significant activity that takes place outside of this six-month window is the Trailblazer or Pathfinder exercise, which is a detailed dress rehearsal of all procedures involved in handling the power system, its nuclear material, and any system associated with them. This activity typically takes place 12-18 months prior to launch, and requires the exercise of all detailed procedures by all organizations involved (NASA mission team, DOE, KSC, ULA, USAF, etc.).

The various combinations and permutations of assembling an FPS, providing for power system check-out, providing for a fully integrated check-out with spacecraft systems, and then movement of the various systems to the VIF and launch pad, were thoroughly considered, analyzed and assessed by the ATLO team based on the currently available information. Based on “negative” potential discriminators including the need for possible re-design of the Atlas V fairing and significant modifications to the VIF internal structures, the number of attractive options decreased from six to two. Both of these involved fully integrating the FPS into the launch vehicle fairing prior to movement of the fairing over to the VIF for integration with the rocket.

Keywords: RPS, FPS, Mission Study, ATLO

Democritos: preparing demonstrators for high power nuclear electric space propulsion

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Abstract. The Democritos project aims at preparing demonstrators for a mega-watt class nuclear-electric space propulsion. It is funded by Horizon 2020, the R&T program of the European Community. It is a new European and Russian project, including as partners: Nuclear National Laboratory (U.K.), DLR (Germany), The Keldysh Research Center (Russia), Thales Alenia Space Italia (Italy), Snecma (France), ESF (France) and CNES (France). IEAV (Brazil) will join as an observer. Democritos is the follow-up of the Megahit project.

During Megahit project, a reference architecture was established for 1MWe nuclear-electric propulsion, and a roadmap was proposed to have a spacecraft available by the early 30's. The main aim of Democritos is to start implementing the Megahit roadmaps by preparing demonstrators for some of the necessary technologies. Democritos features a technical part, with preliminary design of the demonstrators and their test benches. It features also a programmatic part, which will deal with financial and organizational aspects of such an endeavour: the ambition of the project is to initiate international cooperation, as broad as possible, which will lead to the implementation of the demonstrators.

Keywords: Nuclear, electric, space propulsion, Democritos, Megahit.

Benchmark Experiment for Fast Neutron Spectrum Potassium Worth Validation in Space Power Reactor Design

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Abstract. In the early 1960s a series of experiments were performed at the Oak Ridge Critical Experiments Facility (ORCEF) to support validation of reactor calculations and reactor physics methods for the design of small, potassium-cooled space power reactors. Various mock-up critical assemblies were performed using a vertical assembly machine. A separate experiment was performed to specifically test the fast neutron cross sections of potassium, as it was a candidate for coolant in some early space power reactor designs. The experiment was performed on the vertical assembly machine using a bare uranium (93.2 % ^{235}U) annulus constructed from multiple stacked rings of varying heights. The annulus outer diameter was approximately 13 inches (33.02 cm) and the inner diameter was approximately 7 inches (17.78 cm). The stacked critical height was approximately 5.6 inches (14.224 cm). Within the center of the annulus was placed two stainless steel cans. Two configurations of this experiment were measured, one with empty steel cans, and the other with potassium-filled cans. The measured difference in reactivity worth of the two near-critical configurations provided the worth of adding potassium to the system.

These two critical configurations were evaluated according to the guidelines of the *International Handbook of Evaluated Reactor Physics Benchmark Experiments* (IRPhEP Handbook). Physical uncertainties in the experiment, such as mass, enrichment, impurity content, and dimensions, were minimized to increase the accuracy of the results. The total evaluated uncertainty in the near-critical configurations is 37 pcm, of which 32 pcm of the total uncertainty pertains to the uncertainty in the measurement of the system reactivities. The benchmark experiment worth for the addition of approximately 2.4 kg of potassium metal was approximately 11 ± 1 ¢ (~0.0046 ± 0.0005 ¢/g). Calculations were then performed using the benchmark models and the neutron physics code Monte Carlo N-Particle (MCNP6.1) with contemporary neutron cross section libraries. Calculated results for the worth of the potassium were between 70 to 80 % lower than the benchmark values. Efforts continue to finalize benchmark assessment of this experiment for inclusion in the IRPhEP Handbook and identification of errors either in the experimental data or neutron cross section data for potassium.

Keywords: Benchmark, Potassium, Validation

Heat Source Component Manufacturing Qualifications for Radioisotope Power Systems at Oak Ridge National Laboratory

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Abstract. Facilities, processes, equipment, and personnel at Oak Ridge National Laboratory (ORNL) are utilized for development, production, and testing of high-temperature materials and components for radioisotope heat sources. Materials include precious metal alloys for fuel cladding as well as insulation materials such as Carbon Bonded Carbon Fiber (CBCF) to protect the fuel cladding from extremes of temperature under potential reentry scenarios. The precious metals are controlled under a Precious Metals Management Plan in accordance with applicable regulations. Precious metals used by the ORNL Radioisotope Power Systems Program include iridium, platinum, and rhodium for space and terrestrial missions. Qualification of CBCF components requires the measurement of 22 elemental impurities. After reviewing current analytical methods, Glow Discharge Mass Spectrometry (GDMS) was selected for quantification of the majority of specified elements. Neutron Activation Analysis (NAA) was used to quantify impurity levels to establish a Standard Reference Material. The results from repeated NAA analyses were evaluated statistically and further used for calibration of relative sensitivity factors for specified elements in the GDMS analysis. Additionally, analytical reference materials have been produced and characterized to qualify the use of GDMS for certification of chemical impurity levels in platinum-30% rhodium alloy (Pt-30Rh) and Pt powder. The analysis of the Rh content of Pt-30Rh alloy solids by inductively coupled plasma mass spectrometry using high pressure digestion of samples in mixed acid solutions was also qualified. Surface cleanliness of finished Pt-30Rh components is being qualified using x-ray photoelectron spectroscopy. In order to produce welded assemblies for shipment to Los Alamos National Laboratory for fueling, qualification of the welding processes and personnel are conducted by alternate methods as permitted by either American Welding Society (AWS) B2.1 or AWS D17.1. Laser cutting, instead of the current electrical discharge machining, of tensile impact specimens has been shown to produce surfaces free of contamination and no base metal effects. Studies are being conducted to qualify this process.

Acknowledgments. This work was sponsored by the United States Department of Energy (DOE) Office of Space and Defense Power System (NE-75). The authors gratefully acknowledge the support and guidance of Won S. Yoon of the U.S. Department of Energy.

Keywords: Heat source materials, CBCF, precious metals, glow discharge mass spectrometry, qualifications

Optimization of a WCl_6 CVD System to Coat UO_2 Powder with Tungsten

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Abstract. In order to achieve deep space exploration via Nuclear Thermal Propulsion (NTP), Marshall Space Flight Center (MSFC) is developing W-UO_2 CERMET fuel elements, with focus on fabrication, testing, and process optimization. A risk of fuel loss is present due to the CTE mismatch between tungsten and UO_2 in the W-60vol%UO_2 fuel element, leading to high thermal stresses. This fuel loss can be reduced by coating the spherical UO_2 particles with tungsten via H_2/WCl_6 reduction in a fluidized bed CVD system. Since the latest incarnation of the inverted reactor was completed, various minor modifications to the system design were completed, including an inverted frit sublimer. In order to optimize the parameters to achieve the desired tungsten coating thickness, a number of trials using surrogate HfO_2 powder were performed. The furnace temperature was varied between 930°C and 1000°C, and the sublimer temperature was varied between 140°C and 200°C. Each trial lasted 73-82 minutes, with one lasting 205 minutes. A total of 13 trials were performed over the course of three months, two of which were re-coatings of previous trials. The powder samples were weighed before and after coating to roughly determine mass gain, and Scanning Electron Microscope (SEM) data was also obtained. Initial mass results indicated that the rate of layer deposition was lower than desired in all of the trials. SEM confirmed that while a uniform coating was obtained, the average coating thickness was 9.1% of the goal. The two re-coating trials did increase the thickness of the tungsten layer, but only to an average 14.3% of the goal. Therefore, the number of CVD runs required to fully coat one batch of material with the current configuration is not feasible for high production rates. Therefore, the system will be modified to operate with a negative pressure environment. This will allow for better gas mixing and more efficient heating of the substrate material, yielding greater tungsten coating per trial.

Dilatometry Characterization of CeO_2 Ceramic Discs as a Function of Temperature and Atmosphere

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Abstract. PuO_2 fuel pellets are currently employed in space radioisotope power systems (RPS). PuO_2 under various conditions can release oxygen atoms resulting in a change in its stoichiometry. CeO_2 exhibits many similar properties compared to PuO_2 and has the added advantage that it is not radioactive allowing it to be used as a surrogate for PuO_2. In this study a Linseis L75 duel push rod vertical research dilatometer system was used to measure dimensional changes of cold pressed + furnace sintered CeO_2 discs which were next heated to soak temperatures of 1000°C and 1400°C while under various oxidizing (air) and reducing atmospheres (95% argon/5% hydrogen). The dilatometer system employed in these experiments is capable of measuring very small (sub-micron) dimensional changes during a time-temperature-atmosphere dilatometer experiment. The observed dimensional changes occurring in the ceramic discs can be related to changes in the stoichiometry of the CeO_2 which provides insight into how various sintering parameters may affect the mechanical characteristics of a ceramic component such as the manufacturing of a PuO_2 fuel pellet for space nuclear power applications.

Keywords: CeO_2, Thermal expansion, Dilatometry, Sintering, PuO_2, RTG

High-Rate Strain Testing on High-Strength Graphite as a Simulant for Fine Weave Pierced Fabric (FWPF) Aeroshell Material

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Abstract. Exploratory spacecraft to Pluto (New Horizons) and the surface of Mars (rover Curiosity) are powered by space nuclear power systems which convert the heat generated from the decay of the radioisotope plutonium-238 fuel into electricity. The $^{238}PuO_2$ fuel pellets are contained within several protective layers including an outer aeroshell which is fabricated using a ~3-D carbon/carbon composite (Fine Weave Pierced Fabric - FWPF). During an inadvertent launch incident the aeroshell is designed to tumble, and to help protect the integrity of the fuel pellets upon impact. Initial high-strain rate experiments have been performed on test specimens fabricated out of a highstrength graphite, as a low-cost simulant for FWPF, in order to enhance understanding of an aeroshell's response under high-rate strain impact scenarios.

Keywords: Fine Weave Pierced Fabric, FWPF, RTG, MMRTG, PuO_2

Methodology for Producing a Uniform Distribution of UO_2 in a Tungsten Matrix

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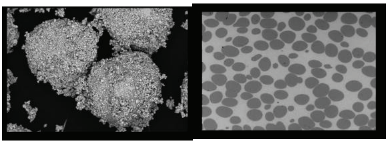
Abstract. Current work at NASA's Marshall Space Flight Center (MSFC) is focused on the development CERMET fuel materials for Nuclear Thermal Propulsion (NTP). The CERMETs consist of uranium dioxide (UO_2) fuel particles embedded in a tungsten (W) metal matrix. Initial testing of W-UO_2 samples fabricated from fine angular powders performed reasonably well, but suffered from significant fuel loss during repeated thermal cycling due to agglomeration of the UO_2 (1). The blended powder mixtures resulted in a non-uniform dispersion of the UO_2 particles in the tungsten matrix, which allows rapid vaporization of the interconnected UO_2 from the sample edges into the bulk material. Also, the angular powders create areas of stress concentrations due to thermal expansion mismatch, which eventually cracks the tungsten matrix. Evenly coating spherical UO_2 particles with chemical vapor deposited (CVD) tungsten prior to consolidation was previously demonstrated to provide improved performance. However, the CVD processing technology is expensive and not currently available.

In order to reduce cost and enhance performance, a powder coating process has been developed at MSFC to produce a uniform distribution of the spherical UO_2 particles in a tungsten matrix. The method involves utilization of a polyethylene binder during mixing which leads to fine tungsten powders clinging to the larger UO_2 spherical particles. This process was developed using HfO_2 as a surrogate for UO_2. Enough powder was mixed to make 8 discs (2cm diameter x 8mm thickness) using spark plasma sintering. A uniaxial pressure of 50 MPa was used at four different temperatures (2 samples at each temperature). The first two samples were heated to 1400C and 1500C respectively for 5 minutes. Densities for these samples were less than 85% of theoretical, so the time at temperature was increased to 20 minutes for the remaining samples. The highest densities were achieved for the two samples sintered at 1700C (~92% of theoretical). Scanning electron microscopy (SEM) of the mixed powders and the sintered samples along with energy dispersive x-ray analysis was obtained. The SEM of the powders clearly show the fine W powder adhered to the larger HfO_2 particles and a uniform distribution of HfO_2 particles in a tungsten matrix upon densification. Vicker's Microhardness testing was also performed on all samples using 0.5, 1.0 and 2.0 kg loads. Five indents were made at each load level. All indents were placed in the tungsten matrix to assist as a proxy in measuring densification. The highest hardness value was obtained for the 1700C specimens. The hardness average for these samples was 312.14 MPa. This powder processing method has been applied to W/UO_2 powders with the SEM of the powders appearing similar to the W/HfO_2 powder images.



SEM Images of Tungsten Coated HfO_2 particles and Resultant Densified Structure

1. R.J. Baker, J.L. Daniel, W.J. Lobsinger, R.J. Scott, F.A. Snojds, E.A. Roake. *Basic Behavior and Properties of W-UO2 CERMETS,* Pacific Northwest Laboratory, 1966. BNWL-394, NASA Report NASA-CR-54840.

Keywords: Cermet, Spark Plasma Sintering, Powder Processing

Assessment of Space Nuclear Thermal Propulsion Facility and Capability Needs

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Abstract. The development of a Nuclear Thermal Propulsion (NTP) system rests heavily upon being able to fabricate and demonstrate the performance of a high temperature nuclear fuel as well as an integrated reactor system prior to launch. A number of studies have been performed in the past which identified the facilities needed and the capabilities available to meet the needs and requirements identified at that time. Unfortunately, many facilities and capabilities within the Department of Energy have been rebuilt for other projects and missions, decommissioned or completely demolished. Any current or future NTP development effort will be subject to vary different constraints under which the Rover/NERVA program was conducted. Nuclear fuel tests and ground test operations of a reactor system will require an exhaust effluent treatment system to ensure only permitted releases of radioisotopes become airborne. Second, significant changes to the federal regulations governing the acquisition of major capital assets have occurred. These regulations will affect the coordination, review and management of design, construction and operation phases of the test facilities. DOE Order 413.3B establishes a sequence of major milestones identified as Critical Decisions from approval of mission need to start of operations. This paper provides a brief overview of the anticipated facility needs and identifies some promising concepts to be considered which could support the development of a nuclear thermal propulsion system. Detailed trade studies will need to be performed to support the decision making process.

Keywords: Nuclear, testing, facilities.

Nuclear Systems Kilopower Project Overview

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Abstract. The Nuclear Systems Kilopower Project was initiated by NASA's Space Technology Mission Directorate/Game Changing Development Program in fiscal year 2015 to demonstrate subsystem level of technology readiness of small space fission power in a relevant environment (Technology Readiness Level 5) for space science and human exploration power needs. The Nuclear Systems Kilopower Project consists of three elements. The primary element is the Kilopower Prototype Test. This element consists of the development and testing of a ¼ electrical power output and full thermal power ground technology demonstration of a small fission power system based on an 800 W_e reference space science power requirement. The second element, the Mars Kilopower System Concept, consists of the analysis and design of a scaled-up version of the 800 W_e reference concept to 3-10 kW_e for Mars surface power requirements. The third element is the design and development of a Kilopower high temperature water heat pipe radiator experiment prototype in preparation for a FY19 or later flight experiment development and test opportunity on the International Space Station.

The core of the Nuclear Systems Kilopower Project is the development and testing of a ¼ power electric, full thermal power ground technology demonstration of a small fission power system based on an 800 W_e space science power requirement. An 800 W_e Kilopower system will use four pairs of Stirling engines, with each pair generating 200 We. All technology objectives can be achieved with only one pair of full-scale Stirling engines. The components of the demonstration include the reactor core, heat pipes to transfer the heat from the core to the power conversion system, the power conversion system, and the radiators to reject power conversion waste heat. Los Alamos National Laboratory will lead the design of the reactor, and the Y-12 National Security Complex will fabricate it. NASA Glenn Research Center (GRC) will design, build, and demonstrate the balance of plant heat transfer, power conversion, and heat rejection portions of the Kilopower Prototype. NASA MSFC will develop an electrical reactor simulator for non-nuclear testing, and the shielding for nuclear testing. A non-nuclear electrically-heated demonstration of sodium heat pipe heat transfer, Stirling engine power conversion, and heat rejection will be assembled and tested at NASA GRC. Once the balance of plant has been tested and the reactor core has been fabricated, the balance of plant system will be reconfigured for a nuclear ground test, and the prototype will be assembled and tested at the Device Assembly Facility at the Nevada Nuclear Test Site. Figure 1 shows the evolution of Kilopower prototype development.

Keywords: Space Fission Power, Space Nuclear Power.

Summary of the Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement

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Abstract. In the summer of 2020, the National Aeronautics and Space Administration (NASA) plans to launch a spacecraft as part of the Mars 2020 mission. One option for the rover on the proposed spacecraft uses a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) to provide continuous electrical and thermal power for the mission. An alternative option considered is a set of solar panels for electrical power with up to 80 Light-Weight Radioisotope Heater Units (LWRHUs) for local component heating. Both the MMRTG and the LWRHUs use radioactive plutonium dioxide. NASA has prepared an Environmental Impact Statement (EIS) in accordance with the National Environmental Policy Act. The EIS includes information on the risks of mission accidents to the general public and on-site workers at the launch complex. The Nuclear Risk Assessment (NRA) addresses the responses of the MMRTG or LWRHU options to potential accident and abort conditions during the launch opportunity for the Mars 2020 mission and the associated consequences. This information provides the technical basis for the radiological risks of both options for the EIS. The paper provides a summary of the methods and results used in the NRA.

Keywords: nuclear risk assessment, environmental impact statement, Mars 2020 mission.

Characterization of Pu-238 Heat Source Granule Containment

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Abstract. The Milliwatt Radioisotopic Themoelectric Generator (RTG) provides power for permissive-action links. Essentially these are nuclear batteries that convert thermal energy to electrical energy using a doped silicon-germanium thermopile. The thermal energy is provided by a heat source made of 238Pu, in the form of 238PuO2 granules. The granules are contained by 3 layers of encapsulation. A thin T-111 liner surrounds the 238PuO2 granules and protects the second layer (strength member) from exposure to the fuel granules. An outer layer of Hastalloy-C protects the T-111 from oxygen embrittlement. The T-111 strength member is considered the critical component in this 238PuO2 containment system. Any compromise in the strength member seen during destructive testing required by the RTG surveillance program is characterized. The T-111 strength member is characterized through Scanning Electron Microscopy (SEM), and Metallography. SEM is used in the Secondary Electron mode to reveal possible grain boundary deformation and/or cracking in the region of the strength member weld. Deformation and cracking uncovered by SEM are further characterized by Metallography. Metallography sections are mounted and polished, observed using optical microscopy, then documented in the form of microphotographs. SEM mat further be used to examine polished Metallography mounts to characterize elements using the SEM mode of Energy Dispersive X-ray spectroscopy (EDS).

Keywords: Characterization, Metallography, Scanning Electron Microscopy

Nuclear Thermal Propulsion Component Development

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Abstract. Nuclear Thermal Propulsion (NTP) can enable rapid-transit of human missions to destinations beyond Low earth orbit. NTP uses many traditional rocket engine components; however, specialized NTP components that do not exist substantially impact engine design due to performance, cost, and schedule assumption uncertainty. NTP specific components that are undergoing development include: 1) a neutron reflector-ring segment with control drum assembly for reactor control, 2) tie-tubes that moderate the neutron spectrum, provide reactor-core structure, and supply the turbo-pump with heated propellant and 3) a combination injector-manifold or “injectifold” for core structure, tie-tube integration with the fuel elements and helps to regulate the core radial power distribution profile. An iterative development approach process of design, manufacture, and test is underway. Prototypes undergo separate effects tests to simulate expected operating conditions to yield preliminary performance data. As experience is gained sub-scale, low-fidelity tests evolve into full-scale, high-fidelity tests at expected engine operating conditions. Empirical results are then compared against analytical predictions and lessons learned are incorporated into the next design iteration. The primary objective is to affordably develop functional specialized NTP components while obtaining actual cost, schedule, and performance values used to anchor existing models.

Keywords: Nuclear, Thermal, Propulsion, Injectifold, Tie-Tube, Reflector.

Chassis Short Mitigation and Characterization Technique for the Multi-Mission Radioisotope Thermoelectric Generator

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Abstract. A flight-proven capable source of power is the Radioisotope Thermoelectric Generator (RTG)–essentially a nuclear battery that reliably converts heat into electricity. NASA and the Department of Energy (DOE) have developed a new generation of such power systems that could be used for a variety of space missions. The newest RTG, called a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), has been designed to operate on Mars and in the vacuum of space. However, shorts between the internal electrical power circuit and chassis frame of the MMRTG have been observed in the engineering unit, qual unit, and flight unit. The internal shorts seemed to appear and sometimes clear spontaneously. A root cause has not been determined for these internal shorts, and the resistance, power rating, and energy rating are largely unknown. The leading hypothesis suggests that these shorts are the result of product from sublimation or cracking at the hot junction of the thermoelectric couples. The engineering unit and qual unit are planned to be electrically heated for performance testing in preparation for the next proposed mission to Mars in the year 2020. This period of performance testing provides an opportunity to test a measurement technique that could characterize the shorts occurring inside the MMRTG. In the event that a short has formed inside the MMRTG, this technique would consist of applying another short (active short) between the internal electrical power circuit and chassis frame of the MMRTG. This measurement technique will attempt to address two main areas of concern: (1) determine if the internal short of the MMRTG can be cleared in the presence of an active short, and (2) quantity the amount of energy required to clear the internal short. The active short will consist of a current sensing resistor that will indicate the amount of current flowing through the internal short of the MMRTG. The circuitry of the active short will allow an individual to control when and where to apply the active short on the MMRTG and to capture the amount of time required to potentially clear the internal short. The active short circuit will also be equipped with multiple safety features including a fuse and current limiting resistor in order to protect the internal components of the MMRTG from exceeding specified current ratings. Currently, if an internal short forms within the engineering unit or qual unit, the action is to do nothing other than to record the time a chassis short has occurred. The active short circuit is a low risk, simple addition to an already existing performance test setup that will potentially characterize and mitigate the internal shorts forming inside the MMRTG. Data from our characterization test can eventually be incorporated into a mitigation technique for future missions of the MMRTG.

Keywords: Internal shorts, MMRTG, active short

The 2014 NASA Nuclear Power Assessment Study: Safety, Environmental Impact, and Launch Approval Considerations and Findings

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Abstract. NASA and the Department of Energy have developed shared principles for safety and environmental considerations for the development and use of space nuclear power systems. These key principles were important considerations during the 2014 NASA Nuclear Power Assessment Study (NPAS). Specifically, they served as a foundation for system studies of notional radioisotope power systems (RPS) and fission power systems (FPS) for two selected NPAS mission studies. This paper summarizes the launch history of U.S. space nuclear power systems, and describes the key safety and environmental principles and processes necessary to design and develop safe space nuclear power systems. This includes the processes mandated under the National Environmental Policy Act (NEPA) of 1969, and Presidential Directive/National Security Council Memorandum-25 (PD/NSC-25) of 1977, as amended, for the development and launch of any space nuclear power system. Finally, it summarizes the findings in this area from NPAS.

Keywords: space nuclear safety, environmental impact, launch approval, NASA nuclear power assessment study.

DOE Radioisotope Power Systems Infrastructure, Technical and Regulatory Challenges, Approaches and Successful Outcomes: How We Got to Where We Are

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Abstract.

The infrastructure for fueling, testing and delivering radioisotope power systems (RPS) has been a Department of Energy (DOE) responsibility since its inception in the early 1960's. In the 1960's and 1970's this was performed at a variety of sites, mostly DOE-facilities, but including some owned and operated by private contractors such as Lockheed Marin of Valley Forge, PA, and Teledyne Energy Systems of Hunt Valley, MD. All those activities that involved handling special nuclear material were gradually located at DOE facilities by the early 1980's. From that time until now there have arisen several challenges that, although handled quietly and with little fanfare, were very serious in nature and had the potential to derail the relative ease with which RPS are provided to NASA for use as an enabling technology for space missions. The challenges were across a variety areas such as: 1) providing the ability to safely and securely transport a fueled RPS from the fueling site to the integration site in compliance with 10CFR71 "Packaging and Transportation of Radioactive Material", 2) providing for a safe and well regulated operational basis for ground operations once the RPS had been delivered to the integration site in compliance with 10CFR830 "Nuclear Operations", and 3) providing for a more secure posture towards safeguarding the special nuclear material (Pu-238) in the aftermath of the events of September 11, 2001. Each of these challenges required deliberate and thoughtful planning, significant funding and a strong commitment by the DOE and its national laboratories. The outcomes were successful and enabled NASA missions such as Cassini (1997), Mars Exploratory Rovers (2003), Pluto-New Horizons (2006) and Mars Science Laboratory (2011) to be supported in a timely fashion. The challenges encountered and the methods employed to successfully overcome the challenges will be presented within the context of the RPS-DOE infrastructure as a responsive and resilient partner with NASA.

Keywords: RPS, DOE

Modeling the Substoichiometric Behavior of $^{238}PuO_2$ and $^{241}AmO_2$ in the Low Oxygen Potential Environments Found in Radioisotope Power Systems

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Abstract. One of the well-known properties of CeO_2, PuO_2, and AmO_2 is their ability to release oxygen and become slightly substoichiometric at high temperatures and low oxygen potentials. Previously, fuels used in radioisotope power systems have always been assumed to be fully stoichiometric (e.g. $^{238}PuO_{2.00}$), but the fuel is exposed to high temperatures and low oxygen potentials at several points. In many cases, including within radioisotope power systems, the fuel is placed in these reducing conditions in the presence of graphite. As the fuel releases oxygen, chemical thermodynamic equations can be used to predict the amount of CO and CO_2 that are produced at the graphite. These ratios can then be used to predict the oxygen potential of the system. Since the behavior of CeO_2, PuO_2, and AmO_2 has been studied under varying oxygen potentials and temperatures, it becomes possible to predict the stoichiometry of these materials under conditions found in fuel processing and use. This model will be developed first on CeO_2 because the literature on the behavior of CeO_2 stoichiometry with temperature and oxygen potential is quite extensive. This model will then be applied to PuO_2 and AmO_2.

Keywords. cerium (IV) oxide, plutonium (IV) oxide, americium (IV) oxide, thermodynamic modeling, substoichiometry

Idaho National Laboratory
Recent Equipment Development for Fueling and Testing Radioisotope Power Systems

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Abstract. We are here, we are thinking about it, and we are coming up with ideas. Idaho National Laboratory's (INL) Radioisotope Power Systems (RPS) Program is providing equipment and capabilities to support NASA's future space missions. INL performs the nuclear fueling, testing, storage and delivery of RPSs for the Department of Energy (DOE) and its customers. Fifty years of Programmatic history and NASA's mission planning provoked some enhancements to complement existing systems such as fueling two RPSs at the same time, sterilizing flight RPS for planetary exploration, power performance in the coldness of space, payload transportation approval, and off-gassing graphite components used for the heartbeat of the RPS—the general purpose heat source (GPHS), containing radioactive fueled clads that generate heat that is converted to electricity. A Multi-Purpose Fueling Glovebox (MFG) was designed and installed to accommodate fueling RPSs (with GPHSs). The addition to the RPS glovebox family increases fueling capability so that two RPSs could be fueled in parallel. The MFG also provides a location to apply vaporous hydrogen peroxide to RPS components--a new Planetary Protection capability. The Planetary Protection system sterilizes the environment within the MFG, and subsequently the components therein, in accordance with requirements proposed as an alternative to NASA's approved dry heat sterilization process. The next generation RPSs may not get thermally hot enough to be self-sterilizing; and it is desirable for an RPS to be microbe-free if it will be used for planetary exploration. (The microbes living on earth need to stay on earth.) Another new capability is testing the RPS, power performance while simulating the coldness of space. While power performance testing has historically been performed, only the vacuum of space is simulated. An existing thermal vacuum testing chamber has been retrofitted with a cryogenic shroud introducing a cold environment to the RPS in addition to the vacuum during power performance testing. While we were at it, we updated the pumping system and can better control the pumping speeds reaching a high vacuum in about 30 minutes. Flight-ready RPSs are transported to Kennedy Space Center in Department of Transportation-certified, Type-B shipping casks. INL is the custodian of the casks for DOE and also provides the transportation trailers that carry the RPS-loaded casks to Kennedy Space Center where they are processed before integration to the space vehicle at the launch site. INL takes a proactive approach to obtaining approval (two-year process) for transporting new, nuclear payloads in the casks well in advance of the need date. Lastly, we are installing a second graphite furnace, doubling our capacity to off-gas graphite components used for the GPHSs. A good thermal conducting GPHS is one that has had impurities baked out of it; and the more heat you can get to a hot shoe of a thermoelectric couple or the head of a stirling system, the better the power performance. Modifying equipment and adding new capabilities in a Nuclear Facility is a lengthy process, and the INL is committed to supporting DOE and its Customers.

Keywords: RPS, GPHS, INL, Planetary Protection

The eMMRTG – To Europa, Titan or Mars

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Abstract. At the NETS 2014 conference, the new enhanced MMRTG (eMMRTG) was introduced as the next generation upgrade to the highly successful MMRTG, currently powering the Mars Curiosity rover. The eMMRTG will use the new skutterudite (SKD) thermoelectric (T/E) materials developed at the Jet Propulsion Lab (JPL) and currently being produced at Teledyne Energy Systems, Inc. (TESI). TESI is funded with a SKD technology transfer contract to scale up batch and T/E puck size as required for eMMRTG production. This contract includes the production of aerogel insulation for T/E couple and T/E module insulation.

Studies performed in 2013 showed that, with minimal risk to the MMRTG design, the eMMRTG could benefit from the inclusion of the SKD materials and provide a beginning of life (BOL) power increase of approximately 25% over the existing MMRTG design. This would be enabled by increasing BOL T/E hot junction temperature to 600°C by properly sizing the T/E elements. The 2013 studies showed that nominal power output at BOL and at 32 Vdc load increased from 117 watts for MMRTG to 145 watts for eMMRTG. This 145 watt power output level is predicted with a thermal inventory of 1920 watts of Pu238 fuel, which is lower than the 2016 watts of fuel in the MSL MMRTG. Efforts are underway in 2014 on the following; 1) three mission profiles for missions to Europa, Titan or Mars, 2) Margin analyses to determine temperature margins, 3) thermal model updates, 4) loss of argon cover gas effects and 5) power output profiles for the three mission profiles. The margin analysis effort focuses on the thermoelectric hot junction temperature and all temperature limiting components. Key issues to be decided are thermal inventories to be considered, maximum system load voltage allowed and the amount of additional temperature margin required. The three mission profiles and their effect on temperature margins are central to this work. The thermal model work is important in understanding the details of maximum component temperatures, in particular, the maximum T/E hot junction temperature. Due to design particulars inherent in the MMRTG design, there is a 10°C to 20°C spread from the minimum to maximum T/E hot junction temperature. Additionally, the General Purpose Heat Source (GPHS) specification ranges from 244 to 256 watts/GPHS, which has about a 13°C effect on T/E hot junction temperature. Finally, every extra two volts of higher load voltage adds about 6°C to the T/E hot junction temperature. All these effects need to be understood and considered in the design so as to not unduly penalize power output or increase temperatures that may limit system lifetime. Results of engineering studies performed in 2014 will be presented and will address key aspects of temperature margins and design and performance implications. Other efforts planned for 2015 and beyond will focus on a number of details such as; optimizing the design to reduce temperature gradients and enable greater margin/higher temperatures and more detailed thermal and structural models.

Keywords: MMRTG, eMMRTG, GPHS, Skutterudite

Radioisotope Thermoelectric Generators Based on Americium-241

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Abstract. Space nuclear power systems are under development in Europe as part of a European Space Agency (ESA) program with the UK leading the development of a number of key technologies including radioisotope thermoelectric generators (RTG). RTG systems being developed in Europe are targeting the 10 W electric to 50 W electric power generation range. Radiogenic decay heat from radioisotopes can be converted to electrical power by using appropriate semiconductor based thermoelectric materials and the focus in the UK is the development of bismuth telluride based thermoelectric modules. In order to achieve a target of up to 50 W of electrical power, the European program is targeting americium-241 as a fuel source and is maximizing the use of commercially available thermoelectric manufacturing processes in order to accelerate the development of power conversion systems.

A laboratory prototype that uses electrical heating as a substitute for the radioisotope was developed to validate initial flight designs. This prototype has now been tested with three generations of thermoelectric generators each of which represents an incremental improvement in system performance. The outputs from the initial design and experimental phases have been used to derive an overall flight system design and new heat source concept.

This paper outlines the updated requirements for the European ^{241}Am RTG system being developed by a team led by the University of Leicester, describes updates in system design and provides further insight into most recent results from laboratory prototype test campaigns.

Keywords: radioisotope, thermoelectric, generator, americium, space.

Toward Certified Pu^{238} Purification Laboratory

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Abstract: Heat source plutonium, HS-Pu^{238}, has been used by NASA as heat/power source for space exploration due to its relative stability, acceptable lifetime, minimal shielding requirement, and high density. Although there are plans for new production of Pu^{238}, there is not currently a domestic source of Pu^{238} for space missions, rather it is purified from impure oxide and recycled scrap materials that poses significant challenges to obtain relatively pure materials due to presence of high levels of Mn, Ca, Zn, Ce, Al, Cr, Fe, Ni, particularly U^{234}, Np^{237}, Am^{241}, Pu^{236}, and silicon.
Los Alamos National Laboratory (LANL) has produced radioactive heat sources for last 40 years. Indeed, approximately 216 General Purpose Heat Sources (GPHS) and 180 Lightweight Radioisotope Heater Units (LWRHU) used in Cassini (Saturn) mission were manufactured by LANL. More recently, the Spirit and Opportunity, and Curiosity in Mars and Pluto new horizon missions are also powered/heated by Pu^{238} from LANL.

LANL has purified Pu^{238} from scrap materials and aged fuels since 1998. We have optimized oxalic acid precipitation procedures coupled with hydroxyl precipitation to remove remaining Pu^{238} in liquid waste at a subaccountable level to treat the waste in on-site treatment facility. Furthermore, we have continued to improve our processes, yield, product quality, and dose reduction, and moving toward a nationally and internationally recognized certified laboratory status including ISO certified reagents and procedures, and GMP levels practices.

The scrap materials and aged dioxide fuels are received in a special container. They are transferred to glovebox line, opened and combined if necessary. The materials are dissolved in HNO_3 (Nitric Acid) and HF (hydrofluoric acid) for overnight in a vented tantalum vessel. The solution is filtered to remove undissolved pieces that can be reprocessed. Molarity of filtrate is adjusted with diluted nitric acid and plutonium was reduced with hydroxylamine nitrate (HAN) to convert all forms of plutonium into Pu (III). Simultaneously nitrous acid is scavenged with Urea. Finally, Pu (III) is precipitated by addition of oxalic acid and the oxalate cake collected with filtration is calcinated to convert Pu-Oxalate into pure PuO_2 that is used for fuel fabrication. Los Alamos has in house capability to do chemical and physical analysis of purified Pu^{238} and fuel clads. The amount of actinides and trace elements in our purified Pu^{238} oxides meet the customer specifications.
Liquid waste generated during filtration and washing is treated with NaOH and Fe $(NO)_3$ to reduce residual Pu^{238} at the subaccountable levels so that large volume of liquid is treated by on-site waste treatment facility and small hydroxyl cake containing plutonium is sent out for disposal.
Pu^{238} is a strong alpha emitter, thus during treatment with HF and washing with water, it releases large amount of neutrons. In addition to ALARA and glovebox environment, we have added specially designed lab wares and hydrogenous shielding in front of glove box lines to reduce the exposures of our workers to radiation.
LANL is equipped to purify Pu^{238} at small manual-intensive and large semi-automated scales from old fuels and various scrap materials in several glovebox lines. We are on the process of upgrading our capabilities from purification and particles analysis to metallographic analysis of fuel clads.

Keywords: Heat Source Pu^{238}, Oxalate and hydroxyl precipitation, GPHS and LWRHU

Limits of the Advanced Nuclear Power Systems for Space Exploration

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Abstract. Nuclear power as we know it today is in its infancy and has a long way to evolve before reaching its limits. The proposed advanced nuclear systems, based on heterogeneity by design, represent one step forward but surely not the ultimate end. Compact power supplies, based on direct nuclear energy conversion into electricity, a kind of super-capacitor charged by the kinetic energy of product nuclear particles and discharged as electricity, has a major strategic importance. This device will power the electric thrusters of a spacecraft, its directed energy systems, the shielding and all the rest of equipment onboard. One must consider that all this power in part becomes heat, and the spaceship have to deal with it, in part by converting it into electricity, via switched thermo-electric devices, and in part by removing it via heat-pumps to dump it into space. One may immediately see the tradeoff.

Space is a hostile place for life. Novel nuclear materials developed based on nano-technologies can be used as shielding and to create materials that self-repair from radiation damage. A combination of radiation guides in nano-structure shield tiles and in direct nuclear energy conversion tiles may be used as active shielding and remote power transport and, when combined with classical radiation absorption materials, may create for astronauts a safe habitable zone in the spaceship. Complex, multi-spectrum nuclear detectors can help in evaluating the environment and study all the aspects of outer space.

The biggest limitation with respect to the range a manned spaceship may reach comes from its propulsion, which requires mass much larger than that of the spacecraft to be ejected in order to transfer momentum. Basically, it does not help to eject into space a small mass with high speed. Better propulsion efficiency is obtained if energy is distributed to a mass equal to that of the spaceship. This is a very strong constraint, implying that, even with the best nuclear power driving the best rocket propulsion, we may reach the outer boundaries of the Solar System, the Oort cloud, but no further than ½ light-year. In order to have interstellar spaceships we need to drastically improve propulsion and further use advanced nuclear power in various systems onboard.

Keywords: nuclear power, heterogeneity by design, jet propulsion, nano-micro hetero-materials, solar system, galactic spaceship.

Direct Energy Conversion Radioisotopes Based Battery

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Abstract.
Direct Nuclear Energy Conversion into Electricity is a process that uses the kinetic energy of the nuclear particles, into a super-capacitor like hetero-nano structure, harvesting the energy of knock-on electrons produced in the interaction between the nuclear particle and the lattice, and discharges directly delivering electricity similar to a battery. The structure may be morphed on the energy source that can be a nuclear fuel, delivering energetic fission products, or a radioactive isotope delivering alpha, beta or gamma radiation from its natural decay.
For the most practical uses in near vicinity of the biological systems, there are preferred those radioisotopes that emit mainly charged particles with minimum associated gamma rays. The most preferred radioisotopes are ^{238}Pu, ^{241}Am, and ^{90}Sr, ^{210}Po, but there are many others that might be used if their production costs might be lower.
The use of these gamma ray "free" alpha or beta emitters makes the nuclear battery very small, looking like a 50 microns thick foil, with the minimum dimensions down to 0.1 mm, and power versus halving time given by the type of radioisotope used. The power for such a small battery element is of about few nW for 90 years for ^{238}Po, by 4-5 times less for ^{241}Am with 431 years half-life, and few microWatt for ½ year for ^{210}Po. The battery may be morphed on the case surface, on the printed circuit or on the electronic parts, may be distributed along the electronic modules, making self-powered electronic modules or even parts, being customized to the needed parameters (V,I, P, $T_{½}$ etc.). The use of such power sources, may drive to super-miniaturization of the circuits, increase in reliability, being fit for space applications due to their energy mass ratio, one battery being equivalent to more than 100,000 chemical batteries.

Keywords: Isotope-battery, direct-energy-conversion, micro-nano-hetero-structure, charged-particles, "self-powered"-electronics .

Sintering Trials of Ceria as an Analogue of Americium-241

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Abstract. The development of americium-241 based radioisotope thermoelectric generators (RTGs) and heater units (RHUs) in Europe is currently focused on the production of a stable ceramic fuel form as well as raising the technology readiness level of radioisotope containment structures and radiogenic thermal to electric conversion systems. Surrogate materials can be used to understand the physical and chemical behavior of americium-241 based ceramic fuels i.e. oxides of Am. Ceria has been identified as a possible analogue material and the central aim of this work was to determine how CeO_2 behaves as an analogue of AmO_2 under different sintering conditions. A number of sintering studies have been carried out to determine how the sintering conditions and processes affect the cerium to oxygen ratio and affect the mechanical and chemical properties of the ceramic fuel analogue. Understanding oxygen mobility in ceria under different sintering conditions will be essential to understanding its stability and suitability as an analogue of americium oxide based ceramic fuels. In these studies both conventional cold pressing and sintering as well as spark plasma sintering have been targeted. Greater control over conditions and extended sintering periods of the former are traded off against the latter process, which is characterized by fast processing times and the ability to produce a variety of near net shape structures. The initial results from these studies are reported and an initial set of recommendations is provided for future research.

Keywords: americium, ceria, oxygen, sintering, space applications.

Sintering Trials of Ceria as an Analogue of Americium-241

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Abstract. The development of americium-241 based radioisotope thermoelectric generators (RTGs) and heater units (RHUs) in Europe is currently focused on the production of a stable ceramic fuel form as well as raising the technology readiness level of radioisotope containment structures and radiogenic thermal to electric conversion systems. Surrogate materials can be used to understand the physical and chemical behavior of americium-241 based ceramic fuels i.e. oxides of Am. Ceria has been identified as a possible analogue material and the central aim of this work was to determine how CeO_2 behaves as an analogue of AmO_2 under different sintering conditions. A number of sintering studies have been carried out to determine how the sintering conditions and processes affect the cerium to oxygen ratio and affect the mechanical and chemical properties of the ceramic fuel analogue. Understanding oxygen mobility in ceria under different sintering conditions will be essential to understanding its stability and suitability as an analogue of americium oxide based ceramic fuels. In these studies both conventional cold pressing and sintering as well as spark plasma sintering have been targeted. Greater control over conditions and extended sintering periods of the former are traded off against the latter process, which is characterized by fast processing times and the ability to produce a variety of near net shape structures. The initial results from these studies are reported and an initial set of recommendations is provided for future research.

Keywords: americium, ceria, oxygen, sintering, space applications.

The Performance of an Accident-tolerant Control Drum System for HEU-fueled Space Reactors

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Abstract. In our previous work, the concept of an accident-tolerant control drum (ATCD) system as a reactivity control system of a space reactor was proposed and its neutronic performance during the reactor's life time and the safety performance in various launch accident scenarios were demonstrated when an ATCD system was adopted in LEU-fueled space reactors. The accident-tolerant control drum consists not only of an absorber part and a reflector part but also of a fuel part which comprises the reactor core when the drums are in operation position. The neutronic performance of reactors with an ATCD system was similar to that with a control rod system during their life time except for the drum/rod worth at the beginning of life cold zero power state. The accident-tolerant control drum has a large drum worth not only because the absorber part is inserted deep into the core and the fuel part is moved to a position far from the core when the drum is in shutdown position. The reactors with an ATCD system remained subcritical even when some or all the control drums are missing without any damage in reflector as a result of launch accident while the reactors with a control rod system became supercritical when some or all the control rods are missing without any damage in reflector, which means that the ATCD system is much more reliable than the control rod system during various launch accidents.

In this paper, the neutronic performance during the reactor's life time and the safety performance in various launch accident scenarios will be demonstrated when an ATCD system is adopted in HEU-fueled space reactors. As in the LEU-fueled space reactor cases, the HEU-fueled space reactors with an ATCD system remained subcritical even when some or all the control drums are missing without any damage in reflector while the reactors with a control rod system became supercritical when the control rod is missing without any damage in reflector, which means that the ATCD system is much more reliable than the control rod system during various launch accidents not only in the LEU-fueled space reactor case but also in the HEU-fueled space reactor case. The details will be presented in a full paper.

Keywords: Accident-tolerant Control Drum, HEU-fueled Space Reactor, Launch Accident.

Fusion and Transmutation Energy Sources

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Abstract. The development of instrumentation in 20th century has enabled observation of several anomalies with respect to the energy balance in chemical reactions, driving strong suspicion that some kind of hitherto unknown nuclear reaction may be taking place. Over time researchers have associated various names with these anomalies, and over 1000 papers have been published, introducing over a hundred reaction models but without explaining the observed phenomena. The most recent research points to quantum nuclear reactions that are favored in nano-structures and drives to a nuclear reaction with a quantum state entanglement, similar to that obtained in quantum state teleportation. Here comes into play new physics that is sometimes seen to contradictory to current understanding. However, considering the history of science, this may be seen as a normal development that has appeared many times in the past, such as when Newtonian physics was complemented by Relativity, with no contradiction. Thus the current understanding of nuclear physics may be complemented by an understanding of nuclear reactions driven by assemblies of quantum states.

No matter how we explain the process, what is obvious in many experiments is that these strange nuclear reactions spontaneously occurring in chemical assemblies are producing significant amounts of energy, making possible new power sources for space applications.

Fusion and transmutation power sources rely on a chemical reaction to be able to generate in controlled manner active nuclear environments, where a low energy transition in a quantum assembly drives a high energy output, observed via charged particle and radiation emission. Some reactions emit no radiation, with all energy gradually being transferred to phonons and heating up the structure. The fusion of deuterium in palladium deuteride lattices is likely to enable in such nuclear energy conversion devices. The reaction produces an energetic alpha particle of about 22 MeV and a recoiled Palladium with about 0.3 MeV. Using a combination of electromagnetic fields it will be possible to produce a high density of active nuclear reaction sites a few nano-meters wide, which could deliver high power density or high temperature for power sources for space.

Conduct of the deuterium fusion reaction in a nickel-hydride structure may enable the transmutation of nickel atoms and of other elements, releasing several MeV per reaction. The devices presented are in early conceptual stage, TRL=3, and the R&D will apply many modifications to the current concepts until a reliable power source for space applications is obtained.

Keywords: fusion, transmutation, quantum-entanglement, active-nuclear-environment, power source.

Hot Pressing of CeO_2 Ceramic Pellets

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Abstract. Over the last several years a number of different ceramic processing unit operations have been studied for fabricating sintered CeO_2 ceramic compacts as a surrogate for understanding the ceramic behavior of PuO_2, including: classical cold pressed + furnace sintering, and Spark Plasma Sintering (SPS). The present work centers on the application of Hot Pressing, which is another ceramic processing technique that utilizes both temperature and pressure for obtaining sintered ceramic compacts. A series of hot press experiments were performed with CeO_2 powder employing processing temperatures of up to 1600°C with pressures of up to 6000 psi (~40 MPa). CeO_2 integral pellets have been obtained with some examples being sectioned and polished employing typical ceramic specimen preparation techniques. Comparisons of the microstructures obtained on both classical cold pressed + furnace sintered CeO_2 pellets, and hot pressed CeO_2 pellets will also be discussed.

Keywords: Hot Pressing, CeO_2, Sintering, Pellets, PuO_2

One Bit, One Joule : Data Return, Science Value and Power on Deep-Space Missions

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Abstract. I review the energy required for an instrument to obtain one bit of scientific information, the energy required to transmit it to Earth, and other energy requirements associated with spacecraft operation. A previous 1J/bit correlation that is useful for zero-order mission energy requirement definition is critically reviewed.

Spacecraft and mission design is usually an iterative process, but rapid convergence benefits from accurate initial estimation of engineering requirements. One critical parameter is electrical power or energy, and in order to inform requirements for post-Cassini Titan missions, Lorenz (J. Brit. Interplan. Soc., 2000) noted an approximate correlation from several planetary missions, emphasizing in-situ probes/landers. Specifically, over several orders of magnitude, the telemetered data return in bits correlated essentially one-to-one with the installed energy capacity in Joules. Hence, the rule of thumb 'One bit, one Joule', which was applied to argue that post-Cassini in-situ Titan missions, which for a substantial science increment beyond the Huygens probe should have a data return larger than its telemetry output of ~100 Mb, should therefore have an installed energy capacity of >> 10 MJ (i.e. 3kW-hr). Since primary battery technology typically offers ~100 W-hr/kg, this would imply uncomfortably massive batteries and, since solar power is impractical at Titan's surface, necessitates radioisotope power.

In this new work, we examine the energy/data correlation more deeply. First, some distinctions exist among different instrument types (e.g. passive optical instruments such as cameras and spectrometers can generate large volumes of data with modest power demands, whereas active systems like radars can demand more power ; similarly in-situ meteorology data is energy-inexpensive, whereas chemical analyses that involve elaborate valve control or sample acquisition or heating may demand more energy per bit to acquire the data). Some example data acquisition energy costs per bit will be presented.

An energy overhead is demanded for spacecraft operations. In some environments, notably Martian winter and at Titan, heating can be an important energy demand. Finally, a certain energy per bit is required for data transmission (indeed, the term Eb/No appears in spacecraft link budgets, associated with a given probability of bit error), which depends on antenna size, range to Earth. In some settings, such as Titan surface with Direct-To-Earth (DTE) telecom, this energy term may be dominant. Note that both heating requirements, and transmit energy per bit, increase with increasing distance from the sun.

We can also consider science value. Some data are more valuable than others – publications reporting just a few hundred bits of information such as the abundance of specific compounds or isotopes in a planetary atmosphere can be very highly cited, indicating great scientific impact. Survey data (e.g. optical or radar maps, long time-series of particles-and-fields or meteorological/seismological data) may have a science value that varies as something like the logarithm of data return : detecting the millionth crater or lightning strike is not as significant as detecting the first. As is well-known, the science value per bit can be enhanced by data selection and compression. Time series data can be compressed and events autonomously detected; spectra and images can be windowed/subframed, averaged, and otherwise compressed. These measures require CPU cycles, with which there is also an energy cost. Low-resolution data can be telemetered to Earth and science teams on the ground can determine the highest-value subset to be transmitted at the original high quality.

These considerations will be reviewed to assess how science value may relate to the energy demand of a mission and ultimately the 'science return per dollar' that is a claimed metric for mission prioritization.

Keywords: Planetary Missions; Power Requirements.

Lifecycle Testing of the EU/QU MMRTG

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Abstract. UDRI has established the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) Lifecycle Testing Laboratory, which is dedicated to conducting life-cycle testing of electrically heated versions of the MMRTG. There is considerable interest in performance testing on the limited number of available MMRTGs since there are only three assembled units currently in existence, and one of them is on Mars powering the Curiosity rover as part of the Mars Science Laboratory (MSL). Depending on the Martian season, Curiosity's MMRTG experiences a temperature variation during a Martian solar day (Sol) between –65°C to –75°C at night, and 0°C to 7°C during the day. Historical terrestrial life-testing of MMRTGs have generally been at constant temperature in order to characterize the power output performance as a function of time. However, MSL has experienced approximately 900 diurnal temperature cycles during the surface science mission to date, and the effect of this difference on the operating lifetime of the MMRTG is uncertain. Under contract to the U.S. Department of Energy (DOE), researchers at UDRI are collaborating with NASA JPL, NASA GRC, and Radioisotope Power System (RPS) developers like Aerojet Rocketdyne and Teledyne Energy Systems to develop relevant testing of the Engineering Unit (EU) for mission planners and RPS design efforts. Similar experiments are also being developed for the Qualification Unit (QU) that will be adjusted for the harsh environments an MMRTG would encounter during a deep space mission.

Keywords: MMRTG, Life-Testing, Diurnal Cycling

Sublimation Suppression Coatings for Thermoelectric Materials

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Abstract. The p-type thermoelectric material utilized in the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is TAGS-85, which has a nominal composition of $(AgSbTe_2)_{15}(GeTe)_{85}$. Telluride materials are limited to a maximum use temperature of ~550°C. Due to the deleterious effects of oxygen on these materials and their high vapor pressures, telluride-based thermoelectric materials must be operated in a sealed generator with an inert cover gas to retard sublimation and vapor phase transport within the converter. Researchers at UDRI and PneumatiCoat Technologies have developed an atomic layer deposition (ALD) coating process for TAGS-85 that dramatically reduces the sublimation and vapor phase transport of the high vapor pressure constituents of TAGS-85. Incorporation of this coating process will potentially increase the performance and operating lifetimes of future MMRTGs. Skutterudite based thermoelectric materials have been developed by the NASA Jet Propulsion Laboratory (JPL) that will potentially offer higher-efficiency power systems with improved performance over long operating lifetimes. This coating technology platform may also prove to be beneficial once Skutterudite-based thermoelectrics become fully characterized.

Keywords: Atomic Layer Deposition, TAGS-85, Sublimation Suppression

Low-Cost Radiator for Fission Power Thermal Control

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Abstract. NASA Glenn Research Center (GRC) is developing fission power system technology for future Lunar/Martian surface power applications. The systems are envisioned in the 10 to 100kW$_e$ range and have an anticipated design life of 8 to 15 years with no maintenance. NASA GRC is currently setting up a Technology Demonstration Unit (TDU) to validate such systems. The TDU is a 55kW$_e$ non-nuclear system ground test in thermal-vacuum which will demonstrate the transfer of heat from the reactor, convert the heat into electricity, reject waste heat, process the electrical output, and demonstrate overall system performance. Reducing the radiator mass, size, and cost is essential to the success of the program. Currently, Advanced Cooling Technologies, Inc. (ACT) and subcontractor Vanguard Space Technologies, Inc. (VST) are under a Phase II SBIR contract with NASA GRC to develop the TDU radiator for a nominal waste heat load of 40kW.

The single, direct-bond facesheet radiator has the advantages of reducing mass and cost of the system by eliminating the graphite foam saddles, aluminum honeycomb, and one of the graphite fiber reinforced composite (GFRC) facesheets, which are present in typical heat pipe radiators. Furthermore, the direct-bond radiator design eliminates the CTE mismatch in one direction by allowing each heat pipe to have its own individual facesheet (not shown in picture). This paper will focus on the design, fabrication and testing of a single, full-scale VCHP and associated direct-bonded facesheet. A series of lap shear tests were performed for a variety of adhesives and cure processes in order to determine the configuration with the best direct bond performance. Performance testing of the completed VCHP radiator module will include heat transport capability as well as thermal cycle testing to determine the thermal resistance, temperature uniformity, and overall quality of the direct bond.

Keywords: heat pipe, VCHP, GFRC, low-cost radiator, fission power, direct bond

Optimized Backup Cooling System for the Advanced Stirling Radioisotope Generator

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Abstract. In a Stirling Radioisotope Power System (RPS), heat must be continuously removed from the General Purpose Heat Source (GPHS) modules to maintain the modules and surrounding insulation at acceptable temperatures. The Stirling convertor normally provides this cooling. If the Stirling convertor stops in the current system, the insulation is designed to spoil, preventing damage to the GPHS at the cost of an early termination of the mission. An alkali-metal Variable Conductance Heat Pipe (VCHP) can be used to passively allow multiple stops and restarts of the Stirling convertor. In a previous NASA SBIR Program, Advanced Cooling Technologies, Inc. (ACT) developed a series of sodium VCHPs as backup cooling systems for Stirling RPS. In 2012 one of the VCHPs was successfully tested at NASA Glenn Research Center (GRC) with a Stirling convertor as an Advanced Stirling Radioisotope Generator (ASRG) back up cooling system. The prototype however was not optimized and did not reflect the final heat rejection path. ACT through further funding has developed a semi-optimized prototype with the finalized heat path for testing at GRC with a Stirling. The semi-optimized system features a two phase radiator and is significantly smaller and lighter than the prior prototype to reflect a flight ready system. The VCHP is designed to activate and remove heat from the stopped convertor with a small temperature increase from the nominal vapor temperature. This small temperature increase from nominal is low enough to avoid risking standard ASRG operation and spoiling of the Multi-Layer Insulation (MLI). The VCHP passively allows the Stirling to be turned off multiples times during a mission with potentially unlimited off durations. Having the ability to turn the Stirling off allows for the Stirling to be reset and reduces vibrations on the platform during sensitive measurement or procedures. This paper presents the design of the VCHP and preliminary test results with a Stirling simulator.

Keywords: Heat pipe, cooling, Stirling engine, space power

Skutterudites for Space Power—Developing Flight Capable Thermoelectric Modules

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Abstract. Born out of the success of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) as a reliable power source on-board the *Curiosity rover, part of the* Mars Science Laboratory mission, , an effort has started to evaluate skutterudite (SKD) thermoelectric materials as a low risk evolutionary upgrade to the MMRTG. This effort seeks to build on the laboratory scale materials developed at JPL and produce flight capable thermoelectric couples and modules that can be integrated into the proven MMRTG design . This *enhanced* generator (so-named the eMMRTG) will provide a 25% increase in beginning-of-life output power owing to the SKD materials having higher thermoelectric (TE) efficiencies at high temperatures compared to those of the heritage MMRTG materials , as well as an increase in the hot junction temperature made possible by the higher thermal stability of the SKD materials. This is expected to improve the end of life power by up to 50%. Recent efforts within the program have focused on achieving production level synthesis capabilities, developing SKD–interconnect joining methods, incorporating aerogel insulation in the TE module design, and the design and development of material and device characterization methods and apparatuses. The progress in these areas and an overview of the direction and scope of program will be presented.

Keywords: skutterudite, thermoelectric, RTG.

Radiation Guiding in Active Nano-Structures for Shielding and Nuclear Reaction Control Systems

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Abstract. In outer space the radiation complex having many origins, as galactic, solar and local from the spaceship own power system, that for the moment is dominant and is pounding the nuclear power systems for space.

The actual nuclear reactors for space are using booms, and partial shielding, in order to reduce the radiation inside the crew chambers, and to be as light as possible. This solution has the disadvantage that it reduces the outside maneuverability space for docking and space-walk that has to take in consideration the radiation zones around the spaceship. The main radiation attenuation method is called mass, because no matter (with some approximation) what material we are using, in order to get a radiation attenuation ratio, about same mass is required, no matter if it is hydrogen, water or tungsten for electromagnetic radiations with energies above 300 keV, inside gamma ray domain. For neutron attenuation, light, neutron absorbent materials are used for shielding surrounded by gamma absorbent shielding, which all together makes the nuclear power source heavier by a factor of 2 to 10 times.

The novel material relies on trapping the gamma radiation and neutrons inside specially engineered nano-structures, which guides it along the structure, changing its direction without changing its energy.

This type of material may take the emergent radiation, and redirect it on a preferred escape direction or towards an absorbent element. It may also turn around the neutrons, normally being lost outside through external surfaces and redirect them inwards to the reactor's core, and increasing its reactivity. Adding electrically controlled structures on along the radiation guide, that acts as electrically controlled path switches, for radiation, it is possible to control the radiation final direction. Using the radiation switches we may drive the escaped neutrons towards the reactor core, increasing its reactivity and power, or towards an absorbent where it can do fuel breeding or special isotope production, and decrease the core, power and reactivity. This is what is called active nuclear reaction shielding, because it acts like the actual reflector drums and shielding. This material is also good for other applications very useful in space as radiation concentrators for imaging or non-imaging purposes, and radiation modulators.

The shield made of the new material is lighter that the actual shielding, and it may be used as reactivity control device, having a response time in micro-seconds being by at least 1000 times faster than the actual reflective drums, allowing the nuclear reactor power (amplitude) modulation up to MHz frequencies, good for neutrino communication systems.

Keywords: radiation-guide, nano-structures, reactor-shield, active-shield, radiation concentrator, neutrino-communication, reactor-power-modulation.

Shielding Development for Nuclear Thermal Propulsion

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Abstract. Radiation shielding analysis and development for the Nuclear Cryogenic Propulsion Stage (NCPS) effort is currently in progress and preliminary results have enabled consideration for critical interfaces in the reactor and propulsion stage systems. Early analyses have highlighted a number of engineering constraints, challenges, and possible mitigating solutions. Performance constraints include permissible crew dose rates (shared with expected cosmic ray dose), radiation heating flux into cryogenic propellant, and material radiation damage in critical components. Design strategies in staging can serve to reduce radiation scatter and enhance the effectiveness of inherent shielding within the spacecraft while minimizing the required mass of shielding in the reactor system. Within the reactor system, shield design is further constrained by the need for active cooling with minimal radiation streaming through flow channels. Material selection and thermal design must maximize the reliability of the shield to survive the extreme environment through a long duration mission with multiple engine restarts. A discussion of these challenges and relevant design strategies are provided for the mitigation of radiation in nuclear thermal propulsion.

Keywords: NTP, shielding, radiation, dose, heating

Kinetics of the High Temperature Oxygen Exchange Reaction on $^{238}PuO_2$ Powder

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Abstract. Naturally occurring ^{18}O and ^{17}O isotopes cause a significant increase in the neutron radiation that is emitted from $^{238}PuO_2$ fuel sources through a secondary (alpha,n) nuclear reaction. Prior to fueling a radioisotope power system, an oxygen exchange reaction is utilized to remove the detrimental oxygen isotopes from the fuel and replace them with the more benign ^{16}O. Historical experiments have provided enough data to develop an oxygen exchange procedure that has allowed the safe and efficient removal of ^{18}O and ^{17}O from $^{238}PuO_2$ fuel sources, but detailed studies of the kinetics and mechanisms of the reaction have not been published in the open literature. Without knowledge of the mechanism and kinetics of this reaction, a full development effort may be required to adapt to processing changes or to implement an oxygen exchange procedure at a new site. Improved understanding of the oxygen exchange reaction will help minimize the cost and resources necessary for any future development in this area, and will help sites that produce and process $^{238}PuO_2$ avoid any pitfalls that may accompany potential processing changes. Previous studies on the oxygen exchange reaction with the cold surrogate CeO_2 indicate that the kinetics of the oxygen exchange reaction are actually quite complex. Three different mechanisms were observed to dominate the reaction, depending on the temperature and the characteristics of the CeO_2 powder. Recent oxygen exchange kinetic experiments were performed on $^{238}PuO_2$. Results from these experiments will be reported, analyzed, and compared to the oxygen exchange behavior on CeO_2.

Keywords. plutonium (IV) oxide, oxygen exchange, reaction mechanisms, kinetics

A Historical Review of Cermet Fuel Development and the Engine Performance Implications

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Abstract. This paper reviews test data from cermet fuel development in the 1960's to better quantify Nuclear Thermal Propulsion (NTP) cermet engine performance, and to better understand contemporary fuel testing results. The important engine performance questions concern the maximum temperature and heat deposition rate that cermet fuels can withstand.

NTP rocket engines use a nuclear reaction to heat propellant, in contrast to traditional rockets, which use a chemical reaction. High energy density nuclear fuel in high thrust engines operating at high specific impulse (Isp ≥ 900s) represents the next evolutionary step in liquid rocket engines. NASA's NCPS (Nuclear Cryogenic Propellant Stage) program is recapturing NTP fuel element fabrication techniques and design knowledge for two fuel types—one graphite based, the other cermet—from the Rover/NERVA program of the 1960's. Although cermet fuel elements were not tested in reactor conditions (NERVA graphite fuel elements were reactor/engine tested), extensive fuel sample testing and evaluation took place at DOE's Argonne, Pacific Northwest, and Los Alamos National Laboratories, NASA Lewis Research Center, and General Electric. Nearly 200 cermet samples have been identified that were tested at or above 2500°C in hydrogen. This historical fuel testing was well documented and can provide valuable insights into cermet fuel and engine performance.

Cermet fuel elements include surface cladding, fuel stabilizers, and fuel particle coatings to minimize fuel loss at high engine temperatures. Sample testing revealed two reasons why these design features are important. First, at temperatures above 2000°K, uranium dioxide vaporizes rapidly, and cladding or coating is necessary. Second, at temperatures above 2200°K, uranium dioxide undergoes reduction and becomes sub-stoichiometric in oxygen, UO_{2-x}; in hydrogen, water will form and remove this oxygen. With cooling, this reduction reaction reverses, but free uranium forms if oxygen has been removed. With cooling below 500°C, uranium hydride forms that forces apart grain boundaries. Thermal cycling (corresponding to engine burns) repeats this process and eventually disrupts fuel integrity and allows rapid fuel vaporization. Cladding, stabilizers, and fuel particle coatings delay fuel failure. Engine performance depends on the maximum possible fuel temperature, and the historical data provides valuable insights into how effective cladding, stabilizers, and fuel particle coating can be. Other, secondary, processes and designs will be noted.

The size of the high temperature fuel region within the fuel element is also important. NTP engines are unique, in that, heat is deposited in the nuclear fuel and is conducted through the fuel to coolant channels and propellant. The peak fuel temperature exceeds the propellant exit temperature and, typically, occurs on the exterior surface of the fuel element towards the hot end. Coolant channel geometry and heat deposition rate can have a significant effect on peak temperature. The paper will use multi-physics simulation results to identify high temperature regions of the fuel, and promising fuel element geometries.

Keywords: Nuclear Thermal Propulsion, fuel development, cermet fuel,

Initial Characterization of the Advanced Stirling Radioisotope Generator EU2

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Abstract. Significant progress was made developing the Advanced Stirling Radioisotope Generator (ASRG), a 140-watt radioisotope power system. While the ASRG flight development project has ended, the hardware that was designed and built under the project is continuing to be tested to support future Stirling-based power system development. NASA GRC recently completed the build and assembly of the ASRG EU2. The ASRG EU2 consists of the first pair of ASC-E3 convertors, Lockheed Martin's Engineering Development Unit (EDU) 4 controller (a fourth generation controller), and an aluminum housing. The ASC-E3 convertors and aluminum housing are integrated into a Generator Housing Assembly (GHA) which closely matches the intended ASRG Qualification Unit flight design. A series of tests were conducted to initially characterize the EU2, its controller, and the convertors in a flight-like GHA. The GHA contained an argon cover gas for this testing. Initial characterization tests included:

- Measurement of convertor, controller, and generator performance and efficiency
- Quantification of control authority of the controller
- Disturbance force measurement with varying piston phase and piston amplitude
- Effect of spacecraft DC bus voltage variation on EU2 performance

The results of these tests are summarized and discussed, providing a basic understanding of EU2 characteristics. Further tests are planned, which will more fully characterize EU2 steady-state and transient performance under a variety of operating conditions. These future tests are briefly discussed.

Figure 1. ASRG EU2 under test in NASA GRC's Stirling Research Lab.

Benchmark Evaluation of Fuel Effect and Material Worth Measurements for a Beryllium-Reflected Space Reactor Mockup

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Abstract. The critical configuration of the small, compact critical assembly (SCCA) experiments performed at the Oak Ridge Critical Experiments Facility (ORCEF) in 1962-1965 have been evaluated as acceptable benchmark experiments for inclusion in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments*. The initial intent of these experiments was to support the design of the Medium Power Reactor Experiment (MPRE) program, whose purpose was to study "power plants for the production of electrical power in space vehicles." The third configuration in this series of experiments was a beryllium-reflected assembly of stainless-steel-clad, highly enriched uranium (HEU)-O_2 fuel mockup of a potassium-cooled space power reactor. Reactivity measurements cadmium ratio spectral measurements and fission rate measurements were measured through the core and top reflector. Fuel effect worth measurements and neutron moderating and absorbing material worths were also measured in the assembly fuel region. The cadmium ratios, fission rate, and worth measurements were evaluated for inclusion in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments*. The fuel tube effect and neutron moderating and absorbing material worth measurements are the focus of this paper. Additionally, a measurement of the worth of potassium filling the core region was performed but has not yet been evaluated

Pellets of 93.15 wt.% enriched uranium dioxide (UO_2) were stacked in 30.48 cm tall stainless steel fuel tubes (0.3 cm tall end caps). Each fuel tube had 26 pellets with a total mass of 295.8 g UO_2 per tube. 253 tubes were arranged in 1.506-cm triangular lattice. An additional 7-tube cluster critical configuration was also measured but not used for any physics measurements. The core was surrounded on all side by a beryllium reflector.

The fuel effect worths were measured by removing fuel tubes at various radius. An accident scenario was also simulated by moving outward twenty fuel rods from the periphery of the core so they were touching the core tank. The change in the system reactivity when the fuel tube(s) were removed/moved compared with the base configuration was the worth of the fuel tubes or accident scenario.

The worth of neutron absorbing and moderating materials was measured by inserting material rods into the core at regular intervals or placing lids at the top of the core tank. Stainless steel 347, tungsten, niobium, polyethylene, graphite, boron carbide, aluminum and cadmium rods and/or lid worths were all measured. The change in the system reactivity when a material was inserted into the core is the worth of the material.

Keywords: Critical experiment, Uranium dioxide, Beryllium reflected, Reactivity measurement.

Real-Time Electrical Advanced Stirling Convertor Simulator

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Abstract. A real-time electrical simulator of the Sunpower Advanced Stirling Convertor (ASC) has been developed by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) and is being used to support development of compact, efficient, convertor controllers. The simulator models the electrical and thermal behavior of an ASC in response to loading conditions on its alternator output. An operating mode that speeds up thermal changes by 500 times can be selected to avoid the slow (tens of minutes) normal response time. Other switch-selectable options include simulating behavior while absorbing power during start-up, different cold-end temperatures, and thermal-source mismatch between convertors. Versions of the simulator that model both single- and dual-convertor configurations have been implemented. The simulator output power, including instantaneous current, voltage and power factor, varies in response to changes in load conditions as a real ASC would. The simulator also has auxiliary analog outputs of piston and displacer position, hot-end temperature, and case velocity.

The simulator is based on a linearized mathematical model originally developed at the NASA Glenn Research Center. A small, commercial digital signal processing board is programmed with the model to calculate the convertor ASC alternator back-EMF source voltage from measured alternator current. An A/D acquires samples of alternator current as sensed by a commercial current transducer, while a D/A converts the EMF voltage to an analog signal. All samples have 14-bit resolution, and calculations are performed in single-precision floating point at 10.2 kHz. The back-EMF signal drives a commercial 400 W bipolar operational power supply/amplifier capable of four-quadrant operation that boosts power to match actual ASC output levels. ASC alternator series inductance and resistance are modeled with a physical resistor and a custom designed and wound inductor that matches those of the ASC.

The simulator has been used to support development of a fault-tolerant dual ASC active controller. Numerous controller performance improvements were made based on testing with the simulator. These include:

- Reduced piston amplitude variation due to reduced alternator current sampling noise,
- Reduced output current ripple,
- Improved tolerance to output voltage variation,
- Detection and response to a wide range of faults,
- Improvement of switching between redundant controller sides, and
- Verification of safe convertor operation throughout the process of switching active controllers.

Working with the simulator is much more convenient than using an actual ASC, especially while evaluating electrical behavior of a controller. Risk of damage to an ASC is reduced, and the iteration time to study circuit changes is much shorter since no additional time is needed to heat and cool a real convertor. The simulator also provides useful auxiliary data including back-EMF and piston/displacer waveforms.

A version of the simulator has been built to support the radioisotope power sources system integration laboratory at the NASA Glenn Research Center. That simulator models a dual 77-turn alternator ASC configuration, and will be used to evaluate and test integration of the Advanced Stirling Radioisotope Generator (ASRG) with typical spacecraft systems.

Keywords: Real-time Stirling simulation, Stirling controller, advanced Stirling convertor

Turbo-Brayton Power Converter for Spaceflight Applications

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

Development of turbo-Brayton converter technology for space is under way at Creare. The approach builds upon a 35-year foundation of advanced turbo-Brayton components and systems Creare has developed for numerous NASA, DoD, and DoE applications; including the NICMOS Cryogenic Cooler on the Hubble Space Telescope. This prior work provides critical technology and expertise regarding spaceflight Brayton systems, which is now being leveraged to develop power converters for space. The technology is readily scalable for power levels from tens of watts to hundreds of kilowatts and beyond. Potential near-term NASA applications include Radioisotope Power System (RPS) devices, "Kilopower" spacecraft, and Fission Surface Power (FSP).

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

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

Creare is developing the laboratory converter with SBIR Phase II funding. Detailed design and critical fabrication trials have been completed, and we have begun component fabrication activities. Testing is planned to begin this fall.

Keywords: Brayton, power converter, turbomachine

Liquid Metal Thermo-magnetic Systems for Space, Nuclear and Industrial Applications

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

Liquid metal-cooled reactors are both moderated and cooled by a liquid metal solution. These reactors are typically very compact and they can be used in regular electric power production, for naval and space propulsion systems or in fission surface power systems for planetary exploration. Liquid metals in fusion reactors can be used in heat exchange, tritium breeder systems and in first wall protection, using a flowing liquid metal surface as a plasma facing component. Liquid metal targets and beam dumps for spallation and for heat removal will also be needed at many high power particle accelerator facilities where the severe constraints arising from a megawatt beam deposited on targets and absorbers will require complex procedures to dilute the beam, and liquid metals constitute an excellent working fluid due to its intrinsic characteristics. In the metal industry, thermo-magnetic systems are used to transport the molten metal in between processes. By developing methods to control the surface tension of liquid metals, applications can be developed in configurable electronics, microfluidic channels and MEMS.

But the coupling between the electromagnetics and thermo-fluid mechanical phenomena observed in liquid metal thermo-magnetic systems, and the determination of its geometry and electrical configuration, gives rise to complex engineering magnetohydrodynamics and numerical problems were techniques for global optimization has to be used, MHD instabilities understood -or quantified- and multiphysics models analyzed. The environment of operation adds even further complexity, i.e. vacuum, high temperature gradients and radiation, whilst the presence of external factors, such as the presence of time and space varying magnetic fields, can lead to the need of developing active flow control systems.

Keywords: liquid metals, magneto-hydrodynamics, thermo-magnetic systems, electromagnetic pumps.

Refurbishment of LANL's Heat Source Manufacturing Infrastructure to Meet Future Mission Needs

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Abstract. Radioisotope power systems (RPSs) are a unique technology used in situations that require a long-term, unattended source of heat and/or supply of electrical power in harsh and remote environments. These unique systems are reliable, maintenance free, and capable of producing heat or electricity for decades. The plutonium-238 (^{238}Pu) in these units serves as the source for generating heat and electricity, but the physical, chemical, and radiological properties of ^{238}Pu make this material difficult to handle, process, and contain. For example, pure ^{238}Pu has a high specific activity of 17.1 curies per gram (Ci/g) (compared to 0.062 Ci/g for Plutonium-239) and produces 0.56 watts per gram (W/g) of decay heat. These effects generate thermal hazards that increase the degradation rate for glovebox (GB) gloves, gaskets, and other sealing materials.

The LANL ^{238}Pu heat source manufacturing operations are housed in the Plutonium Facility (PF-4), which is the nation's only Security Category I, Hazard Category 2, multi-user plutonium facility. The ^{238}Pu heat source manufacturing operations currently consume approximately 9,600 sq. ft. of 60,000 sq. ft. of total PF-4 main-floor laboratory space. The operational infrastructure consists of equipment and gloveboxes installed in the mid-1970s up to the mid-2000s. Some of the equipment and gloveboxes were manufactured in the 1950s, used at PF-4's predecessor plutonium facility, then transferred and installed for the 1978 commissioning of PF-4. The thermal hazard that accelerates the aging of the glovebox gaskets and equipment poses a significant, but manageable, programmatic and safety challenge. This paper will present a brief history of LANL's more than forty years of continuous experience in developing, characterizing, testing, and manufacturing ^{238}Pu heat sources and plans for future infrastructure improvements that will minimizes overall cost by focusing on establishing redundancy of key equipment, establishing an improved analytical chemistry component, and a disciplined maintenance program supported by a continued investment in the refurbishment of existing gloveboxes and processes to decrease programmatic risk and improve costs. This paper discusses the key science, engineering, and operational considerations and constraints involving ^{238}Pu glovebox maintenance and operation. Existing glovebox technology is reviewed and the potential for adding automation, robotics, and telecommunications to the ^{238}Pu processing area is discussed.

Keywords: Glovebox; ^{238}Pu; RPS; Refurbishment; and Manufacturing

High Temperature Water-Titanium Heat Pipes for Spacecraft Fission Power

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Abstract. NASA is examining small fission reactors for future space transportation and surface power applications. The Kilopower system will use a nuclear reactor to supply energy to Stirling convertors to produce electricity. Titanium/water heat pipes will be used to carry the waste heat from the Stirling to a radiator, where the heat is rejected. Most current water heat pipe designs are for surface fission power, and use gravity aided heat pipes (thermosyphons). The Kilopower system will be designed to operate in space, which will require a different heat pipe design than the thermosyphons used in surface applications. The heat pipe design needs to support the Kilopower system through four different operating conditions: operation in space, with zero gravity; operation on earth, with a slight adverse orientation, to estimate performance in space; ground testing, with the heat pipes operating gravity aided; and launch, with the evaporator elevated above the condenser. During the last two conditions, vertical ground testing and launch, the heat pipe wick will deprime and will need to re-prime for operation in space operation after launch. Two heat pipe wick designs were identified as readily repriming after depriming: grooved wick heat pipes and self-venting arterial heat pipes. In the grooved wick design a screen or sintered wick is required in the evaporator during start-up. This hybrid-wick design is necessary to supply liquid to the evaporator during vertical operation. Two heat pipes were designed, fabricated and tested: a self-venting arterial wick and a hybrid groove-screen wick design. This paper presents the design of the two heat pipes and test results which were used to evaluate which heat pipe wick design is better suited for the Kilopower system .

Keywords: Kilopower, heat pipe, hybrid wick, self-venting arterial wick

Pyroshock Induced Loads Driving Electrical, Thermal, and Structural Impacts in Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs)

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Abstract. Severe pyroshock environments due to several shock separation devices in the close proximity of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) were derived for the Mars Science Laboratory (MSL) project. During the MMRTG pryoshock qualification unit and engineering unit tests, the power output from each system temporarily decreased, but fully recovered after the shock signature subsided. An effort is underway to understand the root causes of the RTG temporary power losses, and a detailed system fault tree and associated system analyses have been developed to establish specific root-cause and recovery pathways. As part of this effort, the shock-induced loads and accompanying electrical/thermal/structural impacts within the system are currently being modeled. In this paper, the MMRTG shock qualification test results are reviewed and the preliminary shock prediction results are provided. The analysis includes predicting the dynamic, structural, and thermal responses of the MMRTG's critical internal interfaces to experimentally generated input transient shock loads. The shock analysis approach consists of two parts: First, transient normal-mode finite-element analysis is performed to predict the acceleration and the displacement responses at various RTG interfaces. Second, shock wave propagation is predicted through the interfaces, by taking advantage of the empirically defined shock impedances at the RTG internal interfaces. The potential applicability of the high-fidelity advanced-simulation codes to model the high frequency shock waves propagating through complex RTG internal interfaces is discussed. The impact of transient normal-modes and shock wave propagation on electrical circuit networks and electrical contact interfaces, thermal networks and interfaces, and structural components and interfaces within the MMRTG is then evaluated and quantified through electrical and thermal modeling, all of which is correlated and tied to system fault tree pathways to identify and prioritize likely causes and recovery mechanisms. This study suggests that the combination of the proposed computational and empirical techniques may provide computationally-robust wave propagation prediction schemes within the MMRTG coupled to MMRTG electrical and thermal predictive models to track and predict pyroshock effects and impact magnitudes. The results from this study will be used to understand the root causes of the pyroshock anomaly observed during MMRTG shock qualification testing and recommend corrective or mitigating MMRTG design techniques.

Keywords: Pyroshock environments, shock waves, shock predictions, transient analysis, pyroshock electrical analysis, pyroshock thermal analysis

Chemical Separations of Pu-238 from Irradiated Neptunium Targets

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Abstract. The Oak Ridge National Laboratory is developing chemical separation techniques for the recovery of large amounts of plutonium-238 from irradiated neptunium targets. After the individual unit operations are successfully tested, an integrated demonstration with two-cycle irradiated targets will be made before proceeding to full production. These operations include a two-step target dissolution to remove aluminum from the cladding and pellet matrix with caustic followed by the dissolution of neptunium and plutonium oxides in nitric acid. The primary separation of the neptunium, plutonium, and fission products is expected to be accomplished using solvent extraction with 30% tri-butyl phosphate in Exxsol® diluent using counter-current mixer/settler contactors. Additional purification methods such as anion exchange and oxalate precipitation will also be tested for effectiveness. Various options will be tested to determine which processes will provide the necessary product with acceptable waste generation. The processing of the irradiated targets will be performed in equipment currently installed in the hot cells and glove boxes of the Radiochemical Engineering Development Center. New techniques and equipment for the exchange of oxygen-17/18 with enriched $^{16}O_2$ on the plutonium oxide product to lower the neutron emission rate must be developed and designed to meet storage requirements. An overview of the current development and planned activities will be presented.

Keywords: Plutonium-238, irradiated targets, chemical processing

DEVELOPMENT OF ADVANCED COATINGS FOR NERVA-TYPE FUEL ELEMENTS

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Abstract. Despite impressive improvements in the quality of the coatings during the Rover and NERVA programs, ”midrange corrosion (erosion)” resulting in a significant mass loss of the fuel rods was a major issue affecting engine life and engine neutronics. Cracks were observed in the coatings in the midrange area of the fuel rods due to a mismatch in the coefficients of thermal expansion (CTE) of the coating and the matrix thereby enabling hydrogen ingress to the graphite (Gr) in the fuel element matrix. The present research proposes a new multilayered coating concept designed to solve the midrange corrosion problem. The concept envisions designing either a functionally graded or multilayered coatings to minimize the thermal expansion mismatch between the ZrC outer coating and the Gr/(U,Zr)C fuel matrix while acting as compliant layers as well as diffusion barriers separating the carbon and hydrogen. Single and multilayered coatings were deposited on Gr substrates by chemical vapor deposition (CVD). These trials have established that it is possible to deposit multilayered coatings by CVD although the quality of the coatings and the uniformity of their thicknesses require further improvement. Experimental studies are also underway to understand the diffusion of the various elements within the layers.

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

New Horizons NEPA/LA Lessons Learned

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Abstract. New Horizons (NH), as the first Principal Investigator (PI)-led and competed NASA Radioisotope Power System (RPS) mission, is on target to reconnoiter the Pluto system in July 2015. Launching an RPS mission requires compliance with two federal mandates: the National Environmental Policy Act of 1969 (NEPA), and launch approval (LA) as directed by Presidential Directive / National Security Council memorandum 25 (PD/NSC-25). The origins, planning, and development aspects of the New Horizons project, not only in science and technology but also in policy and politics, have been described elsewhere. Here, the NEPA/LA aspects of New Horizons are presented. The project's management of the NEPA/LA processes emphasized a collaborative, interactive approach among the many agencies and organizations involved, and obtained Presidential launch approval in less than four years. Specific accomplishments, from pre-proposal in November 2000, to launch approval and then launch in January 2006, are described and their criticality assessed. Lessons learned on various aspects, and applicability to future PI-led and competed NASA RPS missions, are offered. These NEPA/LA lessons learned are from the mission manager's implementation perspective.

Keywords: New Horizons, NEPA/LA implementation, PI-led and competed NASA RPS mission, lessons learned

Integrated Surface Power Strategy For Mars

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Abstract.

A National Aeronautics and Space Administration (NASA) study team evaluated surface power needs for a conceptual crewed 500-day Mars mission. This study had four goals:

1. Determine estimated surface power needed to support the reference mission;
2. Explore alternatives to minimize landed power system mass;
3. Explore alternatives to minimize Mars Lander power self-sufficiency burden; and
4. Explore alternatives to minimize power system handling and surface transportation mass.

The study team concluded that Mars Ascent Vehicle (MAV) oxygen propellant production drives the overall surface power needed for the reference mission. Switching to multiple, small Kilopower fission systems can potentially save four to eight metric tons of landed mass, as compared to a single, large Fission Surface Power (FSP) concept. Breaking the power system up into modular packages creates new operational opportunities, with benefits ranging from reduced lander self-sufficiency for power, to extending the exploration distance from a single landing site. Although a large FSP trades well for operational complexity, a modular approach potentially allows Program Managers more flexibility to absorb late mission changes with less schedule or mass risk, better supports small precursor missions, and allows a program to slowly build up mission capability over time. A number of Kilopower disadvantages—and mitigation strategies—were also explored.

Keywords: Mars, Kilopower, fission

Revised Point-of-Departure Design Options for Nuclear Thermal Propulsion

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Abstract. In an effort to further refine potential point-of-departure nuclear thermal engine designs, four engine designs representing two thrust classes and utilizing two different near-term fuel matrix types are designed, analyzed, and the resulting engine performance and mass characteristics presented. Two of these nuclear rocket engine designs utilize a W-UO_2 cermet (ceramic-metal) fuel with a prismatic geometry based on the GE-710, while the other two designs are based on the (U,ZrC)C-based composite fuel and prismatic fuel element geometry developed during the Rover/NERVA (Nuclear Engine for Rocket Vehicle Applications) program which ran from 1955-1973. The two engines analyzed for each fuel type include a small criticality limited design and a 111.2 kN (25 klb_f) thrust engine design. The 111.2 kN (25 klb_f) thrust class has been the focus of numerous manned mission studies, including NASA's Design Reference Architecture (DRA) 5.0.

The analysis presented here begins with a highly detailed Monte Carlo N-Particle (MCNP) model of the reactor core for each design which is developed and exercised to determine the energy deposited in both the fuel matrix itself and the various engine components via decelerating fission products and scattered neutrons and photons. These results, along with other rocket engine design inputs including desired chamber pressure, nozzle area ratio, and pressure drops along the flow circuit are then used by NASA's Nuclear Engine System Simulation (NESS) code to determine the engine's performance characteristics, the thermodynamic state points throughout the engine cycle, and to estimate the engine's mass and overall geometric envelope.

Although there are many rocket engine cycles available, all of the designs presented here are based on the closed expander cycle. This particular cycle was studied extensively for use in nuclear thermal rocket engines under the Rover/NERVA program, and also has an extensive heritage spanning over 50 years via the RL10 family of chemical rocket engines. One limiting factor of the expander cycle is obtaining adequate thermal energy in the turbine drive flow to drive the turbo-machinery, and thus thermodynamically close the engine cycle. Both of the NERVA based engine designs presented here utilize tie-tubes which allow for the extraction of thermal energy directly from the reactor core in order to heat the turbine drive flow, thus insuring adequate turbine drive power. The cermet-based designs, however, lack tie-tubes. Therefore, fuel elements located at the periphery of the reactor core are utilized to provide the additional thermal energy required by the turbine drive flow for these designs.

Keywords: NTR, NTP, Propulsion, Space.

Iridium Welding Process Improvement

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Abstract. An investigation is underway to evaluate an improvement to an iridium welding process. A pulsed gas tungsten arc welding (GTAW) process is being evaluated to replace the existing GTAW process which uses a magnetic arc oscillator. The magnetic arc oscillator has been credited with refinement of the weld grain structure and improved fracture toughness, which is critical to this iridium alloy as it is susceptible to rapid grain growth during welding, however, the actual magnetic deflection of the arc cannot be measured, thus this aspect of the process cannot be calibrated and the appropriate operating conditions cannot be confirmed and maintained. A pulsed current GTAW process, developed for a tantalum alloy with grain growth issues similar to iridium, has shown improved grain refinement and ductility compared to a conventional constant current GTAW process, so this pulsed current approach is being investigated for the iridium welding process. The discussion includes background of iridium welding issues, the development approach and results from the tantalum pulsed weld, and the results to date on the iridium weld investigation.

Keywords: Iridium, GTAW.

Personnel Dose Cost Considerations for Pu-238 Heat-Source Production

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Abstract. For many years, Los Alamos National Laboratory has fabricated plutonium-238 (Pu-238) heat sources for space applications. Pu-238 has a relatively short half-life (87.7 years) and decays by emission of energetic alpha particles. These alpha particles interact with nearby oxygen atoms and give rise to an alpha-n source that make Pu-238 processing problematic from a radiological protection perspective as neutrons are difficult to shield without relatively thick hydrogenous materials. The federal limit for whole-body exposure to a worker is 5,000 millirem (mrem), but regulations require dose to remain below this level and as low as reasonably achievable (ALARA). Los Alamos policy limits the whole-body exposure to 2,000 mrem and begins more concerted tracking of exposure at 1,000 mrem. However, there are trends in all nuclear operations to push dose levels down irrespective of the operational cost of doing so.

This study analyzes the costs associated with a workforce-management approach to dose reduction. The International Commission on Radiological Protection (ICRP) defines the principle of optimization as "the magnitude of individual doses, the number of people exposed, and the likelihood of potential exposure as low as reasonably achievable below the appropriate dose constraints..." With this in mind, historical exposure records from Los Alamos organizations involved in Pu-238 heat source development and fabrication between the years of 1988 and 2013 are analyzed along with each group's operating budget to develop an estimate of the costs associated with reducing the dose to maximally exposed individuals by means of personnel management. Example cases demonstrate that dose-reduction expenditures are more efficient when the dose limit to the maximally exposed individual is high and that large dose reduction can require costs that are likely unsupportable.

Keywords: Pu-238; Manufacturing; Dose, Cost

NASA's Nuclear Thermal Propulsion Project

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Abstract. Space fission power systems can provide a power rich environment anywhere in the solar system, independent of available sunlight. Space fission propulsion offers the potential for enabling rapid, affordable access to any point in the solar system. One type of space fission propulsion is Nuclear Thermal Propulsion (NTP).

NTP systems operate by using a fission reactor to heat hydrogen to very high temperature (>2500 K) and expanding the hot hydrogen through a supersonic nozzle. First generation NTP systems are designed to have an Isp of ~900 s. The high Isp of NTP enables rapid crew transfer to destinations such as Mars, and can also help reduce mission cost, improve logistics (fewer launches), and provide other benefits. However, for NTP systems to be utilized they must be affordable and viable to develop.

NASA's Advanced Exploration Systems (AES) NTP project is a technology development project that will help assess the affordability and viability of NTP. Early work has included fabrication of representative graphite composite fuel element segments, coating of representative graphite composite fuel element segments, fabrication of representative cermet fuel element segments, and testing of fuel element segments in the Compact Fuel Element Environmental Tester (CFEET). Near-term activities will include testing ~16" fuel element segments in the Nuclear Thermal Rocket Element Environmental Simulator (NTREES), and ongoing research into improving fuel microstructure and coatings.

Along with recapturing fuels technology, affordable development, qualification, and utilization strategies must be devised. In addition to historical NTP concepts using highly enriched uranium (HEU), low enrichment uranium (LEU) options are also being assessed. LEU options typically require development of a key technology before they can be applied to NTP in the thrust range of interest. Ground test facilities will be required, especially if NTP is to be used in conjunction with high value or crewed missions. There are potential options for either modifying existing facilities or constructing new ground test facilities. At least three potential options exist for reducing (or eliminating) the release of radioactivity into the environment during ground testing. These include fully containing the NTP exhaust during the ground test, scrubbing the exhaust, or utilizing an existing borehole at the Nevada National Security Site (NNSS) to filter the exhaust.

Finally, the project is considering the potential for an early flight demonstration of an engine very similar to one that could be used to support human Mars or other ambitious missions. The flight demonstration could be an important step towards the eventual utilization of NTP.

Keywords: Nuclear, Propulsion, Mars, NASA, Affordable

Advanced Radioisotope Thermoelectric Generators (ARTGs) that Leverage Segmented Thermoelectric Technology

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Abstract. Advanced thermoelectric materials and couple technologies are being successfully developed at JPL under the NASA sponsored Advanced Thermoelectric Couple (ATEC) program. The new materials have demonstrated a real improvement in power conversion efficiency with thermoelectric couple tests demonstrating more than 15% thermal to electric efficiency across a 1273 K to 473 K ΔT, which is twice that of current thermoelectric materials used in space applications. These advanced materials are the first new and truly promising technology available to radioisotope thermoelectric generator developers in decades.

The advanced thermoelectric materials include skutterudite (SKD) materials for operating at temperatures up to about 873K and $La_{3-x}Te_4/Yb_{14}MnSb_{11}$ Zintl materials for extending the operating temperature up to the 1273 K when segmented with the lower temperature SKD materials. The SKD technology is now sufficiently developed that the technology is being transferred to industry (Teledyne Energy Systems) under the Technology Maturation Project. System studies have shown that the SKD couples implemented in the MMRTG generator will result in an enhanced MMRTG (eMMRTG) capable of providing a sizable 25% power boost for the MMRTG. Technology insertion into the existing MMRTG platform provides a low risk path to a very high performing multi-mission generator.

The next step will transition the n-type $La_{3-x}Te_4$ and p-type $Yb_{14}MnSb_{11}$ technologies to production. These materials, when segmented with the SKD materials, produce a high temperature couple suitable for integration with a deep space vacuum generator. Tests of the segmented couples have demonstrated more than 15% thermal to electric efficiency, about twice that of the Cassini style RTG. This high performance generator has the potential to provide power levels and specific power levels much higher than ever before, making missions more capable, cost effective, and potentially even enabling new classes of missions (for example, REP). The new thermoelectric technology, when integrated with existing generator technology, holds the promise of a much shorter generator development cycle with lower development cost/risk.

A design study was conducted to understand the first order design tradeoffs between mass, power, and efficiency for a deep space generator implementing the advanced segmented thermoelectric materials. The thermoelectric sizing and layout options were evaluated using the measured thermoelectric material properties. The sizing options were integrated with the generator thermal and heat rejection designs to allow parametric evaluation of the system considering a range of hot and cold junction temperatures. The study evaluated vacuum systems ranging in size from 200 W to 500 W. A modular design approach covering the full range up to 500 W was also evaluated. The study findings include parametric performance results for the various system options, including the system power, mass, efficiency, and specific power. This presentation will summarize the parametric study approach and the parametric results.

Keywords: Radioisotope, RTG, ARTG, thermoelectric.

Skutterudite-Based Advanced Thermoelectric Technology for Potential Integration Into an Enhanced MMRTG

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Abstract. Radioisotope Thermoelectric Generators (RTGs) generate electrical power by converting the heat released from the nuclear decay of radioactive isotopes (typically plutonium-238) into electricity using a thermoelectric (TE) converter. RTGs have been successfully used to power a number of space missions including the Apollo lunar missions, the Viking Mars landers, Pioneer 10 and 11, and the Voyager, Ulysses, Galileo, Cassini, and New Horizons outer planet spacecrafts. MSL's Curiosity rover is powered by the Multi-Mission Radioisotope Generator (MMRTG). Teledyne Energy Systems Inc. (TESI) and prime contractor, Pratt & Whitney Rocketdyne, working in partnership with the Department of Energy, produced this generator for Curiosity. RTGs have demonstrated their reliability over extended periods of time (tens of years) and are compact, rugged, radiation resistant, scalable, and produce no noise, vibration or torque during operation. NASA's Radioisotope Power Systems Technology Advancement Program is pursuing the development of more efficient TE technologies that can increase performance over state-of-practice RTGs, which are limited to device-level thermal-to-electrical energy conversion efficiencies of 7.5% or less, and system-level specific power of 2.4 to 5.1 W/kg. The Jet Propulsion Laboratory (JPL), under funding from the NASA Radioisotope Power Systems Project, under the Advanced Thermoelectric Couple (ATEC) task, has developed couples based on advanced skutterudite (SKD) thermoelectric materials. Conversion efficiency values on the order of 9% have been demonstrated for SKD-based un-segmented couples when operating at a hot-junction of 873K and a cold-junction of 473K. This represents ~ a 25% improvement over the conversion efficiency of PbTe/TAGS MMRTG couples. JPL and TESI are collaborating on a project to transfer the technology to TESI, to further mature this technology, to develop the manufacturing capabilities for SKD TE materials, couples, and modules at TESI, and to demonstrate their performance and conduct a life assessment for this technology. This paper provides a status of the technology development and life assessment at JPL, the progress of the technology development at TESI, as well as a brief description of the technology maturation future plan.

GEANT4 Based Assessment of the Cosmic Radiation Transport in Space: Examples of International Space Station and Apollo Missions

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Abstract. Future manned and unmanned space travel requires accurate models of radiation transport through spacecraft to predict dose to protect astronauts, predict energy deposition within sensitive electronics and sensors, and develop new more effective radiation shielding from the radiation environment of Galactic Cosmic Rays, Radiation Belts, and Solar Particle Events. GEANT4 provides a powerful platform in C++ for simulation of radiation transport through spacecraft based on Monte Carlo method. The newest version of GEANT4 supports multithreading and MPI allowing for much faster distributive processing of simulations across many computers. We introduce a new application that greatly reduces computational time using multiple threads and nodes. The computational time is reduced from weeks to days without any post simulation processing. We also introduce a new set of sensitive simulation detectors besides the historically used International Commission of Radiation Units (ICRU) spheres for calculating dose distribution including a Thermoluminescent Detector (TLD), Tissue Equivalent Proportional Counter (TEPC), and human phantom along with a series of new primitive scorers in GEANT4 applicable to calculate dose equivalence based on the International Commission of Radiation Protection (ICRP) standards.

In this paper we present GEANT4 assessment of the dose deposition in the International Space Station within 10% of experimental measurements. Additionally, GEANT4 based assessment of the dose rates during the Apollo 11 and Apollo 14 mission are presented. During normal missions, the greatest contributor to radiation dose is from Galactic Cosmic Rays due to the short time within the radiation belts. The Apollo 14 dose measurements were significantly higher compared to other Apollo missions, with the variation hypothesized to be caused by the location of dosimeters within the spacecraft. However, our GEANT4 model of the Apollo Command Module show only very small differences in dose distribution across the capsule and consistent doses from Galactic Cosmic Rays and Radiation Belts for all missions. By the time of the Conference we will provide additional assessments of how cosmic radiation may affect ten-fold increase in radiation doses in Apollo 14 vs. other Apollo missions.

Keywords: Shielding, Monte Carlo, GEANT4, Apollo Mission, International Space Station

Thermoelectric module mechanical performance effects in Am-241 Radioisotope Thermoelectric Generators.

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Abstract. European Radioisotope Thermoelectric Generator (RTG) developments are targeted at the use of Am-241 based fuel. Recent laboratory 'breadboard' testing and analysis has demonstrated that bismuth telluride based thermoelectric materials offer a viable power conversion option. Thermoelectric modules based on commercially available units have been shown to offer a promising solution with clear benefits in lower development risk due to proven commercial manufacturing routes. A disadvantage of conventional bismuth telluride based thermoelectric materials is the poor mechanical integrity due to cleavage along the basal crystallographic plane. However, recent experimental studies have shown that (1) conventional modules can still withstand relatively high through-thickness compression loads, and (2) polycrystalline materials produced by spark plasma sintering and strengthened with dispersed phases offer improved material performance. The relationship between the compressive force clamping the thermoelectric modules to the heat source, and overall RTG performance has not been investigated for Am-241 RTGs. It is likely to be an important trade in the system due to the lower power density of Am-241 compared to Pu-238, and the need for high-aspect ratio thermoelectric legs. The results of a system-level modelling study on this effect, along with relevant mechanical experimental results will be reported.

Keywords: americium, RTG, bismuth telluride, system performance, mechanical properties

Feasibility Study on Polonium Isotopes as Radioisotope Fuel for Space Nuclear Power

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Abstract. This study aims to evaluate the performance of Po isotopes as a radioisotope fuel for use in space radioisotope power generators. Historically, plutonium-238 has been proven to be the best radioisotope for the provision of space nuclear power because of its high power density (540 W/kg), enough half-life (87.7 years), low radiation levels, and stable fuel form at high temperature. However, current concerns over the limited supply and difficult treatment of ^{238}Pu have increased the need to explore alternative isotopes for space nuclear power applications. Polonium-209 has the possibility to be an alternative material of ^{238}Pu. It has enough half-life of 102 years and the specific power of 490 W/kg. The ^{209}Bi (p, n)^{209}Po reaction is the most simple production path from natural element. The production method by this reaction with proton accelerators is independent of nuclear fuel. The reaction chain of ^{209}Bi (n, γ)^{210}Bi (β decay) ^{210}Po (n, 2n)^{209}Po is another production path. This reaction may be possible in a system to use nuclear reactor such as a Lead-Bismuth cooled fast reactor or an Accelerator Driven system (ADS) with Lead-Bismuth target. To evaluate the production method, calculations for the production rate of Po isotopes with proton accelerators were performed using the PHTIS code with a simple geometry. The target was natural Bi (metallic form of ^{209}Bi) and was thick enough that all protons stopped completely. The calculation results showed that the beam current of 14 A with 40 MeV proton energy was required for annual production of 1kg ^{209}Po. However, the requirement for accelerator is quite large in comparison with the current accelerator technology. Additionally, Polonium-208 ($t_{1/2}$=2.898 years) is generated and the ratio of ^{209}Pu/($^{208+209}$Pu) was constant of about 0.2 above 20 MeV. It means that enough cooling time is required for ^{209}Po. On the other hand, it is also possible to use ^{208}Po as a radioisotope fuel since it has a large power density (18300 W/kg).

Keywords: Polonium-209, Polonium-208, Plutonium-238, Radioisotope Fuel, RTG.

Determining an Affordable Mars Mission Capable NTP Thrust Size

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Abstract. Future exploration missions across the Solar System need technologies that reduce the time of flight, provide efficient payload capability, and reduce the size and the number of launch systems in order to reduce mission risk and cost. NTP is the proven, high TRL (Technology Readiness Level) technology, which provides the performance to enable rapid transit and can minimize the number of spacecraft stages due to the higher ISP (specific impulse). The future of human Mar exploration will see substantial benefit in terms of lower mission mass and faster trip times when Nuclear Thermal Propulsion is employed.

Also, architectures that have the local planetary exploration elements pre-deployed ahead of the human crew can have a significant impact on the design of the human NTP spacecraft or transfer vehicle. The desire would be to get the human crewed vehicle to be as small as technically feasible to permit it to optimize to using multiple NTP systems at the lowest required thrust. This could drive the NTP design to have a smaller reactor and present a more affordable development and operational footprint for future human Mars exploration.

Using Aerojet Rocketdyne's multidisciplinary design analysis capability, a detailed mission and vehicle model has been used to examine how the thrust size and number of NTP systems impact a fast transit human Mars mission. Trends for the propulsion system mass as a function of power level (i.e. thrust size) are established using AR designs and correlated against data created over the past forty years. The resulting mission trades presented in this paper used a comprehensive modeling approach that captures the mission payload requirements, trajectory velocity and gravity losses requirements, vehicle subsystems design, and NTP sizing. The mission analysis and architecture tool used for the trade study is mature and discussed in a previous paper where it was used for examining the design of bimodal NTP systems.

There is no doubt that technically, NTP technology and design can enable robust, sustainable exploration for human Mars exploration. NTP has been proven scientifically and many engineering challenges have been addressed in past ground testing of the larger reactor cores. The challenge today is to create an affordable, highly capable in-space propulsion system. It is Aerojet Rocketdyne's belief that this could be achieved based on using smaller reactor in the NTP (e.g., < 500 MWt) that spring-board off the knowledge gained from past research and development and apply new technologies to improve the life and provide eventually reusability.

Approaches to use as small as possible NTP reactor cores could provide a development cost benefit with less uranium content and are more easily tested with a smaller facility foot-print. The smaller facility and lower exhaust flow rate provides for less effluent to clean and manage, which, in turn, reduces the development cost due to environmental safety and nuclear material security concerns. Fundamentally a lower power NTP reactor core (< 500 MWt) can reduce the development, procurement, and operational costs making it a more affordable NTP system for a nuclear cryogenic propulsion stage.

Aerojet Rocketdyne (AR) has been working on the several NTP system designs that have characterized a wide range of thrust (core) sizes and the scalability to robotic and human exploration systems. Studies performed in 2011 through 2013 identified NTP approaches for using the capability smaller size NTP systems for robotic and human Solar System missions. This paper will re-examine past trades using larger NTP sizes and discuss recent trade studies performed examining the impact of smaller NTP thrust sizes, number of engines, rector core type and the resulting stages designed for fast transit human Mars missions.

Nuclear Thermal Propulsion Development Risks

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Abstract. There are clear advantages of development of a Nuclear Thermal Propulsion (NTP) for a crewed mission to Mars. NTP for in-space propulsion enables more ambitious space missions by providing high thrust at high specific impulse (~900 sec) that is 2 times the best theoretical performance possible for chemical rockets. Missions can be optimized for maximum payload capability to take more payload with reduced total mass to orbit; saving cost on reduction of the number of launch vehicles needed. Or missions can be optimized to minimize trip time significantly to reduce the deep space radiation exposure to the crew. NTR propulsion technology is a game changer for space exploration to Mars and beyond.

However, "NUCLEAR" is a word that is feared and vilified by some groups and the hostility towards development of any nuclear systems can meet great opposition by the public as well as from national leaders and people in authority. The public often associates the "nuclear" word with weapons of mass destruction. The development NTP is at risk due to unwarranted public fears and clear honest communication of nuclear safety will be critical to the success of the development of the NTP technology.

Reducing cost to NTP development is critical to its acceptance and funding. In the past, highly inflated cost estimates of a full-scale development nuclear engine due to Category I nuclear security requirements and costly regulatory requirements have put the NTP technology as a low priority. Innovative approaches utilizing low enriched uranium (LEU).

Even though NTP can be a small source of radiation to the crew, NTP can facilitate significant reduction of crew exposure to solar and cosmic radiation by reducing trip times by 3-4 months. Current Human Mars Mission (HMM) trajectories with conventional propulsion systems and fuel-efficient transfer orbits exceed astronaut radiation exposure limits. Utilizing extra propellant from one additional SLS launch and available energy in the NTP fuel, HMM radiation exposure can be reduced significantly.

Keywords: Nuclear Thermal Propulsion, Project Management, Risk, Technology Development, Human Mars Mission

Enhancing the Performance of Zintl Phases via Defect Chemistry

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Abstract. Radioisotope thermoelectric generators (RTGs) have successfully been used for many NASA missions where photovoltaics or batteries are not practical such as deep space or dusty or dark environments. The systems are reliable, robust and long-lived, however, their thermal-to-electric conversion efficiency is relatively low at only 6%. As the power demands increase for future mission's scientific payload higher efficiency thermoelectric systems are necessary.
The thermoelectric figure of merit (ZT) is an equation that is used to gauge the thermal to electric conversion efficiency of a material and is given by the following equation: $ZT = \alpha^2T/\rho\kappa$ where α is the Seebeck coefficient, ρ is the electrical resistivity, T is the absolute temperature and κ is the thermal conductivity of the material. The ideal thermoelectric material has the electronic properties of heavily doped semiconductor with low metal like resistivity and high Seebeck coefficients and the thermal properties of glass. Recently, complex Zintl phases such as n-type $La_{3-x}Te_4$ and p-type $Yb_{14}MnSb_{11}$ have been developed at the Jet Propulsion Laboratory (JPL) and collaborating institutions over the last few years with ZTs as high as 1.3 at 1275 K, a factor of 2 improvement over the heritage $Si_{0.8}Ge_{0.2}$ alloys. The high ZT in these materials is attributed to inherently low lattice thermal conductivity brought by structural complexity and unique covalent bonding. Classically thought of valence-precise line compound with semiconductor like behavior, it has been found that certain Zintl phases such as AZn_2Sb_2 (A=Ca, Sr, Eu, Yb) contradict this convention by exhibiting metallic behavior or possess extremely low glass-like thermal conductivities of as in the case of $Yb_9M_{4.5-x}Sb_9$ (M=Zn, Mn, $0<x<0.25$). The deviation from the classical Zintl convention is attributed to relatively large single phase width in the compositions which allow for optimization of the thermoelectric properties by simple manipulation of the crystallographic defects. We will present the recent results on AZn_2Sb_2 (A=Ca, Sr, Eu, Yb) and $Yb_9Mn_{4.5-x}Sb_9$ Zintl phases and the impact of their crystallographic defects on the thermal and electronic transport properties.

Keywords: thermoelectric, Zintl phases, defects

Engineering Space Nuclear Power Systems Using a System of Systems Perspective

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Abstract. The Department of Energy and its predecessor agencies have been developing, manufacturing and delivering nuclear power systems in support of space applications for more than fifty years. In addition to these deployed systems, there is a significant additional experience base available from the research and development of space nuclear technologies and systems that were not deployed for a variety of reasons. A review of decades of radioisotope power systems, fission power and nuclear propulsion programs reveals common themes in systems engineering (SE) approach that take into account the unique combination of factors that affect all types of nuclear development for space applications. This SE approach has been highly successful and there is significant documentation on a program-by-program basis, but no concise, recent reference tool is available to stakeholders to explain why the methods work and the basis by which SE application and tailoring decisions should be approached.

Common understandings within the space nuclear community of both the current SE approach and the system development environment are necessary to support informed discussion of the challenges inherent in developing these systems. While the authors acknowledge that some of the factors driving complexity and uncertainty may be inherently irresolvable, developers and stakeholders have always proposed means of mitigating them, but have not adopted any common approach to evaluating their effectiveness, before or after implementation. The authors propose adoption of a System of Systems (SoS) perspective as a first step in developing a decision-making tool set. An overview of the SoS thinking is provided along with rationale for its use. Highlights of historical and current SE approaches for NPS are presented and evaluated in a SoS context, as are several concepts that are emerging regarding how NPS development may proceed in the future. The paper does not conclude with a single recommended SE approach, but does identify the strengths and challenges of some options that have been considered and recommends best practices for analyzing their SoS effects prior to implementation.

Keywords: Systems Engineering, System of Systems, Radioisotope Power Systems, Fission Power Systems, policy

Affordable Development and Demonstration of a Small NTR Engine and Stage: A Preliminary NASA, DOE and Industry Assessment

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Abstract. Nuclear Thermal Rocket (NTR) propulsion represents the next evolutionary step in cryogenic liquid rocket engines. Deriving its energy from fission of Uranium-235 atoms contained within fuel elements that comprise the engine's reactor core, the NTR can generate high thrust at a specific impulse of ~900 seconds or more – twice that of today's best chemical rockets. In FY'11, under the ETDD program, NASA proposed a Nuclear Thermal Propulsion (NTP) effort that envisioned two key activities – "Foundational Technology Development" followed by system-level "Technology Demonstration" projects. Near-term NTP activities initiated under Foundational Technology Development are now part of the Nuclear Cryogenic Propulsion Stage (NCPS) project started in FY'12 and funded by NASA's Advanced Exploration Systems (AES) Division. The NCPS Phase 1 effort is focused on recapturing fuel fabrication techniques, maturing and testing "heritage" fuel element (FE) designs, then selecting between the two candidate fuel forms previously identified by NASA and DOE – NERVA "composite" and UO_2 in tungsten "cermet" fuel. The Phase 1 effort also includes: (1) Mission Analysis and Requirements Definition; (2) Engine Conceptual Design; (3) Determining an Affordable Ground Test Approach; and (4) Formulation of an Affordable and Sustainable NTP Development Strategy. In early 2015, partial-length fuel elements will be fabricated and tested in the NTR Element Environmental Simulator (NTREES) located at NASA's MSFC. NTREES will provide up to ~1.2 MW of RF heating to simulate the NTP thermal environment that includes exposure to hot hydrogen. NTREES will be used to screen candidate fuel element designs, coatings and materials prior to beginning irradiation testing of FEs at a DOE site during Phase 2 of the NCPS project. The Phase 2 effort (FY's 15 – 17) would also include non-nuclear "proof-of-concept" subscale validation of the SAFE (Subsurface Active Filtration of Exhaust) ground test option – also referred to as "Bore-hole" testing – at the Nevada Test Site (NTS).

Successful results from these Phase 1 and 2 efforts could provide the basis for "authority to proceed" with significant system-level demonstration projects that would include ground technology demonstration (GTD) tests at the NTS, followed by a flight technology demonstration (FTD) mission. In order to reduce development costs, the GTD and FTD tests will use a small, low thrust (~7.5 klb_f) engine with a "common" fuel element design that is scalable to the higher thrust (~25 klb_f) engines – like that used in NASA's Mars DRA 5.0 study – by increasing the number of elements in a larger diameter core that can produce greater thermal power output. A small NTP ground test engine is also easier to transport, assemble and disassemble after testing has been completed. The GTD project would build and test several ground test articles plus a flight test article that provides system-level technology demonstration and design validation for a follow-on FTD mission. The small NTP flight demonstration stage would also maximize the use of existing and flight proven liquid rocket and stage components (e.g., TPA, nozzle, hydrogen tank, systems for pressurization, attitude control, avionics and power, plus inter-stage and thrust structure) to further ensure affordability. This paper will provide a preliminary NASA, DOE and industry assessment of what is required (qualification strategy options, key nuclear and non-nuclear component and subsystem development activities, and the associated schedule) to affordably build, ground test and fly a small NTR engine and stage.

Keywords: NTR, NTP, GTD, Engine, FTD, Stage.

Mechanical properties and sublimation studies of composited high temperature thermoelectric lanthanum telluride, $La_{3-x}Te_4$, and 14-1-11 Zintls, $Yb_{14}MnSb_{11}$

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Abstract. Developing thermoelectric couples that operate up to 1275 K is key to improving the performance of radioisotope thermoelectric generators. Lanthanum telluride $La_{3-x}Te_4$ and 14-1-11 Zintls ($Yb_{14}MnSb_{11}$) are promising high temperature materials. Differences in the physical, mechanical, and chemical properties of the materials that make up the thermoelectric couple, especially differences in the coefficients of thermal expansion (CTE), result in undesirable interfacial stresses that can lead to mechanical failure of the device. The problem is complicated by the relatively large CTE values and brittle nature which allows cracks to propagate with minimal resistance. Adding inclusions such as metals or ceramics potentially improves mechanical properties such as hardness and fracture strength without impeding thermoelectric properties or long term stability. Different composites were measured using Vickers hardness and thermally annealed at high temperatures to test sublimation.

Keywords: Thermoelectric, Mechanical properties, sublimation

The Segmented Thermoelectric Module: A Common Converter Building Block for Future Radioisotope and Fission Thermoelectric Generators

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Abstract. Heritage and current Radioisotope Thermoelectric Generator (RTG) systems such as the GPHS-RTG and the Multi-Mission RTG (MMRTG) have mainly used a converter array configuration with hundreds of discrete thermoelectric (TE) couples interconnected on the cold side in a series-parallel "laddering" pattern to achieve high redundancy and eliminate single point failures. However, when scaling up to higher power levels, the use of discrete couples becomes impractical due to the large quantities and constraints posed by system integration. Such TE system configurations, such as the one developed during the SP-100 program for a 100 kW-class fission power system (FPS), have instead used arrays of multi-couple modules.
The use of TE modules is also necessary for "low power" system designs when requirements dictate a high module output voltage (e.g. 32V), which translates into a large number of couples with high aspect ratio. The best approach for practical and efficient thermal and mechanical integration with the heat source and heat rejection system components is to assemble these high aspect ratio couples into robust TE module structures.
The multi-couple segmented TE module is a common building block to potential next generation space nuclear power systems, including the Modular Advanced RTG (Mod-ARTG), a high temperature version of the current MMRTG (HT-MMRTG), and TE-based FPS ranging from the kW to tens of kW power level. Depending on the application and its configuration for coupling to the heat source (radiative or conductive) and heat sink, a basic "skeleton structure" can be integrated into cantilevered or spring-loaded TE module configurations. The "skeleton structure" consists of an array of eight segmented couples mechanically and thermally assembled into a single structure. The module would utilize a common hot shoe, having a compliant metal/ceramic header, and cold side interconnects. The couples are based on ATEC technology, which is being advanced as part of NASA's Thermoelectric Technology Development Project, with skutterudites/$La_{3-x}Te_4$/$Yb_{14}MnSb_{11}$ materials capable of providing up to 15% device efficiency (as demonstrated in 2011 for 1273 K/473 K hot and cold junction temperatures). The eight-couple skeleton structure is already configured internally in a series-parallel laddering circuitry, so that the full converters simply consists of all of the modules connected electrically in series. Additional parallel circuits could be added for higher power systems, and these modules can be arrayed in modular "converter slices". We briefly describe some four-couple and eight-couple segmented TE module prototypes using this new technology that have been developed for proof-of-concept converter demonstrations in solar-thermal (radiative heat source coupling), fossil fuel combustor (conductive heat source coupling) generator and small FPS applications.

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

Thermodynamic Analysis and Radiator Design of a Pulsed Bi-modal Radioisotope Propulsion System

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Abstract. Previous work done at the Center for Space Nuclear Research (CSNR), under Nathan Jerred's NIAC Phase 1 research on Dual-mode Propulsion System, proposed a bi-modal plutonium radioisotope thermal rocket. The power conversion cycle for this system would employ a closed loop Brayton cycle and operate in pulses to deliver upto 25 kW of electrical power that can be used for communications and electric propulsion. During this pulsed power generation, the waste heat will be accumulated in a lithium block, and then radiated to space over a long period of time while the system is in a "warm up" phase. Anticipated advantage was significant reduction in the size of the radiator compared to a continuous system, such as fission reactor, but no quantitative analysis was performed. This paper presents the quantitative analysis and models of the power conversion cycle. Cycle parameters (temperatures and pressures) and radiator geometry were determined in a time-dependent flow and heat transfer simulation. Compressors and turbines were modeled using isentropic flow equations with efficiency corrections. Convective heat transfer in the radioisotope core and lithium radiator flow channels were analysed using one dimensional pipe flow mechanics. Requirements were to produce 25 kW_e for six minutes in every 15 hours, without exceeding 1100 K at turbine inlet. The paper presents the theoretical studies carried out in using helium and hydrogen as working fluids. In both cases a cylindrical block of lithium with a mass of minimum 200 kg was determined to be sufficient enough to sink the waste heat during operation and radiate it to space between cycles. In the propulsion mode, propellant (H_2) is blown through the hot core and expelled through a nozzle, providing 20 N of thrust with specific impulse of 700s. Conducted study confirmed that pulsed Brayton cycles can operate on much smaller radiators than continuous systems, while bi-modal configuration provides moderate thrust needed for impulsive orbital maneuvers.

Keywords: Radioisotope, Propulsion, Power, Brayton Cycle and Heat Transfer.

Initial Operation of the Nuclear Thermal Rocket Element Environmental Simulator

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Abstract. The Nuclear Thermal Rocket Element Environmental Simulator (NTREES) facility is designed to perform realistic non-nuclear testing of nuclear thermal rocket (NTR) fuel elements and fuel materials. Although the NTREES facility cannot mimic the neutron and gamma environment of an operating NTR, it can simulate the thermal hydraulic environment within an NTR fuel element to provide critical information on material performance and compatibility. The NTREES facility has recently been upgraded such that the power capabilities of the facility have been increased significantly. At its present 1.2 MW power level, more prototypical fuel element temperatures nay now be reached. The new 1.2 MW induction heater consists of three physical units consisting of a transformer, rectifier, and inverter. This multiunit arrangement facilitated increasing the flexibility of the induction heater by more easily allowing variable frequency operation. Frequency ranges between 20 and 60 kHz can accommodated in the new induction heater allowing more representative power distributions to be generated within the test elements. The water cooling system was also upgraded to so as to be capable of removing 100% of the heat generated during testing

In this new higher power configuration, NTREES will be capable of testing fuel elements and fuel materials at near-prototypic power densities. As checkout testing progressed and as higher power levels were achieved, several design deficiencies were discovered and fixed. Most of these design deficiencies were related to stray RF energy causing various components to encounter unexpected heating. Copper shielding around these components largely eliminated these problems. Other problems encountered involved unexpected movement in the coil due to electromagnetic forces and electrical arcing between the coil and a dummy test article. The coil movement and arcing which were encountered during the checkout testing effectively destroyed the induction coil in use at the time and resulted in NTREES being out of commission for a couple of months while a new stronger coil was procured. The new coil includes several additional pieces of support structure to prevent coil movement in the future. In addition, new insulating test article support components have been fabricated to prevent unexpected arcing to the test articles.

Additional activities are also now underway to address ways in which the radial temperature profiles across test articles may be controlled such that they are more prototypical of what they would encounter in an operating nuclear engine. The causes of the temperature distribution problem are twofold. First, the fuel element test article is isolated in NTREES as opposed to being in the midst of many other mostly identical fuel elements in a nuclear engine. As a result, the fuel element heat flux boundary conditions in NTREES are far from adiabatic as would normally be the case in a reactor. Second, induction heating skews the power distribution such that power is preferentially deposited near the outside of the fuel element. Nuclear heating, conversely, deposits its power much more uniformly throughout the fuel element. Current studies are now looking at various schemes to adjust the amount of thermal radiation emitted from the fuel element surface so as to essentially vary the thermal boundary conditions on the test article. It is hoped that by properly adjusting the thermal boundary conditions on the fuel element test article, it may be possible to substantially correct for the inappropriate radial power distributions resulting from the induction heating so as to yield a more nearly correct temperature distribution throughout the fuel element.

Keywords: Nuclear, Rocket, Fuel, Testing

Trade Study on Thermodynamic Architectures for Low Specific Mass Nuclear Electric Space Power Systems

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Abstract. This study overviews the thermodynamic architectures which can be used for energy conversion for nuclear electric propulsion. In previous research, power requirements of 10 kg/kWe and an electric power of 5 MWe were identified as power system parameters for competitive nuclear electric propulsion for human Mars missions. Thermoelectric, Brayton, Rankine and Stirling cycles are analyzed as candidates for the power conversion system.

Each thermodynamic architecture was analyzed for feasibility of achieving the power requirements. If feasibility could be established, then systems were further analyzed for configurations that could achieve the requirements. For each thermodynamic architecture, a steady state system model was developed in the Engineering Equation Solver software. The system model utilized parameters such as core inlet temperature, component isentropic efficiency, and pressure loss to determine parameters such as the power and thermal efficiency. A basic component mass model was developed for determining the specific mass of the system.

In addition to the specific mass and power model other logistical and system parameters were evaluated to down select to a single thermodynamic architecture which will later serve as the focus of a in depth system design in future work.

Keywords: Specific Mass, Electric Propulsion, Thermodynamic Architecture, Nuclear Electric Power, Space Fission

Solid Matrix Fuels for Space Power Reactors

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Abstract. Recent advances in nuclear fuel manufacturing are allowing for new types of fuels with superior power density, safety, fabrication cost, and other traits. Spark plasma sintering (SPS) is one such technology that is currently being explored. The University of Florida and the Center for Space Nuclear Research have successfully demonstrated the technology. SPS is unique in its ability to sinter disparate materials together allow for new types of cermets, inhomogeneous metal alloys, and ceramic-ceramic composite fuels. SPS has been successfully demonstrated with fuels such as UO_2-W cermet matrix fuels and UO_2 with high thermal conductivity additives.

SPS opens the door to rapid iteration of new fuel types many of which are highly attractive to space fission. One of the fundamental requirements for space nuclear fuels is a high temperature capability. UO_2 is a high temperature fuel however its thermal conductivity is very low. SPS opens to door to creating composite materials with high thermal conductivity allowing the fuels to reach much higher power densities and lower temperature peaking factors. In addition, safety can be improved by utilizing small fuel pellets sintered to a fuel matrix which can retain fission products, possibly eliminating the need for fuel cladding.

This research focuses on exploring the design space for matrix composite fuels. Matrix material such as W, SiC, Be, BeO, graphite are looked at and fuels such as UO_2, UN, and UC are explored. This analysis investigates, neutronic properties, thermal conductivity, tensile strength, and burn up for infinite lattices of the composite fuel and moderating elements in hexagonal fuel formats.

Keywords: Spark Plasma Sintering, Space, Composite Fuels, Material Properties

Zintl Thermoelectrics for Power Generation in Space

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Abstract. Zintl phase pnictides are promising candidates of next generation thermoelectric materials for radioisiotope power generation. These phases are typically small-band gap semiconductors with complex crystal structures. Due to structural complexity, Zintl compounds exhibit some of the lowest reported lattice thermal conductivities (κ_L) among bulk materials. In addition, such phases allow fine tuning of carrier concentration without disrupting electronic mobility, which is essential for optimizing thermoelectric efficiency. In the past decade, a number of complex Sb-based Zintl phases have been identified as promising thermoelectric materials: $Yb_{14}MnSb_{11}$, $Yb_9Mn_{4.2}Sb$, Ca_3AlSb_3, Sr_3GaSb_3, $Ca_5In_{2-x}Zn_xSb_6$, etc. The Zintl phase $Yb_{14}MnSb_{11}$ exhibits incredibly low κ_L (~0.4 $Wm^{-1}K^{-1}$), and has a peak zT of 1.3 at 1223 K when doped with Al. Due to its status as one of the best high temperature p-type thermoelectric materials, it is currently being developed for use in radioisotope thermoelectric generators (RTG) by NASA's Jet Propulsion Laboratory. Herein, we will present the preparation, chemical characterization and the thermoelectric properties of new Zintl phase pnictides displaying desirable thermoelectric properties.

Keywords: Zintl phase pnictides, Thermoelectrics, Power generation.

Lanthanum Telluride-Nickel Thermoelectric Composites with Enhanced Mechanical Strength and Toughness

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Abstract. For the past 50 years, the National Aeronautics and Space Administration (NASA) has successfully powered 17 missions utilizing solid-state thermoelectric devices which convert heat from radioactive decay into electricity through the Seebeck effect. Although effective and reliable, the thermal-to-electric conversion efficiency has been limited to ~6-6.5%. Higher efficiencies would reduce Pu-238 fuel requirements, increase available power to spacecraft instruments..

New thermoelectric materials are under development at the Jet Propulsion Laboratory (JPL) to improve the energy conversion efficiency. One of these materials is the high temperature n-type material lanthanum telluride, $La_{3-x}Te_{4.}$ The carrier optimized material has a high thermoelectric figure of merit of zT = 1.4 and has been used in conjunction with p-type Zintl phase $Yb_{14}MnSb_{11}$ to produce a prototype couple with a demonstrated 10% energy conversion efficiency, a 25% improvement over the state-of-the-art $Si_{0.8}Ge_{0.2}$ system. Although effective as a thermoelectric material, lanthanum telluride behaves as a weak and brittle refractory material resulting in difficulties during manufacturing and reliability.

A possible solution to this problem is the addition of metallic nickel particles to lanthanum telluride to form a ceramic-metal composite, or cermet. A lanthanum telluride-nickel thermoelectric cermet with enhanced mechanical properties will improve strength and reliability of thermoelectric devices. In addition, improve mechanical properties allows for relaxed manufacturing restraints enabling unique complex device architectures.

Micron-sized nickel inclusions were incorporated through bulk powder mixing with ball-milled lanthanum telluride in a shaker mill. The resulting powder mixture was compacted using direct current sintering (spark plasma sintering) and the mechanical properties were evaluated. The mechanical properties of a series of N=10 samples with nickel volume percentages of 2%, 5%, and 10% were studied. There was a negligible improvement in the Vickers Hardness of the thermoelectric cermets, but more importantly there was a 30% improvement in the Vickers Indentation Fracture Toughness thereby improving resistance to brittle failure. In addition, there was 50% improvement in the equibiaxial flexural strength and a 30% improvement in the Weibull moduli in samples with 10 vol% nickel. Analysis of the fractured surfaces through scanning electron microscopy suggests that the primary strengthening mechanism was through crack deflection. The nickel particles serve as an obstruction to crack propagation thereby enhancing the fracture toughness and strength of lanthanum telluride.

Keywords: Lanthanum telluride, thermoelectric, composite, fracture toughness, flexural strength

Radioisotope-Based Propulsion System Enabling Exploration with Small Payloads

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Abstract. Currently small scientific beds geared to performing limited tasks are being developed and launched into low earth orbit (LEO) in the form of small-scale satellite units. These test-beds are gaining popularity among the university and science communities due to their relatively low cost and design flexibility. To date these small units have largely been limited to performing tasks in LEO utilizing solar-based power. If a reasonable propulsion system could be developed, these platforms could be integral in the exploration of various extra-terrestrial bodies within the solar system engaging a broader range of researchers and leading to a more robust knowledge base of our solar system. Researchers at the Center for Space Nuclear Research have completed a nine-month study outlining a conceptual design of a possible radioisotope-based propulsion system that can enable small payloads to perform meaningful exploration into the solar system. The study being presented here was funded by a NASA Innovative and Advanced Concepts (NIAC) Phase I grant.

The proposed radioisotope-based system would leverage the high specific energies [J/kg] associated with radioisotope materials and enhance their inherent low specific powers [W/g] by accumulating thermal energy from radioisotopic decay within a central core over time. This allows for significant amounts of power to be transferred to a flowing gas over short periods of time. In the proposed configuration the stored energy can be utilized in two ways: (1) directly heat propellant creating thrust through a converging-diverging nozzle and (2) heat a working fluid and run it through a Brayton engine creating electrical energy. The first scenario achieves moderate ranges of thrust, but at a greater Isp than traditional chemical-based systems. The second scenario allows for the production of electrical power, which can then be used as needed, e.g. electric propulsion, communication, station keeping, etc.. Ultimately, the proposed platform capitalizes on the flexibilities of radioisotopic power, being made available to complete varous tasks in a mission.

The scope of the NIAC study was to develop an in-space propulsion system to deliver a 6U CubeSat payload to the orbit of the Saturnian moon - Enceladus. Along with the conceptual design, an entire mission architecture for Enceladus was developed targeting a total allowable launch mass of 1,000 kg. This inturn allowed for smaller launch vehicles to be utilized to reach LEO. From LEO the conceptual propulsion system will proceed to achieve Earth escape and transit to the Saturnian system. The results of the study indicates a propulsion system can be designed to deliver a small payload to Enceladus orbit with less than a 1,000 kg launch mass. Additionally, such a propulsion system allows for flexibility in both the payload size and mission destination with only small changes needed. Ultimately, the proposed propulsion system not only extends the capabilities of CubeSat platforms but also extends involvement of outer planetary exploration. This propulsion system fulfills the need of a low mass propulsion/power system for exploration to the outer planets where solar-electric and chemical-based propulsion systems are not feasible. Additionally the system laid out here allows for smaller, cheaper launch vehicles (~1,000 kg to LEO) to be targeted. This, in effect, allows for beneficial exploration to be conducted within limited budgets.

Keywords: Radioisotope Thermal Rocket, Thermal Capacitor, Pulsed Power, Dual-Mode Propulsion, Small Payload Exploration

Microstructured Semiconductor Neutron Detector (MSND)-based Systems for Low-Power, Compact Neutron Detection

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Abstract. Solid-state neutron detectors offer greater ruggedness and lower per-unit cost than many of their gas-filled and scintillating counterparts while maintaining high gamma-ray rejection ratios. Early solid-state neutron detectors involved thin-film-coated diodes that measured the reaction products from a neutron capture within the thin-film coating. Low neutron-absorption and reaction-product counting efficiencies of these devices limited their thermal neutron detection efficiency to 4-5%. Microstructured Semiconductor Neutron Detectors (MSNDs) improved upon these devices by etching perforations into the substrate and backfilling them with neutron converting material. The increased likelihood of capturing incident neutrons and then subsequently counting the produced reaction products led to an order-of-magnitude increase in thermal neutron detection efficiencies. MSNDs with dimensions of 0.5 mm by 2 cm by 2 cm have achieved over 32% intrinsic thermal neutron detection efficiency. Presently, work is ongoing in deploying mass-produced MSNDs into instruments that can be used for various applications. MSNDs are currently mounted to the Domino Electronics Package, which supplies all necessary power and signal readout and processing electronics to serve as a standalone, compact neutron detector package. The Domino electronics package is powered with a 3-5 V input and outputs a 5 V TTL square-wave pulse when a neutron is detected. The current generation Domino draws 3 mW (max) and weighs approximately 9 g. Dominoes can be tiled together to expand the sensitivity of the system as multiple Dominoes connected in parallel will behave as a single large-area detector. Arrays up to 1 m^2 have been produced by tiling Dominoes together. Additionally, a cylindrically-designed MSND-based Helium Replacement device (HeRep) has been fabricated to directly compete with, and replace, aging ^{3}He neutron detectors and has matched the neutron sensitivity of a 4 atm, 2-in. diameter ^{3}He tube with a lower weight and per-unit cost.

Keywords: Neutron Detection, Helium-3 Replacement, Solid-State Detector

Microstructured Semiconductor Neutron Detectors (MSNDs)

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Abstract. Semiconductor diode detectors coated with neutron-reactive materials have been investigated as neutron detectors for many decades, and are fashioned mostly as planar diodes coated with ^{10}B, ^{6}LiF, or Gd. Although effective, planar detectors coated with ^{10}B and ^{6}LiF are limited to less than 5% intrinsic thermal neutron detection efficiency. Detectors coated with Gd can achieve higher efficiencies, but the low energy reaction products are difficult to distinguish from background radiations. Over the past decade, microstructured semiconductor neutron detectors (MSNDs) have been investigated, and can now achieve a tenfold increase in neutron detection efficiency over the simple planar diode designs. These new semiconductor neutron detectors are fashioned with a matrix of microstructured patterns etched deeply into the semiconductor substrate and, subsequently, backfilled with neutron reactive materials. The additional neutron conversion material present within the perforations greatly increases the probability that an incident neutron will be captured. Furthermore, reaction products generated within the perforations from the neutron capture have a much higher likelihood of being counted. Intrinsic thermal-neutron detection efficiencies exceeding 32% have been achieved with devices no thicker than 0.5 mm while operating on less than 5 volts. Stacked devices are capable of >55% intrinsic thermal neutron detection efficiencies. Newer designs indicate that intrinsic thermal neutron detection efficiencies greater than 70% can be achieved. The detectors have been integrated with compact low-noise and low-power electronics, thereby, allowing for rugged instruments and compact arrays to be fashioned from the devices. A discussion on the physics and performance of these MSNDs will be presented.

Keywords: Neutron Detector, Semiconductor, Solid-State

Storing Water Propellant Mined from Asteroids

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Abstract. It has been proposed by planetary scientists that water is more abundant at the hydrated C-Class asteroids in the main asteroid belt than was originally thought. The information presented in this paper is part of a mission architecture study, conducted by a team at the Center for Space Nuclear Research (CSNR). The primary objective was to design the power and propulsion system of a spacecraft that can visit multiple such asteroids. The designed spacecraft will gather information about the asteroid composition using Ground Penetrating Radars. It would then attempt to land at suitable water extraction sites, place a beacon or "Pinger", and then harvest water from the surface. The spacecraft would then blast off to the next target C-Class asteroid. The mined water on each asteroid will be electrolyzed and the hydrogen would be used as a propellant through a bi-modal Low Enriched Uranium Nuclear Thermal Rocket (LEUNTR) with LOX Augmentation. The operational condition of the LEUNTR requires liquid hydrogen as an input. During the thermal thrust mode, liquid hydrogen would flow through the LEUNTR core's tie tubes and undergo a phase change. The hot vapor would then propel the spacecraft. If additional thrust is required on larger asteroids, the hydrogen vapor will be combusted with liquid oxygen in order to augment the chamber temperature like an afterburner. The LOX augmentation improves the thrust but lowers the specific impulse (Isp). This paper presents the detailed design of the cryocooling system that will be used to refrigerate the hydrogen and oxygen for future burns during the transit flight between asteroids. A radiator design was conducted as the primary means to expel the excess heat. During the design process it was found that liquefying hydrogen at the asteroid surface would be too difficult and expensive for the mission architecture. Hence, a potential alternative to liquefying hydrogen was also studied by looking at the fabrication of hydrocarbons on-board. Hydrocarbons are easier to liquefy than hydrogen. The carbonaceous composition of the C-Class Asteroids was identified as a potential carbon source to react the hydrogen for creating hydrocarbons. In this chemical process, one of the key and abundant product would be methane (CH_4). Hence the cryocooling refrigeration process of Methane was also evaluated. In addition to a chemical process to store hydrogen, an alternate physical process to store the hydrogen in Graphene or Carbon Nanotubes (CNTs) was also considered. Graphene has the ability to absorb hydrogen molecules like a sponge. It allows the hydrogen to be stored at a temperature higher than if it were liquefied, thus reducing the size of the radiator needed.

Keywords: Refrigeration, Radiatior Design, NTR with LOX Augmentation, Cryocooling System & Liquid Methane.

Time Dependence of Fission Energy Deposition in Nuclear Thermal Rockets

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Abstract. Presented is a time dependent estimate of the effective energy released per fission or Q^f_{eff} for a nuclear thermal rocket. An estimate of Q^f_{eff} is required for many aspects of thermal, shielding, and burn up analysis for nuclear reactors and it serves as normalization constants to scale effects based upon reactor power. Q^f_{eff} for a reactor is dependent on many factors such as faction of energy leaking out of the system, energy released from radiative capture of neutrons, and energy released from the activated material in the core.

Furthermore, a nuclear thermal rocket operates in a unique regime where decay emissions from fission products are not in equilibrium with fission product production. For analyses of traditional utility and research reactors, estimates of Q^f_{eff} generally assume steady state operation in which the energy deposited by decay emissions from fission products reaches equilibrium with fission product production. Decay of fission products account for ~7% of all energy produced in a nuclear reactor in steady state operation. For analyses of pulse reactors that operate on very short time scales, the decay emissions from fission products can be ignored for many calculations. Nuclear thermal rockets operate on the time scale of 30 minutes, and the time dependence of the build in of fission products cannot be ignored.

MCNP6 was used to estimate the fission energy deposition in a NTP reactor core with special emphasis on tracking energy deposition through time. Estimation of Q^f_{eff} with time-dependence for a representative nuclear thermal rocket was made using the CINDER90 activation and delayed particle algorithm included within the MCNP6 code package. Empirical correlations from the literature for energy emission rate of delayed gamma radiation were also used to compare time dependence of gamma leakage and energy deposition.

Keywords: Q-effective, time-dependent, NTP, MCNP6, CINDER90

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Reflector and Control Drum Design for a Nuclear Thermal Rocket

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Abstract. Solid-core nuclear thermal rocket engines will play a vital role in near-term manned deep space missions. Supporting Marshall Space Flight Center's Space-Capable Cryogenic Thermal Engine (SCCTE) project, different ideas for the radial neutron reflector and control drums are explored. The design under consideration is a radial reflector made of beryllium with dispersed cooling channels for flowing cryogenic hydrogen. Embedded in the reflector, sixteen control drums made from beryllium with boron carbide poison elements control reactivity. The control drums have dispersed cooling channels for cryogenic hydrogen flow. Autodesk Simulation is used to study thermal and flow behavior of the components, and Monte Carlo N-Particle Transport code (MCNP) is used to investigate nuclear aspects. An iterative design approach using Autodesk Simulation and MCNP was undertaken to optimize the integral and differential reactivity worth of the control drums to ensure smooth power transitions during rotation and an adequate Shutdown Margin (SDM) of the reactor, while considering mechanical and thermal aspects of the materials. This was done by varying the size, number, and positioning of cooling channels within the reflector and control drum regions, as well as the geometry of the of the poison elements within the control drums. One potential design for the radial neutron reflector that meets the criteria of the SCCTE project is presented.

Keywords: Nuclear Thermal Rocket, Neutron Reflector, NTR Components

CSNR-Aerojet Rocketdyne Cermet Fuels Research: Summary and Status

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Abstract. In 2014, the Center for Space Nuclear Research (CSNR) continued its research and development of cermet fuels for Nuclear Thermal Propulsion (NTP) applications under contract to Aerojet-Rocketdyne. The cermet fuel fabrication and processing flow sheet that was developed will be presented with respect to initial research to production scale-up activities and design considerations. Testing activities performed in 2014 will also be discussed. These activities include the testing of prototypic fuel element section testing at high temperature and in flowing hydrogen at 1500 °C and 2750 °C. Pathways and approaches for future testing activities in support of cermet fuels development will be discussed.

Keywords: Aerojet, Cermet, CSNR, Fuels, NTP, NTR, Rocketdyne.

Modernizing Welding Capability

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Abstract. The Los Alamos Actinide Engineering and Science team oversees five automated Gas Tungsten Arc welding (GTAW) processes supporting the production of plutonium oxide fueled clads. Welding is a critical part of the manufacturing process, and robust control of the process is essential in providing a safety class container that can be handled outside a controlled environment, and meet stringent safety and performance requirements during launch and space operation. Because of the high specific activity of Plutonium, each container needs to pass rigorous testing and inspections requirements and weld quality is assured through various Nondestructive Evaluation (NDE) test methods. Container materials include alloys of iridium, tantalum, cobalt, and stainless steel. Welding is performed within controlled atmosphere, helium filled glove boxes which provide containment during primary encapsulation, as well as optimum welding conditions and leak testing ability for all containers. The automated welding system is comprised of a programmable process controller, a mechanical fixture which provides rotation of the cylindrical containers, positioning of the welding torch, a weld viewing camera, and in some cases a wire feed drive and positioner. Personnel of Nuclear Components Operations (NCO) assemble and load parts into the weld fixtures, ensuring accurate positioning of the assembly and fixturing, and the weld is performed using a qualified welding script containing the weld parameters. The current welding systems have passed the end of their life cycles and require considerable resources for continuous maintenance and repair, often made more challenging when involving work within the glovebox. The availability of spare parts on hand is limited, and the manufacturers of this equipment no longer provide technical support nor spare parts for these models. The fueled clad welding system is currently being upgraded with welding fixture automation enhancements, and an XM controller from Advanced Manufacturing Engineering Technologies (AMET) Inc. The other clad welding system is also being integrated with an XM controller. Most recently an AMET Advent control system, which provided singular control over two welding fixtures, was replaced with an XM control system for each fixture. This upgrade included critical fixture enhancements and will allow each fixture to be used independently or concurrently. These system enhancements and standardization will provide an improved weld quality and repeatability allowing the capability to meet additional programmatic and future space mission needs.

Keywords: Gas Tungsten Arc Welding, automated

RTG Degradation Primer and Application to the MMRTG

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Abstract. Radioisotope Thermoelectric Generators (RTGs) are extremely reliable power systems. They have been used for many decades to power NASA planetary missions where other power systems cannot offer adequate life or reliability. Although their hallmark is reliable power, this electrical power output does decline with time, in a graceful and predictable manner. Understanding the various factors that produce decline, or degradation, is important for the User and designer of the RTG. The RTG designer needs to understand power output degradation, a priori, so that End-Of-Mission (EOM) design performance optimization can be performed while in the conceptual stages of system design. The RTG User needs to understand power output degradation to make predictions of how the unit(s) will perform with time in various environments and usage cycles.

RTG degradation is primarily a function of heat source thermal decay and the thermoelectric (T/E) material's inherent degradation. Other factors can also play a role, such as gas pressure buildup in the case of vented ^{238}Pu heat sources and insulation degradation. Heat source thermal decay is well understood. The inherent T/E degradation typically presents a greater challenge, especially in terms of understanding all the effects of temperature, time, and any electrical effects upon T/E material properties.

This presentation will focus on the basics of RTG degradation as well as give some examples to give perspective to the various key effects (heat source thermal decay and T/E degradation). The MMRTG degradation will be discussed as well as the key assumptions that play a role. Performance modelling of MMRTG degradation will be presented along with the various tests planned and being performed to develop a long term degradation model.

Keywords: Degradation, MMRTG, RTG.

Exploring the Design Space of CERMET LEU $ZrH_{1.8}$ Moderated Nuclear Thermal Propulsion Systems

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Abstract. A successful Nuclear Thermal Propulsion (NTP) system will greatly contribute NASA's ability to safely accomplish a manned Mars mission in the 2030s timeframe. In an effort to develop affordable NTP technology, a recent push has emerged to investigate NTP technology that uses Low Enriched Uranium (LEU) (<20%w U-235). Presented is a collection of trends found while exploring the design space CERMET LEU $ZrH_{1.8}$ moderated nuclear thermal propulsion systems. This mapping of the design space is vital for developing reactor designs that are high performance and technically informed. In addition, a mapped design space aids in communication between reactor designers, engineers working on other systems, mission planners, and program managers when choosing reactor configuration to focus on and develop.

Central to mapping the design space of CERMET LEU ZrH1.8 moderated nuclear thermal propulsion systems was a computationally intense study in which key parameters were varied. In the past year, work done by the Center for Space Nuclear Research on their nuclear thermal rocket development code called "Space" (previously named IROC), has increased Space's performance to allow for high speed, high fidelity design and iteration of nuclear thermal rocket reactor cores. Space in combination with the Idaho National Laboratories High Performance Computing resources (INL HPC) was used to analyze several thousand CERMET LEU ZrH1.8 moderated nuclear thermal propulsion system designs.

This study parametrically varied coolant channel radius, webbing thickness, channels per fuel element, fuel to moderator element ratios, reflector thickness, core length, core radius, and number of coolant passes in the fuel. All designs were constrained to have an inlet temperature of 300 K, inlet pressure of 5.5 MPa, 26500 lbs-f thrust, maximum fuel temperature of 2850 K, and a k_{eff} above 0.99 with control drums inserted half way.

It was found that long fuel elements, two pass systems and small coolant channels all greatly increase maximum achievable I_{sp} at a given reactor mass. Webbing thickness had little effect on maximum achievable I_{sp}. In addition, the possible tradeoffs, manufacturability, and reactor operation for options in design space are briefly discussed.

Keywords: LEU NTP, Reactor Design, SPACE

The Nuclear Power Assessment Study

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Abstract. In the early 1950's the Atomic Energy Commission (AEC) was actively investigating the production of power for reconnaissance satellites using both radioisotope power supplies and small fission reactors. The Systems for Nuclear Auxiliary Power (SNAP) program, initiated under President Eisenhower's Atoms for Peace program, pursued both approaches for space and terrestrial use. While only one U.S. space reactor was flown (the 500 W_e SNAP-10A in April 1965), the radioisotope power program led to less-powerful, but more-used power systems on a variety of both U.S. military and scientific satellites. With evolving national priorities and needs, and with the end of the Cold War, use of such small nuclear power systems has shifted more and more to the National Aeronautics and Space Administration (NASA). In 2001, a Radioisotope Power System (RPS) Provisioning Strategy Team issued a report summarizing NASA's then-estimated needs for radioisotope power systems for the following decade and beyond. That report advocated two development projects: a Stirling RPS, with higher electrical conversion efficiency; and, a new radioisotope thermoelectric generator (RTG) with less development risk, which could operate in the Martian atmosphere. Both would allow for operation both in deep space and in the atmosphere of Mars. The new RTG was viewed as a backup for the Stirling RPS, reducing both programmatic and development risks. Additional purchases of plutonium-238 (Pu-238) from Russia were viewed as required, as new domestic production was then thought not to be occurring until 2008 or 2009, and the immediate need would be for providing fuel for the RPS on the "Mars Smart Lander" (MSL) due for launch in 2007. By 2011, new domestic Pu-238 production had not yet begun, and the Stirling development was proving to be challenging. However, the newest model of RTG, relying on technology similar to that of the SNAP-19s used on the Viking Mars landers, the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) was developed and implemented successfully. MSL, rechristened as the Mars Science Laboratory mission with its subsequently named "Curiosity" rover, and the New Horizons mission to Pluto and the Kuiper Belt were launched (in 2011 and 2006, respectively) – the latter as a competed mission that is using the final remaining General Purpose Heat Source (GPHS)-RTG of the generation employed on Galileo, Ulysses, and Cassini, and with a mixture of both newer and older Pu-238 nuclear fuel. The current Nuclear Power Assessment Study (NPAS) was chartered by NASA on March 15, 2014 against this backdrop of events to "Identify opportunities and challenges of a sustainable provisioning strategy for safe, reliable, and affordable nuclear power systems that enable NASA Science Mission Directorate (SMD) missions and are extensible to Human Exploration and Operations Mission Directorate (HEOMD) needs in the next 20 years." This report contains the methodology used, analyses performed, and the findings that resulted in the course of conducting the NPAS.

Keywords: Radioisotope power system; Fission Power System; Robotic Space Exploration.

Temperature Profile in Fuel and Tie-Tubes for Nuclear Thermal Propulsion Systems

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Abstract. A finite element method to calculate temperature profiles in heterogeneous geometries of tie-tube moderated LEU nuclear thermal propulsion systems and HEU designs with tie-tubes is developed and implemented in MATLAB. This new method is compared to previous methods to demonstrate shortcomings in those methods. Typical methods to analyze peak fuel centerline temperature in hexagonal geometries rely on spatial homogenization to derive an analytical expression. These methods are not applicable to cores with tie-tube elements because conduction to tie-tubes cannot be accurately modeled with the homogenized models. The fuel centerline temperature directly impacts safety and performance so it must be predicted carefully. The temperature profile in tie-tubes is also important when high temperatures are expected in the fuel because conduction to the tie-tubes may cause melting in tie-tubes, which may set maximum allowable performance. Estimations of maximum tie-tube temperature can be found from equivalent tube methods, however this method tends to be approximate and overly conservative. A finite element model of heat conduction on a unit cell can model spatial dependence and non-linear conductivity for fuel and tie-tube systems allowing for higher design fidelity of Nuclear Thermal Propulsion.

Keywords: Nuclear Thermal Propulsion & Tie-Tubes & Heat Transfer & LEU

Detection and Extraction of Water from Hydrated C-Class Asteroids in the Main Asteroid Belt

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Abstract. Water is a necessity for prolonged deep-space manned missions. Sending spaceships from earth, carrying water as a cargo will be an extremely expensive itinerary for both government and private enterprises. A team at the Center for Space Nuclear Research (CSNR) conducted a mission architecture study of an asteroid mapper mission that will detect the presence of water in the main asteroid belt. This information can then be sold to space mission architects for strategizing cheaper missions, by enabling ISRU on the bodies containing water, as a pit stop to the final target. With more research being conducted by planetary scientists, it is slowly coming to light that water is rather an abundant molecule in the solar system. It has been located on the subsurface Mars, on the moons around Saturn and on asteroids in the main asteroid belt. This paper presents the detection and extraction methods of water on the asteroid surface evaluated in the mission architecture. For the detection method, a neutron source from a radioisotope such as Curium (Cm) was evaluated. Two different design concepts were assessed that were capable of producing a directed neutron beam towards a target body. The first idea was to use the radioisotope core of a Radioisotope Thermal Rocket (RTR) as a neutron source. For this concept the fuel element was ^{244}Cm, because it is an excellent source of neutrons due to spontaneous fission. The second concept was to employ a neutron gun carrying a ^{244}Cm radioisotope as a separate system on the spacecraft. For both concept designs, Monte Carlo N-Particle (MCNP) transport code was used to evaluate the flow of reflected neutrons across a simulated detector surface. For water extraction, direct heating of the surface of the asteroid using microwaves was considered first. The water vapor leaving the asteroid would collide a cold metal collector, which would be at a low enough temperature to cause the water to re-solidify on the surface. The major challenge faced in this idea was only a fraction of the water would be able to escape the asteroid in the direction of the spacecraft. This severely limited the amount of water the spacecraft can collect at any given location on the asteroid. Hence an alternative idea was evaluated to use drilling equipment in order to collect the frozen surface water and the water trapped in the soil. This process will use drill bits connected to each leg of the spacecraft. The drill bits will drill into the surface and remove the soil samples containing water. These samples will be pulled, with the drill bit, into a containment vessel, where the heating of water will take place to change its phase into storable liquid form.

Keywords: MCNP modelling, Neutron gun, Radioisotope thermal rocket, Water detection, drilling, Water ISRU.

Beta Voltaic Power Source Design using an Electron Emitting Radioisotope source for a Pinger Device to be dropped on a Hydrated C-Class Asteroid

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Abstract. The work presented herein was developed with the funding and support of the summer fellowship program at the Center for Space Nuclear Research (CSNR) under Director Dr. Steven Howe. The purpose of this work was to design a beta-voltaic (BV) power source for a pinger (beacon) device. The pinger would be dropped on a hydrated C-Class asteroid for ownership purposes and indication of water availability to a future spacecraft that might be travelling in the asteroid's direction. This work is part of a preliminary design review of an Asteroid Mapper mission architecture. The primary objective of the asteroid mapper spacecraft will be to map and tag water contained in hydrated C-Class asteroids, in the main asteroid belt. The current chemical batteries have many disadvantages such as short life span and limited temperature & pressure tolerances. However, a BV cell will be an ideal power supply to the pinger. It would generate sufficient low power required to drive the pinger electronics, will be long-lived by lasting for more than 20 years and would be very light weight. The BV cell designs considered in this study consists of a non-conducting plate coated with an electron emitting radioisotope material such as Nickel – 63 (^{63}Ni), Cesium – 137 (^{137}Cs), Technetium - 99 (^{99}Tc) or Strontium – 90 (^{90}Sr) on one side that would be separated by a small distance from a p-n diode. The working of the BV cell is analogous to that of a solar cell. In the proposed BV cell design, current will be generated, when a high-energy electron strikes the depletion region of the p-n diode generating electron-hole pairs due to impact ionization. These electron-hole pairs are separated by the built-in electric field and are drifted apart. The separated electron hole pairs make the p-n diode forward biased and are collected at the negative and positive terminals respectively, there by driving the load connected to the BV cell. The design of the BV cell is based upon the Child-Langmuir's law of space charge limited current in a plane diode. The energy density of ^{90}Sr, ^{99}Tc, ^{63}Ni and ^{137}Cs were calculated for ten different values of distances between the non-conducting plate and the semiconductor using Monte Carlo N-Particle (MCNP) transport code. The power output required from the beta voltaic battery was limited to 1 mW. Given the power output and fixing the width of the receiving plate the area of the receiving plate was calculated using Child-Langmuir's law. Out of all the four radioisotopes considered as electron emitting sources, ^{137}Cs provided the smallest plate area of the non-conducting plate. However, due to the high gamma radiation of ^{137}Cs, ^{90}Sr turned out to be the most suitable candidate for this device.

Keywords: Beta Voltaic Battery, MCNP, Cesium-137, Strontium-90, Pinger, Beacon, Asteroid

Reference Power System Options for the Nuclear Power Assessment Study

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Abstract. The Nuclear Power Assessment Study (NPAS) System Team included participants from NASA, DOE, and industry with expertise in Pu-238 fuel, General Purpose Heat Source (GPHS) module integration, U-235 fuel, fission reactor design, radiation shielding, thermoelectric (TE) power conversion, Stirling power conversion, electrical controllers, system testing, and systems analysis. A primary study objective was to develop new power system options, beyond those that are currently available, for future planetary science missions that could also be extensible to human exploration missions. The NPAS considered a 20-year time horizon from 2016-2036. This limited the trade space to those technologies that were already in development or were close derivatives of current systems. An emphasis was given to system options that build on the current Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) or recent Advanced Stirling Radioisotope Generator (ASRG) while infusing new component technologies that improve performance, mass, cost, robustness, or mission applicability. High value was placed on components or technologies that could be shared between Radioisotope Power Systems (RPS) and Fission Power Systems (FPS).

The deliverables from the System Team included a parameterized set of RPS and FPS concepts that could support the Design Reference Missions (DRM) specified by the Mission Study Team. The RPS options included an Advanced RTG (ARTG) with segmented skutterudite, LaTe, and Zintl TE modules and a Stirling Radioisotope Generator (SRG) using ASRG-derived Stirling convertors. The ARTG approach utilized a modular 4-GPHS building block that could be stacked for generators with up to 16 GPHS, with the NPAS reference 16-GPHS ARTG producing about 350 We End of Mission (EOM, 17 years). The SRG approach included a common 200-We Stirling convertor building block that could be implemented in generator configurations with 3, 6, or 8 GPHS modules, with the reference 6-GPHS SRG producing about 300 We EOM. The FPS approach assumed a cast UMo core, sodium heat pipe cooling, and either TE or Stirling power conversion. 1 kWe EOM FPS using either ARTG-derived TE module technology or SRG-derived Stirling convertors was developed as an alternative to using multiple RPS on the planetary science DRMs. The Stirling FPS could be scaled to 10 kWe using the same reactor technology and larger Stirling convertors for planetary electric propulsion missions or Mars surface missions.

Keywords: Radioisotope Power, Fission Power, System Studies

Advanced Stirling Radioisotope Generator Engineering Unit 2 Final Assembly

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Abstract. NASA GRC has recently completed the assembly of a unique Stirling convertor test article for laboratory experimentation. While the ASRG flight development contract was still in place, NASA GRC initiated a task to design and fabricate a flightlike generator for in-house testing. This test article was given the name ASRG EU2 as it was effectively the second engineering unit to be built within the ASRG project. The design of the test article was to duplicate Lockheed Martin's qual-unit ASRG design as much as possible to enable system-level tests not previously possible at GRC. During the cancellation of the ASRG flight development contract, the decision was made to continue progress on the EU2 build, and make use of a portion of the hardware and personnel from Lockheed Martin's flight ASRG activity. GRC and Lockheed Martin engineers collaborated to develop assembly procedures, leveraging the valuable knowledge gathered by Lockheed Martin during the ASRG development contract. The ASRG EU2 was then assembled per these procedures at GRC with Lockheed Martin engineers on site. The assembly was completed in August 2014. This paper details the components that were used for the assembly, and the assembly process itself.

Status Update on the Fission Surface Power Technology Demonstration Unit

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Abstract. Fission Surface Power Systems (FSPS) are being considered for use in potential manned missions to Mars. One proposed system uses a pumped liquid metal loop to deliver 186 kW of heat from a fission reactor to four Stirling Power Conversion Units (PCU), which produce 48 kW of electrical power and rejects waste heat to titanium-water heat pipe radiators. The Fission Surface Power (FSP) Technology Demonstration Unit (TDU) is a system level demonstration of FSP technology using full-scale components in thermal vacuum at the NASA Glenn Research Center (GRC). At this point all component and sub-system level testing has been completed in support of the FSP TDU. Prior testing included sub-scale and full-scale heat-pipe radiator testing, sub-system testing of the TDU Heat Rejection System (HRS), sub-scale engine testing in a pumped liquid-metal loop, sub-scale engine testing using combined gas inventory, full-scale engine testing using electrical heaters, electromagnetic liquid metal pump testing, and Reactor Core Simulator testing. The most recent milestone achieved was the completion of Reactor Simulator Subsystem (RxSim) testing at GRC. The RxSim consist of the TDU Core Simulator and an Annular Linear Induction Pump (ALIP) used to move NaK (a eutectic mixture of sodium and potassium) throughout the test loop. This test was used to measure component performance, verify integrity of structural elements through the entire operating range, calibrate numerical models, and refine operational, NaK handling, and safety procedures. The completion of RxSim subsystem testing marked the final testing milestone prior to system-level TDU testing. The majority of the build-up for system level TDU testing was completed during sub-system testing of the HRS and RxSim. The only remaining tasks prior to system-level testing are fabrication and assembly of a NaK heat exchanger onto the Stirling PCU and installation of the PCU into the existing test loop.

Keywords: Nuclear Fission Surface Power Energy Conversion Space

Hot Isostatic Pressing (HIP) of W-UO_2 CERMETS for Nuclear Thermal Propulsion

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Abstract. A key enabling technology for Nuclear Thermal Propulsion is the fabrication of a stable high temperature nuclear fuel form. Although much of the technology was demonstrated during previous programs, there are currently no qualified fuel materials or processes. Work at MSFC is focused on developing a Hot Isostatic Press (HIP) process for the fabrication of W-UO_2 CERMET fuels. Samples are being fabricated and tested in flowing hot hydrogen to understand processing and performance relationships. Previous work showed significant loss of fuel and structural integrity for samples fabricated with an elemental blend of W and UO_2 powders. The samples suffered from a non-uniform dispersion of the UO_2 particles in the W matrix, which allowed rapid vaporization of the interconnected UO_2. Recently, W-UO_2 samples have been fabricated using W powder coated UO_2 feedstocks that produced a uniform distribution of the UO_2 spheres. The samples are being characterized to evaluate microstructure, density, and chemistry. Hot hydrogen testing is also being performed on a 19-hole prototypic cross section samples with integral W claddings. The purpose of this paper is to provide status on the HIP fabrication and testing effort.

Keywords: Tungsten, Uranium Dioxide, Nuclear Thermal Propulsion

Full Submersion Criticality Accident Mitigation in the Carbide LEU-NTR

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Abstract. The present study seeks to characterize various methods by which the full submersion criticality accident can be mitigated in the Carbide Low Enriched Uranium Nuclear Thermal Rocket (Carbide LEU-NTR). In previous work, it was found that the increase in reactivity in the case of the full submersion is largely due to two factors: increased self-shielding by the core and an infinite reflector on the outside of the core. In order to mitigate this accident scenario, each cause for increased reactivity has to be resolved individually. In the case of the infinite external reflector, the possibility of adding a layer of neutron absorbing material to the outside of the radial and axial reflectors is explored. The minimum layer thickness required to neutronicaly isolate the active core from the outside is determined along with the associated minimum mass increase. The increased core self-shielding is addressed in two ways. First, the effects of increasing the reflector thickness are characterizing, including the spectrum softening in the active core periphery and its ability to minimize core leakage, enhancing the over-moderated characteristics of the carbide composite core. Second, the possibility of neutron spectrum hardening is explored along with the potential to implement neutron spectral shift absorber in the active core region, increasing the absorption of heavily thermalized neutrons in the case of a full core submersion.

Keywords: Full submersion criticality, LEU-NTR, carbide composite, neutron spectrum tailoring, over-moderation, spectral shift absorber

Compatibility of TantalumCoated Stainless Steel with Compounds of ^{238}Pu

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Abstract. Repurification and reprecipitation of $^{238}PuO_2$ is a necessary step in preparing suitable fuel for production of new $^{238}PuO_2$ heat sources. Aqueous repurification reduces the amount of ^{234}U in the oxide, the product of radioactive decay of the ^{238}Pu. The current aqueous processing scheme adequately purifies the incoming $^{238}PuO_2$ fuel to meet specifications for actinide, anionic, and cationic impurities with minimal loss of ^{238}Pu. Repurification is a multistep process including size reduction, dissolution of the impure oxide, filtration to remove any undissolved fraction, adjustment of acid concentration, and precipitation of plutonium (III) oxalate. Dissolution of the refractive oxide requires a solution of concentrated HNO_3 with an admixture of HF. A full batch of ^{238}Pu oxide generates sufficient heat that the process is maintained at temperatures near 90ºC, which exacerbates the corrosive character of the solution. The combination of a highly corrosive chemical environment with the relatively high dose rates imposed by the ^{238}Pu isotope places unusual demands on the processing vessels. The vessel must be both noncorrosive and stable in a highradiation environment. Historically, this has limited the choice of materials to solid tantalum, which are difficult to fabricate and too heavy to handle conveniently at the long ergonomic standoff imposed by the glovebox geometry. Recently, a customdesigned stainless steel processing vessel and associated filtration apparatus has been fabricated. The vessel was then coated with a layer of tantalum metal using a proprietary process developed by Tantaline, Inc. Design features of the vessel and filtration apparatus will be discussed in terms of improvements in efficiency. Limitations on porosity and thickness of the coating are imposed by the extreme chemical environment. The potential for radiation damage imposes a minimum bound on the thickness of the tantalum layer, and places requirements on the morphology of the coating. Design parameters will be discussed, along with engineering and ergonomic performance of the improved apparatus.

Development of Ambiently Dried Aerogels for Thermoelectric Power Generators

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Abstract. The objective of this work is to develop ambiently dried aerogels, which are processed without the practical application limitations of typical supercritical drying steps and to demonstrate that they can be used for encapsulation of thermoelectric (TE) couples and modules of Radioisotope Thermoelectric Generators (RTG). Aerogel serves as both a sublimation barrier as well as a thermal insulation layer for TE power generation devices operating at high temperatures and the benefit of ambiently dried aerogel will be evaluated through extensive couple testing. The thermal stability and thermal conductivity of ambiently dried aerogels will be characterized as a function of temperature, with the goal of achieving comparable thermal properties to those of supercritically dried JPL aerogels.

Nuclear Technologies for Space Applications: Past, Present, and Future.

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Abstract. Nuclear concepts have been investigated for space applications for nearly 60 years. Such concepts include radioisotope power systems, fission power systems, nuclear electric propulsion, nuclear thermal propulsion, and other advanced concepts. These technologies have enabled a variety of missions to explore the solar system and continue to make deep space exploration and manned mission architectures possible. This paper describes these technologies as they have been developed and implemented throughout history.

Keywords: Radioisotope, Fission, Power, Propulsion, History

An Arcjet Augmented Nuclear Thermal Rocket for Interplanetary Exploration

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Abstract. The nuclear thermal rocket (NTR) has been the corner stone of Mars mission architectures since the late 1960s, and they are required for any serious manned-exploration of the solar system. The current state of the art for NTR technology is the NERVA engines that were designed and built in the late 60s early 70s. A potential improvement to nuclear rocket technology can be realized if the nozzle exit temperature can be increased beyond the material temperature limits of tungsten. The hydrogen arcjet is considered in this work to boost the Isp performance of the current generation of nuclear powered rockets. This reactor concept has the capability to produce power to be used for electric propulsion or any other multitude of applications requiring a massive amount of electrical power in space. It builds upon three proven technologies to provide an increase in space propulsion capabilities.

Keywords: arcjet, nuclear rocket, thermionic, interplanetary, tungsten cermet.

Preliminary Design of an Ultra-high Temperature Reactor Using MHD Power Conversion for Mars Exploration

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Abstract. The very high conversion efficiency of MHD (magnetohydrodynamics) reactor power source makes it a highly potential space power source in the future. Research work about ultra-high temperature reactor suitable for MHD power conversion is performed in this paper. A reactor scheme using cermet fuel is presented as well as the calculation results of the reactor physics and thermal-hydraulics. Besides, preliminary calculation of nuclear criticality safety during launch crash accident is also carried out.

Keywords: MHD power conversion; ultra-high temperature reactor; cermet fuel.

Stirling Technology Research Overview

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Abstract. The Advanced Stirling Radioisotope Generator (ASRG) was under flight development to provide robotic spacecraft power for future space science missions. Subsystem verification has been completed on NASA owned engineering hardware, including the Advanced Stirling Convertor (ASC) delivered by Sunpower, Inc., and the ASC Controller Unit (ACU) delivered by Lockheed Martin Space Systems Company. Also, electrically-heated ground testing has been initiated on the ASRG EU2, which utilizes the ACU, ASCs, and an aluminum Generator Housing Assembly (GHA). Radioisotope Power System (RPS) Stirling development has been in reformulation and, starting in FY2015, is part of the Stirling Cycle Technology Development Project (SCTDP). The SCTDP will continue generator, convertor, and controller testing, as well as development of maturing technologies focused on demonstration in higher fidelity systems and representative environments to increase the technology readiness level (TRL) from 1-3. Under the Stirling Technology Research area, tasks focus on a wide variety of objectives, including increasing performance, reducing mass and/or size, improving reliability or system fault tolerance, and developing alternative designs. While the current ASC design enables many relevant mission environments, an increase in cold-end temperature could enable additional mission environments, such as a Venus flyby or lunar surface. Recent efforts have been aimed at increasing cold-end performance by roughly 50 °C, including high temperature characterization of the magnets and organic materials used in the construction of the linear alternator. A multi-layered insulation package is being prepared for high-temperature testing in vacuum with the ultimate goal of reducing size and mass, compared to baseline designs. The cold-side adapter flange is attached to the heat rejection zone of the ASC, in order to provide structural support and conductive heat rejection to the GHA. An alternative heat pipe design has been demonstrated in numerous relevant environments to provide equivalent performance with a 4x mass reduction over the ASC design. To enable control of Stirling convertor temperatures during nominal and fault conditions, a variable conductance heat pipe (VCHP) is under development with Advanced Cooling Technologies, Inc. The VCHP would enable necessary rejection of excess heat for convertors that are not operating and enable heat addition when convertors are started. An active balancer is being pursued to demonstrate vibration reduction to adequate levels for when one convertor is turned off in a dual-opposed configuration or to enable a single convertor configuration for smaller system designs. Finally, a Single Convertor Controller (SCC), developed under the International Lunar Network program, has completed performance testing and over 6,500 hours of extended duration testing. The Dual Convertor Controller (DCC), a version of the SCC able to control two convertors, has successfully completed verification testing where it was connected to the RPS Systems Integration Lab (RSIL), a test environment designed to evaluate electrical interactions between a Stirling generator, electrical controller, power bus, and representative spacecraft electrical loads. These tasks are being performed under GRC's SCTDP Stirling Technology Research to develop relevant technologies for demonstration in higher fidelity systems and representative environments.

Keywords: Stirling, ASC, ASRG, RPS, Advanced Stirling Convertor, variable conductance heat pipe, multi-layer insulation

Reduction of CeO_2, a PuO_2 Surrogate, Via Gas Phase Interaction with Graphite

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Abstract. Cerium oxide can be isolated in many forms: CeO_2, Ce_2O_3, Ce_4O_7 and many non-stoichiometric forms ($CeO_{2.000-x}$) where x ranges between 0 and 0.5. This wide variety of stoichiometry is a result of the well documented behavior of Ce(IV) reducing to Ce(III) under even moderate reducing conditions. The reduction of CeO_2 to CeO_{2-x} has been performed previously using hydrogen as the reducing agent. Here, we use cerium as a plutonium surrogate and utilize graphite as the reducing agent, which is more similar to the conditions found in a General Purpose Heat Source system. Using an in-house constructed, volume calibrated Schlenk line we have been able to precisely measure the quantity of gases produced by the reaction between mixed and physically separated CeO_2 and graphite powders. Analysis of the gases produced by this reaction has been performed, along with structural analysis of the final CeO_{2-x} product.

Keywords. cerium (IV) oxide, plutonium (IV) oxide, reduction, graphite

Computational Predictions of the Reactor Simulator Subsystem at NASA GRC

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Abstract
Testing of the Fission Surface Power (FSP) Technology Demonstration Unit (TDU) is being conducted at NASA GRC. The TDU consists of three subsystems: the Reactor Simulator (RxSim), the Stirling Power Conversion Unit (PCU), and the Heat Exchanger Manifold (HXM). It also has an Annular Linear Induction Pump (ALIP) which is used to drive the working fluid. The RxSim has been integrated with the TDU (which excludes the PCU for now), and has been used recently to conduct flow tests, which were performed in Vacuum Facility 6 (VF 6). In parallel, a computational model of the RxSim subsystem was created based on the CAD model and used to predict loop pressure losses over a range of mass flows. This was done to assess the ability of the pump to meet the design intent mass flow demand of 1.75 kg/sec.

In the RxSim subsystem, an Annular Linear Induction Pump (ALIP) is required to drive the working fluid, which is a liquid metal. The ALIP is an electromagnetic pump that moves the liquid metal by applying an alternating magnetic field. Two pump choices are available, which included the Technology Demonstration Unit (TDU) ALIP and the Fission Surface Power (FSP) ALIP. Both pumps were tested previously at NASA MSFC in their ALIP Test Circuit (ATC). These tests produced pump curves and performance maps which defined the expected pump performance. RxSim testing performed at NASA MSFC was done using the TDU ALIP, which was not capable of providing the nominal TDU flow rate of 1.75 kg/sec. As a result, the NASA GRC tests of the RxSim subsystem was done with the FSP ALIP instead. In addition, computational predictions were generated to verify and validate the FSP ALIP's ability to provide the nominal flow.

The CAD (Computer-Aided-Design) model of the TDU was used to generate the computational model. The FSP ALIP, PCU and the Heat Exchanger Manifold (HXM) were removed from the model, and a wedge flow meter was added. The FSP ALIP was removed so that the inlet and exit boundary conditions could be applied at those locations. Calculated pressure drops will indicate what is required by the ALIP at various mass flows. The PCU was removed because it represents a pressure loss that is not currently part of the system. The purpose of the HXM is to deliver heat to the PCU, which is not of part of these tests yet. Therefore, the HXM was also removed from the model. The primary components in the current configuration are the flow meter and the core simulator.

Measured data indicates that the pump can produce 2.333 kg/sec of flow, which is enough to supply the RxSim subsystem with the nominal flow of 1.75 kg/sec. Computational predictions using two different turbulence models were conducted to observe these models' predictive capability. The turbulence models used include the Spalart-Allmaras one-equation turbulence model, and the Realizeable k-ε two-equation turbulence model. Computational predictions indicated that the pump could provide 2.157 kg/sec (using the Spalart-Allmaras turbulence model), and 2.223 kg/sec (using the Realizeable k- ε turbulence model). The computational error of the predictions for the available mass flow is ± 0.176 kg/sec (with the S-A turbulence model) and ± 0.110 kg/sec (with the Realizeable k- ε turbulence model) when compared to measured data. More sophisticated turbulence models could potentially reduce the magnitude of this error, but at the cost of increased computational resources (slower run times).

Keywords: Fission Surface Power, Reactor Simulator, Technology Demonstrator Unit, CFD.

An Analysis of Projected Risks from Abnormal Occurrences During Ground Based Testing and Development of Space Nuclear Systems

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Abstract. Probably the biggest concern over the development of space nuclear systems – especially propulsion systems such as Nuclear Thermal Propulsion (NTP) - involves the ground testing of the systems. Unlike in the NERVA days, there are significantly greater restrictions of the ways in which systems can be tested. With concepts such as full-containment, it appears that many of the concerns can be managed – for nominal conditions. But what happens in an accident scenario?

The purpose of this paper is to briefly examine the various accident scenarios for potential nuclear systems during ground testing and determine what would be the projected risk to the workers, the environment and the public. Illustrative worst-case scenarios will be considered with various mitigating factors to see such results as potential plume paths and heavy metal dispersion areas around the test facilities.

Calculated fission product inventories as well as various structural aspects of possible test facilities will be used in the analyses. Currently available radioactive accident management systems will be used to determine realistic risk data.

While generic site data is projected for use in this study, the results will be highly valuable in correctly quantifying the real risk ground testing will pose. This data is very important for educated decision making as to where or if ground testing will take place. But at this point, adequately detailed analyses have not yet been performed. The data presented in this paper will be instrumental in properly identifying the risk – and thus the actual possibility of ground testing – for nuclear space systems.

Keywords: NTP, propulsion, surface power, accident, ground-testing

Space Nuclear System Development Process Risk Mitigation

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Abstract. The development of space nuclear systems is considered a high risk technology effort. Considerations of high thrust to weight (for propulsion systems) as well as pure mass consideration for surface power systems, are two examples of the low TRL level areas that are currently on the critical paths and must be addressed for successful development of space nuclear systems.

However, there are possible methods to reduce the up front development risks by utilizing technologies that are currently at higher TRL levels and adjusting development profiles (performance requirements, etc.) such that incremental milestones (with potentially actual operational capabilities – although reduced - being available at said milestones) become more achievable on a reduced schedule and at lower cost. One such example is the use of less exotic cladding material for fuel elements. While such materials may be temperature limited and thus reduce the overall Isp for early engine iterations, the general fuel element design could be the same as for higher Isp systems and the resulting fuel may be perfectly suitable for surface power applications.

The previous mentioned example is just one of many ways that development risk (which translates into cost and schedule) can be reduced. Still, there are other considerations, such as preventing orphaned development paths. Risk mitigation paths should not lead to dead-end efforts. Commonality and interchangeability should be driving forces in any risk mitigation effort.

This purpose of this paper is to examine and present multiple risk mitigation efforts that could possibly reduce cost and schedule while also providing incremental operational capabilities during the development schedule. The areas addressed will include both propulsion and power generation. In addition, means of leveraging related development efforts will be examined - such as terrestrial Small Modular Reactors (SMRs) – to determine if there are any potential overlap or cooperative opportunities.

This paper will, by necessity, only be an overview or survey of potential developmental risk mitigation options. However, it will serve to identity and increase discussions on this very important topic and increase the knowledge base for the various options – thus leading to better informed decision making.

Keywords: Risk Mitigation, Materials, Schedule and Cost, Development, SMR

Potential Regulatory Processes and Frameworks to Support Space Nuclear Development

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Abstract. The development of low enriched uranium (LEU) based nuclear systems to support space operations (for both propulsion and/or power generation) do not conveniently fit within the currently regulatory framework for nuclear development in the United States. Current and past Department of Energy (DOE) space related work has been primarily highly enriched uranium (HEU) based or utilized other radioactive material, and thus is now strictly controlled due to proliferation concerns. These restrictions have also limited the commercial development of space nuclear systems. Until recently, it could be argued that a market has not existed for commercially developed systems, but that is changing with the increased commercialization of space.

Purely commercial development will, by statute, fall under the authority of the Nuclear Regulatory Commission (NRC). And any such development will almost certainly be restricted to LEU systems. Purely government development efforts could still fall under the authority of the DOE, whether using LEU or HEU as long as the development takes place at a DOE facility. As future development efforts may well be hybrid (government/commercial efforts) a new look at the regulatory issues is required.

New regulatory processes and frameworks will need to considered and likely put into place to support future development efforts for nuclear space systems. Various combinations of DOE and NRC regulations, with the possible addition/modification of existing regulations, will need to be examined in conjunction with the various potential development efforts.

This paper will provide an analysis and summary of the various regulatory permutations to support space nuclear systems of various kinds and provide suggested paths forward to put the necessary frameworks in place to support such development efforts. Considering that the regulatory issues involved with any space nuclear system will have a significant impact on cost and schedule, this area must be given the highest priority.

Keywords: Regulations, DOE, NRC, HEU, LEU

The Magneto-Confined Fusion Ion Thruster

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Abstract. The pulsed Magneto Fusion thruster [MFT] of the magneto-plasma dynamic type represents a promising and cheap solution to today's propulsion challenges in space. The work presented in this paper covers new information the most common configuration considered for Magneto Confined Fusion [MCF] propulsion systems which is the "tandem mirror" system. This system uses magnets to confine the plasma, with two magnetic "mirrors" for to confine the plasma at each end. One mirror is made slightly weaker, which permits some of the plasma to escape, producing propulsive thrust while the other TOKAMAK uses a doughnut-shaped configuration with a plasma diverter in order to greatly reduce the size of the reactor. However efforts have been made to develop techniques to ensure increase in the thrust by magnetic confinement design at the weaker mirror in case of tandem mirror system and an alternative to the both the above is proposed. Also, the new technique is expected to give a break to both the above tandem mirror technique as well as TOKAMAK technique. The new design is much efficient, cost effective and much safer.

Keywords: Confinement, Dipoles, Multipoles, Nuclear Reactions, Nucleosysthesis, Plasma Confinement, Energy Sources, Magnetic Confinement, Magnetic Dipoles, Rockets, Space Flight, Thermonuclear Reactions

CrYOgenic to High TEmperature (CYOHTE) Test Train for Transient Reactor Testing of Fuels

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Abstract. A concept Test Train design for the cryogenic to high temperature nuclear transient testing in the TREAT Reactor will be presented. The system test train is designed to cool a test specimen to cryogenic temperatures prior to transient testing. An insulation scheme allows for encapsulated samples to reach high temperatures of operation. The initial design allows for the filling of the sample test capsule with static hydrogen or inert gas. Shaping of the reactor transient pulse Full Width Half-Maximum (FWHM) allows for the simulation of specific reactor design heating rates and thus for the associated performance assessment of candidate fuels under these conditions.

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

Magnetic Collector for Traveling Wave Direct Energy Conversion of Fission Reaction Fragments

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Abstract. This research is part of a feasibility study on the direct energy conversion of fission fragments thorough a novel approach based on the traveling wave direct energy convertor scheme (TWDEC) that was originally developed for aneutronic fusion applications. This TWDEC application takes advantage of the fragments positive electric charge, as they can capacitively induce a time-varying electric potential on a conductor when traveling next to it. To enhance the conversion efficiency a series of ring-shaped electrode pairs is actually considered, while the fragments need to be collected and arranged into linear, collimated (charged) bunches.

This paper is analyzing the process of magnetic collection/collimation and bunching for fission fragments generated from a quasi-isotropic source and with the appropriate mass and double-hump velocity distribution typical of the U-235 fission reaction. A Particle-in-cell model is also introduced for the study of realistic experimental configurations.

Keywords. Fission Fragments. Direct Energy Conversion.

Nuclear Thermal Propulsion: Considerations for Affordable Development Strategies

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Abstract: The development of a nuclear thermal rocket engine for human space travel will involve significant expenditures and require major technology development efforts. The development effort must be economically viable yet sufficient to validate the systems designed and assure the safety astronauts and success of the mission. Issues associated with the development of a nuclear thermal rocket engine include: how to safely test development fuels and engines on the ground, human flight certification requirements, development flight programs, and how best to obtain license and treaty authority for launching enriched uranium. Since it has been many years since the Nation has developed a nuclear rocket engine and much has changed in the way engineering is done, the question of how many development units should be made and what the nature of the test campaign should be is unanswered. Efforts are underway within the NASA Nuclear Thermal Propulsion Project to study what features a viable program might have and how that might compare to a conventional rocket engine design, development and testing programs in the past. Evaluations are also being performed of the risks and benefits associated with each of the identified options.

Keywords: Test, Analysis, Cost, Risk, Design

Progress in Development of an LENR Power Cell for Space

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Abstract. Since originally reported at NETS 2013, considerable progress has been achieved in development of a revolutionary new nuclear power unit using Low Energy Nuclear Reactions (LENRs). Test units now produce power densities equivalent to fission power plants, but work still needs to be done to insure the long lifetimes required for space applications. If successful, LENR reactors will allow small power units that could provide a vital new power supply for both space station power and propulsion. Due to the low energy of reactants, the compound nucleus formed in LENRs has little excess energy, thus the resulting breakout products are mainly channeled into stable or near-stable products, avoiding significant radioactivity or nuclear waste problems. Such a power source enables a tremendous advantage in energy density, lifetime, and tolerance to wide differences in environmental conditions (temperature, pressure).

During the past decade, extensive experimental and theoretical work worldwide has been done to study the basic LENR phenomena and to understand the underlying physics. At the most recent international meeting on the subject at the University of Missouri, several companies announced progress on gas loaded nickel nano-particle units designed for MW size plants. Others, including Lenuco LLC in collaboration with the NPRE department at the U of Illinois., are working on development of small 10's of kW units. Physically these power units are very simple. Special Ni alloy nano-particles are placed in a pressure vessel which is then pressurized to 60-100 psi with hydrogen to initiate the reaction. With pressure control, these units are expected to run for several years, before replacement of the nano-particles is required due to buildup of transmutation products. Replacement is simply done by substitution of a new cylinder containing fresh particles while the used particles are recycled for use in fresh nano-particles. Our results in terms of energy gain from the pressurized nano-particles are among the best reported in the field to date.

The main obstacle to development of a practical unit is preventing the hot nanoparticles from overheating and sintering together, limiting unit run time. Thus present work is focused on overcoming that problem. Two approaches are under test. One is to provide thicker oxide coating and somewhat larger nanoparticle. The other is to use plasma surface bombardment to create nanostructures on Ni wire mesh. Both approaches use a gas loading system using with a cylinder or vessel to hold the nickel based alloy nano-particles or nickel alloy mess wire. A large output of heat is then released when pressurized to 60~100 psi with hydrogen (alternately deuterium gas using a Pd rich version of the metal alloy can be used).The discovery at the University of Illinois of the existence of Ultra-High-Density clusters inside the host material is a break-through development that provides a reproducible approach to loading and subsequent heat production. Both experimental and theoretical studies have demonstrated that the hydrogen atoms in these clusters (almost metallic hydrogen) are close enough together that diffusion of another atom into the cluster transfers sufficient momentum to create a nuclear transmutation reaction with the hydrogen and host nickel atoms. Incorporating these clusters into the material has resulted in excess heat experiments that reproducibly produces orders of magnitude more heat energy out than energy in. Since the chemical heat release is limited to the initial pressurization, the energy “gain” for long run is extremely large.

Keywords: Low energy nuclear reactions (LENRs), Space power, space energy, LENR power cell.

Thermal Power Scaling of the Kilopower Reactor Concept

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Abstract. The Kilopower reactor concept is one of the simplest space power reactor concepts ever proposed. The key attribute that makes Kilopower simple is low power; as in the name – Kilopower implies kilowatt. The simplest Kilopower reactor would provide only 2.5 kWt (~500 We), and the "reference" Kilopower reactor provides ~5 kWt (~1 kWe). This paper investigates how well the Kilopower concept might scale to higher powers, without any significant changes in reactor technology (note: in the past it's been a mistake to hope that all aspects of the reactor technology might scale to high powers, because if a program fails, nothing scales).

The Kilopower reactor concept uses heat pipes to transfer fission energy from a solid block of fuel. Perhaps the most important "simplicity" of the system is in neutron kinetics and system dynamics. The kinetics of a compact, fast reactor are dominated by one factor – changes in material density/geometry. The Kilopower solid core eliminates potential movements of fuel rods/pieces relative to other, and the reflector is fixed (except for small potential relative movements due to thermal expansion), thus the only major reactivity effects are changes in neutron leakage/reallocation due to material expansion. This makes the reactor component of startup and operational system dynamics easy to predict/verify. The compact size also allows for a simple approach to launch safety, transport, nuclear and non-nuclear system testing.

The basic Kilopower reactor components are: fuel, heat pipes, structure/bonding, control, reflector, and shield. The simplicity of each component, and how they integrate together, is a strong function of power and temperature. At low powers (<100 kWt) changes in power level have little impact on reflector and shield design (thermal and irradiation issues are minor). At a given temperature, the impact of power level on heat pipes is pretty straightforward – more power requires more heat pipes and/or wider heat pipes. There are 2 potential power-level impacts on the control system. First, at very low powers (~10 kW) the burnup reactivity of a fast reactor is so small that a long lifetime (10+ yr) could be achieved without any reactivity control needed. Second, at modest powers (~100s of kWt) a space reactor system can generally survive worst case transients (e.g. loss of power conversion heat removal) without any control action, depending on passive heat loss paths.

The desired heat-pipe bonding technique is very sensitive to design power. At low powers <~5 kWt, the delta-T across the fuel is small enough the heatpipes can be placed only on the perimeter of the core. This makes bonding much simpler, and if power is low enough, forced contact pressure can provide an adequate gap conductance. At powers >>5 kWt, it is necessary to place heat pipes within the fuel block to keep delta-Ts manageable, which limits the options to force pressurized contact (except perhaps an extreme shrink/expansion fit). Also, a high conductance bond is desirable to minimize the temperature drop at higher powers. At power levels >~10 kWt braze is likely the preferred option of heat-pipe-to-fuel bonding (or perhaps a liquid metal bond). The fuel selection is also very sensitive to design power. A UMo metal fuel has been selected for Kilopower largely because it is the only HEU fuel form that could be produced without substantial upfront cost or effort. Fortunately, UMo has some ideal properties for Kilopower, including high uranium loading and high thermal conductivity. The drawbacks of UMo are a relatively low melting point and lack of chemical compatibility with most materials at elevated temperatures. At higher powers another significant drawback appears – fuel swelling. In general, fuel swelling should be manageable if kept <1%, which generally corresponds to <1a/o fuel burnup. Burnup approaches 1% at ~50 kWt, so above ~50 kWt swelling might become a major issue (structurally and/or neutronically).

Keywords: Space Nuclear Power, Space Fission Reactor, Heat Pipe Reactor

Reactor Design Comparison of 25-klb Composite and Cermet Fueled NTRs

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Abstract. The potential success or demise of a nuclear thermal propulsion (NTP) program may lie in the fuel selection. Recently NASA has been trying to determine potential discriminators between carbon-based composite fuel and UO2/W cermet fuel, including a design comparison of 25-klb thrust, 900-s Isp concepts. This paper presents some of these concepts, and then discusses some of the key differences between the two.

There is no major difference in steady-state performance of the concepts evaluated. The composite concept has the advantage of requiring a lower power/pressure turbopump, while the cermet concept has a lower mass (thus higher thrust-to-weight). Overall, the vast majority of discriminators between the composite and cermet concepts do not involve steady-state performance parameters. The most important discriminator is probably the ability of the fuel to survive the extreme temperatures, power densities, structural loads, and coolant corrosion/erosion of an NTR. Both of the proposed concepts assume a 2850 K peak fuel temperature, although it is difficult to say which is closer to its operational limit; however the cermet concept operates at a substantially higher peak power density, 17 MW/l versus only 6.22 MW/l for the composite. There is no operational data for either concept at these levels, but graphite-based fuels were tested extensively in the ROVER/NERVA programs at levels approaching this performance (albeit with a prior generation of engineers), whereas there has been limited experience with cermet fuels in any generation. The ROVER/NERVA program also developed various technologies that could be built upon for either concept, but again the composite concept has much more direct heritage – in particular technologies involving core structure and plena.

The cermet concept has a few key advantages that arise from the inherent physics of the two concepts; one advantage is in launch safety. The cermet concept intrinsically remains subcritical when flooded with water, the composite concept does not (the unmitigated flooded keff is 1.40). The reference option to achieve launch safety is to place removable Gd wires in the flow channels, which indeed keeps the reactor subcritical during flooding (assuming the wires remain in place during potential impacts); however in the current concept this approach requires that wires are placed in at least half of the over 10,000 flow channels. Another potentially significant discriminator is in reactivity effects and reactor dynamics. The cermet concept is neutronically simple, while the composite concept has far more reactivity effects, higher magnitude effects, and larger neutronic uncertainties. One issue with the composite concept involves changes in core reactivity due to fuel burnup, fission-product poisoning, loss of graphite/fuel, etc. Control drums can be designed with enough worth to handle these changes, but when control drum position is changed, the element power-peaking factors change, which can have a significant impact on peak and bulk temperatures (thus Isp). A substantial discriminator might be the large reactivity coefficients associated with the hydrogen coolant and the moderated tie-tubes of the composite concept. The worth of the hydrogen coolant in the composite concept is ~$4 (from zero pressure to nominal pressure/temperature); this worth is problematic because the majority of this pressure is supplied by a turbopump. Thus, a positive feedback loop is created – increased power to the turbopump causes increased power/temperature in the reactor, which causes increased power to the turbopump, etc. Furthermore, there is a very large negative temperature coefficient associated with the ZrH moderator. The injection of higher-pressure, higher-velocity hydrogen will cool the ZrH and induce even more positive reactivity. A control system could indeed be developed to coordinate the required actions for the composite core, but it might take several prototypic full-power startups, and potential failures to learn how to do so.

Keywords: Nuclear Thermal Propulsion, NTP, Nuclear Thermal Rocket, NTR

Development of High Temperature Device Technologies for the Advanced Thermoelectric Couple Project (ATEC)

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Abstract. Radioisotope Thermoelectric Generators (RTGs) have been used successfully to power spacecraft for deep space missions, as well as for terrestrial applications where unattended operation in remote locations is required. RTGs have consistently demonstrated their extraordinary reliability and longevity (more than 30 years of life). NASA's Radioisotope Power Systems Technology Advancement Project is pursuing the development of more efficient thermoelectric technologies that can increase conversion efficiency and specific power performance by a factor of 2 to 4X over state-of-practice RTGs. The ATEC project is focused on the development, fabrication and testing of power generating segmented couple technologies that incorporate several advanced thermoelectric materials with significantly higher figures of merit. These materials have demonstrated excellent thermal stability and the ability to be processed into relatively robust couple components. To date, conversion efficiencies of up to 15% have been demonstrated for spring-loaded segmented couples fabricated using n-type $La_{3-x}Te_4$, p-type $Yb_{14}MnSb_{11}$ upper temperature segments and skutterudite lower temperature segments and tested in a vacuum environment for up to ~9,000 hours at hot-junction temperatures ranging from 973 K to 1273 K and at a cold-junction temperature of 473 K. 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 for the development of advanced thermoelectric converters applicable to both radioisotope and fission power systems will be presented as well as progress to date in resolving some of these key challenges.

Keywords: Thermoelectrics

Nuclear Thermal Propulsion: Considerations for Affordable Development Strategies

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Abstract: The development of a nuclear thermal rocket engine for human space travel will involve significant expenditures and require major technology development efforts. The development effort must be economically viable yet sufficient to validate the systems designed and assure the safety astronauts and success of the mission. Issues associated with the development of a nuclear thermal rocket engine include: how to safely test development fuels and engines on the ground, human flight certification requirements, development flight programs, and how best to obtain license and treaty authority for launching enriched uranium. Since it has been many years since the Nation has developed a nuclear rocket engine and much has changed in the way engineering is done, the question of how many development units should be made and what the nature of the test campaign should be is unanswered. Efforts are underway within the NASA Nuclear Thermal Propulsion Project to study what features a viable program might have and how that might compare to a conventional rocket engine design, development and testing programs in the past. Evaluations are also being performed of the risks and benefits associated with each of the identified options.

Keywords: Test, Analysis, Cost, Risk, Design

THERMAL ROCKET NUCLEAR DESIGN EVALUATION AND CONTROL SYSTEM MODIFICATION USING MCNP

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Abstract. The original idea for the solid core nuclear rocket was initially proposed back in the late 1950s. The General Electric (GE) 710 nuclear reactor was one of the initial designs employing this concept, developed under joint sponsorship by the Air Force and NASA. Utilizing stored liquid hydrogen as propellant and coolant for the reactor, specific impulses approximately twice that of a chemical rocket could be obtained. This high specific impulse significantly decreased the amount of fuel necessary for a round-trip Mars mission. The objective for this study was to examine, using the MCNP neutron transport program, various design parameters for the reactor creating thrust for the nuclear thermal rocket (NTR). Major focusses include: maintaining adequate excess reactivity, obtaining an appropriate amount of control, flattening the radial power across the reactor, evaluating the nuclear effects of different materials, and a brief analysis of a manned mission to Mars and back to Earth. A final design proposal is provided as a result of various perturbations made on the reactor dimensions. This final design provides a 10% range in k_{eff} from 0.948 with the control drums rotated toward the core, to 1.047 with the control drums rotated away from the core. Evidence is provided ensuring that this is more than enough excess reactivity to account for reactor operating parameter changes and burn-up on the entire trip.

Keywords: Thermal Rocket, Criticality, MCNP

Chassis Short Characterization and Potential Mitigation Technique for the Multi-Mission Radioisotope Thermoelectric Generator

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Abstract. A flight-proven capable source of power is the Radioisotope Thermoelectric Generator (RTG)–essentially a nuclear battery that reliably converts heat into electricity. NASA and the Department of Energy (DOE) have developed a new generation of such power systems that could be used for a variety of space missions. The newest RTG, called a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), has been designed to operate on Mars and in the vacuum of space. The MMRTG has been working on Mars for the Mars Science Laboratory mission successfully for about 2.5 years. However, shorts between the internal electrical power circuit and chassis frame of the MMRTG have been observed in the Engineering Unit, Qualification Unit, and flight unit. The internal shorts seem to appear relatively frequently and clear spontaneously. A root cause has not been determined for these internal shorts. In addition, the resistance, power rating, and energy rating of the chassis shorts are largely unknown. Since these internal shorts are likely to occur, there is potential risk of MMRTG power loss or damaging of subsystems within a spacecraft in the case of multiple shorts forming. In order to quantify and potentially mitigate this risk, an internal MMRTG chassis short characterization technique was developed. The leading hypothesis suggests that the FOD which is causing the internal shorts are extremely small pieces of material that could potentially melt and or sublimate away given a sufficient amount of current. The engineering unit and qualification unit are planned to be electrically heated for performance testing in preparation for the next proposed mission to Mars in the year 2020. This period of performance testing will provide an opportunity to test this measurement technique that could characterize these shorts occurring inside the MMRTG. In the event that a short has formed inside the MMRTG, this technique would consist of applying another short (an active short) between the internal electrical power circuit and chassis frame of the MMRTG. This measurement technique will attempt to: (1) measure and characterize the MMRTG internal short to chassis, (2) safely determine if the MMRTG internal short can be cleared in the presence of another controlled short and (3) quantify the amount of energy required to clear the MMRTG internal short. The active short technique is a low risk, simple addition to an already existing performance test setup that will characterize and potentially mitigate the internal shorts forming inside the MMRTG. Data from the characterization test can potentially be incorporated into a mitigation technique for future missions of the MMRTG.

Keywords: MMRTG, MMRTG chassis short, active short

CSNR Space Propulsion Optimization Code: SPOC

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Abstract. The LEU NTR represents a significant optimization opportunity because of the numerous design parameters that can be adjusted to improve system performance. Performing these optimization studies requires an automated analysis tool that allows for thousands of NTR design iterations to be considered. A code developed by the Center for Space Nuclear Research (CSNR), known as SPOC, brings MCNP, SERPENT and a range of analysis tools together, which makes performing these trade studies substantially faster than was previously possible. In addition to performing rapid analysis, SPOC has unique capabilities which facilitate the optimization of the neutron energy spectrum in a manner that has not been previously discussed in the literature.

Keywords: CSNR SPOC NTR LEU Cermet

Dilatometry Characterization of CeO_2 Ceramic Discs as a Function of Temperature and Atmosphere

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Abstract. PuO_2 fuel pellets are currently employed in space radioisotope power systems (RPS). PuO_2 under various conditions can release oxygen atoms resulting in a change in its stoichiometry. CeO_2 exhibits many similar properties compared to PuO_2 and has the added advantage that it is not radioactive allowing it to be used as a surrogate for PuO_2. In this study a Linseis L75 duel push rod vertical research dilatometer system was used to measure dimensional changes of cold pressed + furnace sintered CeO_2 discs which were next heated to soak temperatures of 1000°C and 1400°C while under various oxidizing (air) and reducing atmospheres (95% argon/5% hydrogen). The dilatometer system employed in these experiments is capable of measuring very small (sub-micron) dimensional changes during a time-temperature-atmosphere dilatometer experiment. The observed dimensional changes occurring in the ceramic discs can be related to changes in the stoichiometry of the CeO_2 which provides insight into how various sintering parameters may affect the mechanical characteristics of a ceramic component such as the manufacturing of a PuO_2 fuel pellet for space nuclear power applications.

Keywords: CeO_2, Thermal expansion, Dilatometry, Sintering, PuO_2, RTG

High-Rate Strain Testing on High-Strength Graphite as a Simulant for Fine Weave Pierced Fabric (FWPF) Aeroshell Material

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Abstract. Exploratory spacecraft to Pluto (New Horizons) and the surface of Mars (rover Curiosity) are powered by space nuclear power systems which convert the heat generated from the decay of the radioisotope plutonium-238 fuel into electricity. The $^{238}PuO_2$ fuel pellets are contained within several protective layers including an outer aeroshell which is fabricated using a ~3-D carbon/carbon composite (Fine Weave Pierced Fabric - FWPF). During an inadvertent launch incident the aeroshell is designed to tumble, and to help protect the integrity of the fuel pellets upon impact. Initial high-strain rate experiments have been performed on test specimens fabricated out of a highstrength graphite, as a low-cost simulant for FWPF, in order to enhance understanding of an aeroshell's response under high-rate strain impact scenarios.

Keywords: Fine Weave Pierced Fabric, FWPF, RTG, MMRTG, PuO_2

Radioisotope Fueled Thermophotovoltaic Power Systems for Space Applications

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Abstract. Thermo-photovoltaic (TPV) based power systems are of particular interest to any system requiring solid state long life power, such as deep space missions. General Atomics has done extensive testing and development in small-scale TPV power systems in the milli-Watt to 10s of Watts scale. The most significant contributions have been in the electrical testing of a watt-scale TPV system and in studying neutron degradation in a mW-scale, fueled TPV power source. When comparing competing technologies for use with a radioisotope heat source, a critical criteria is that the power generating technology is not subject to excessive degradation due to exposure to the heat source radiation or space based radiation. This paper describes the analysis, modeling and testing of 0.6 eV Indium Gallium Arsenide (InGaAs) fueled TPV devices with special consideration paid to neutron degradation. The purpose of the paper is to present the research showing the relative device degradation as observed in actual radioisotope fueled power systems, as well as the design space and considerations of an electrically heated TPV power system. As part of General Atomics Internal Research and Development (IRAD) program the microscale mW power level MIPS was scaled up to designs at the single Watt and multi Watt level. Neutron degradation of 0.6% per year of the InGaAs TPV devices has been predicted and measured for Plutonium 238 radioisotope heat sources. Leading from the small scale TPV power system work, larger scale systems were designed and an electrically heated 1-2 Watt scale of TPV power system has been tested to assess system efficiency and power output relative to thermal input. In addition, designs for high power systems to many 10s of Watts have been developed based on standard NASA GPHS heat sources.

Keywords: Thermophotovoltaics, Spacepower, Energy Conversion, Radioisotope Power Sources, Solid State Power Conversion, GPHS

Review of Nuclear Thermal Propulsion Engine Ground Test Options

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Abstract: High efficiency of rocket propulsion systems is essential for humanity to venture beyond the moon. Nuclear Thermal Propulsion (NTP) is a promising alternative to conventional chemical rockets with relatively high thrust and twice the efficiency of the Space Shuttle Main Engine. NTP utilizes the coolant of a nuclear reactor to produce propulsive thrust. An NTP engine produces thrust by flowing hydrogen through a nuclear reactor to cool the reactor, heating the hydrogen and expelling it through a rocket nozzle. The hot gaseous hydrogen is nominally expected to be free of radioactive byproducts from the nuclear reactor; however, it has the potential to be contaminated due to off-nominal engine reactor performance.

Several studies have been conducted since the 1970's investigating NTP engine ground test options to understand the technical feasibility, identify technical challenges and associated risks and provide rough order of magnitude cost estimates for facility development and test operations. In 2011, NASA's Advanced Exploration Systems (AES) Office initiated the Nuclear Cryogenic Propulsion Stage (NCPS) Project with the goal of assessing the affordability and viability of an NCPS. Under the NCPS Project effort, NASA started investigating and evaluating ground test facility options that enable environmentally safe and thorough testing of NTP devices. Three options have been considered to mitigate the hazard potential of radioactive byproduct entrainment in the hydrogen flow; (1) Firing the engine exhaust into a large bore hole in alluvium soil to filter the exhaust of potential radioactive by products, (2) Completely containing the engine exhaust during engine test operations and subsequently disposed of it between engine tests, and (3) Flowing the engine exhaust through a series of aerosol and noble gas filters and venting the filtered exhaust to the atmosphere.

This presentation will review the NCPS Project's investigation of respective NTP engine test facilities, compare the options and review the current status of facility cost estimating and the NTP Project plans for 2015 in regard to the engine test facility concept trades.

Keywords: Nuclear Thermal Propulsion, Engine Ground Test

A History, the Development and Potential Mission Uses for a 40mW Radioisotope Power System

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Abstract. This paper discusses the history of the design of the Radioisotope Power System (RPS) which dates back to the late 1960's. Several iterations of the original design have evolved over the years, as both the power system and missions have changed. It started as a potential power source for under water use by the Navy in the 1970's, and has recently evolved into a small power system that could be used by NASA on future space missions. The current RPS design uses a circuit of 676 small Bi_2Te_3 elements arranged in a multiple redundant circuit. It is designed to be powered by a single 1 watt thermal radioisotope heater unit (RHU) which is currently used by NASA for thermal control on-board various deep space missions. The RHU is powered by the heat released by the decay of ^{238}Pu, which has a half-life of 87.7 years.

The original NASA mission intending to use the RPS needed to provide power to 24 weather stations to be placed on the surface of Mars. These stations would provide data to an orbital satellite for relay to Earth.

Other potential missions are anticipated and these include Mars 2020 "drop-and-forget" science/instrumentation packages operating for several years on the Martian surface (beacons, seismometers, weather stations, etc…), a high G-impact mission for penetrators to be launched to investigate the interior temperature and chemistry of various celestial/small bodies. A description of these potential missions is discussed.

Keywords: RPS, RTG, ^{238}Pu

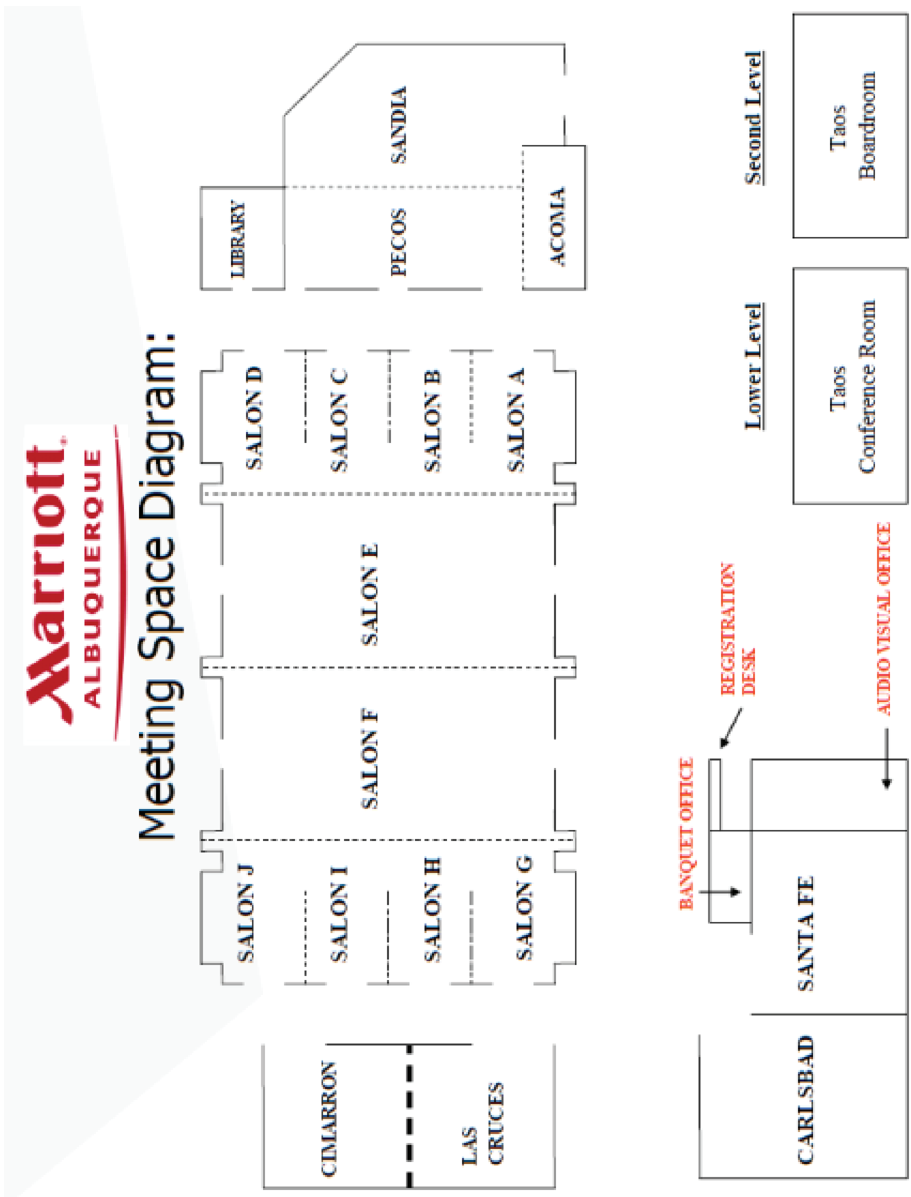
Monday, February 23, 2015

	Room A		Room B		Room C		Room D	
1:30 pm - 2:00 pm	Nuclear Power Assessment Studies	5109						
2:00 PM - 2:30 PM		5014					NEP Space Nuclear Power Programs	5011
2:30 PM - 3:00 PM		5015	Advanced Nuclear Safety and Radiation Detection	5127	NTP Project and Mission Achitecture	5078		5016
3:00 PM - 3:30 PM		5029		5128		5138		5024
3:30 PM - 4:00 PM		5113		5129		5084		5074
4:00 PM - 4:30 PM	30 min break			break		break		break
4:30 PM - 5:00 PM	Radioactive Isotope Studies: Part A	5036		5081		5088		5115
5:00 PM - 5:30 PM		5061		5100		5075		5121
5:30 PM - 6:00 PM		5071		5099				

Tuesday February 24, 2015

	Room A		Room B		Room C		Room D	
8:00 AM - 8:30 AM	Radioactive Isotope Studies: Part A cont'd	5077			NTP Reactor Design & Modeling	5108		
8:30 AM - 9:00 AM		5083	Part A: Power Conversion Technologies	5049		5118	Advanced Nuclear Mission Design	5087
9:00 AM - 9:30 AM		5119		5052		5102		5046
9:30 AM - 10:00 AM	CeO2 as a Fuel Simulant	5020		5080		5136		5037
10:00 AM - 10:30 AM		break		break		break		break
10:30 AM - 11:00 AM		5040		5082		5140		5098
11:00 AM - 11:30 AM		5041		5086		5142		5101
11:30 AM - 12:00 PM		5045		5039		5012		5111
12:00 PM - 12:30 PM		5125				5122		
Lunch								

1:30 PM - 2:00 PM	Radioactive Isotope Studies: Part B	5003	Part B: Power Conversion Technologies	5090	NTP Engine and Component Development	5027	NEP Reactor Physics and Fuel	5064
2:00 PM - 2:30 PM		5005		5091		5110		5017
2:30 PM - 3:00 PM		5013		5096		5008		5042
3:00 PM - 3:30 PM		break		break		break		break
3:30 PM - 4:00 PM		5026		5097		5103		5095
4:00 PM - 4:30 PM		5032		5120		5060		5135
4:30 PM - 5:00 PM		5009		5137				
Wednesday February 25, 2015								
8:00 AM - 8:30 AM	Material or System Testing	5001	Part A: Power System Technologies	5028	NTP Fuel Development	5062		
8:30 AM - 9:00 AM		5002		5034		5116		
9:00 AM - 9:30 AM		5007		5035		5131	NEP Power Conversion and Associated Technologies	5066
9:30 AM - 10:00 AM		5010		5107		5019		5092
10:00 AM - 10:30 AM		break		break		break		break
10:30 AM - 11:00 AM		5021		5112		5022		5094
11:00 AM - 11:30 AM		5025		5114		5072		5123
11:30 AM - 12:00 PM		5047		5141		5105		5069
12:00 PM - 12:30 PM		5048		5147				
Lunch								
1:30 PM - 2:00 PM	Material or System Testing cont'd	5070	Part B: Power System Technologies	5004	NTP Test Facility & Regulatory Considerations	5023	NEP Reactor Analytical Studies	5050
2:00 PM - 2:30 PM		5073		5051		5146		5057
2:30 PM - 3:00 PM	RPS Infrastructure and Capabilities	5018		5063		5085		5067
3:00 PM - 3:30 PM		5031		5065		5093		5126
3:30 PM - 4:00 PM		break		break	30 min break		30 min break	
4:00 PM - 4:30 PM		5033		5079	Fusion and Low Energy Nuclear Reaction Sources	5043		
4:30 PM - 5:00 PM		5068		5124		5134		
5:00 PM - 5:30 PM		5076		5133		5130		
5:30 PM - 6:00 PM		5106		5145		5132		


Marriott
ALBUQUERQUE
Meeting Space Diagram:
LIBRARY
SANDIA
PECOS
ACOMA
SALON D
SALON C
SALON B
SALON A
SALON E
SALON F
SALON J
SALON I
SALON H
SALON G
CIMARRON
LAS CRUCES
Second Level
Taos Boardroom
Lower Level
Taos Conference Room
REGISTRATION DESK
AUDIO VISUAL OFFICE
BANQUET OFFICE
SANTA FE
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