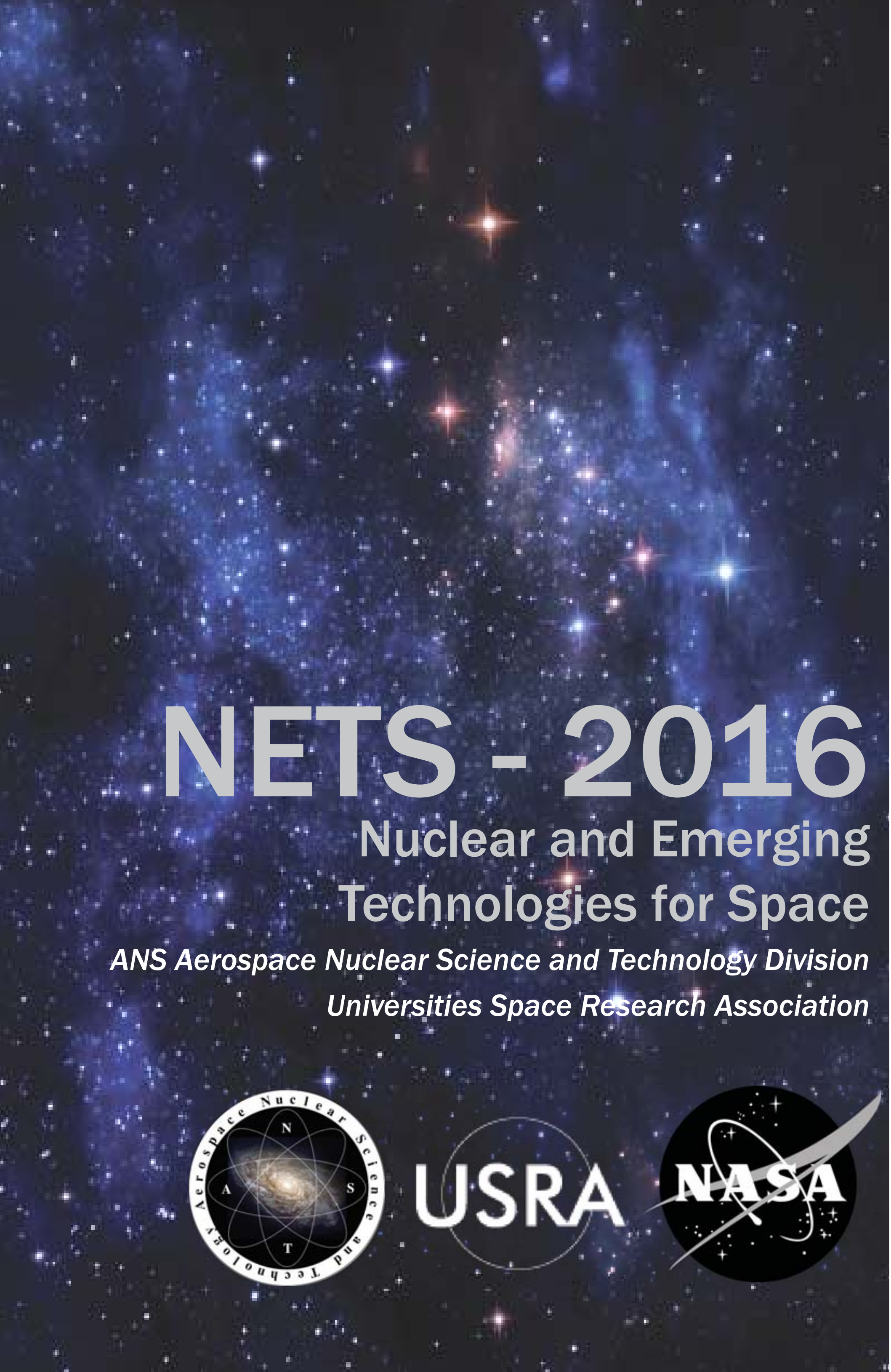


NETS - 2016

Nuclear and Emerging Technologies for Space

ANS Aerospace Nuclear Science and Technology Division

Universities Space Research Association

Full proceedings on jump drive/memory stick

About the Meeting

In February 2016, The Aerospace Nuclear Science and Technology Division (ANSTD) of the American Nuclear Society (ANS) will hold the 2016 Nuclear and Emerging Technologies for Space (NETS 2016) topical meeting at the Von Braun Center in Hunstville, AL. NETS 2016 is the premier conference for landed and in-space application in 2016.

With authors from universities, national laboratories, NASA facilities and industry, NETS 2016 will provide an excellent communication network and forum for information exchange.

Topic Areas

NASA is currently considering capabilities for robotic and crewed missions to the Moon, Mars, and beyond. Strategies that implement advanced power and propulsion technologies, as well as radiation protection, will be important to accomplishing these missions in the future. NETS serves as a major communications network and forum for professionals and students working in the area of space nuclear and management personnel from international government, industry, academia, and national laboratory systems. To this end, the NETS 2016 meeting will address topics ranging from overviews of current programs to methods of meeting the challenges of future endeavors.

Omar Mireles, PhD
General Chair
NASA Marshall Space
Flight Center
omar.r.mireles@nasa.gov

Lee Mason
Honorary Chair
NASA Glenn Research Center

lee.s.mason@nasa.gov

Mike Houts, PhD
Honorary Chair
NASA Marshall Space
Flight Center
michael.houts@nasa.gov

Patrick McClure
Technical Chair, FSP
Los Alamos National
Laboratory
pmcclure@lanl.gov

Daniel Cavender
Technical Chair, NTP
NASA Marshall Space
Flight Center
daniel.p.cavender@nasa.gov

Sal Oriti
Technical Chair, RPS
NASA Glenn Research Center

salvatore.m.oriti@nasa.gov

Nathan Jerred
Publications
Center for Space
Nuclear Research, USRA
njerred.@usra.edu

Margaret Marshall
Publications
Idaho National Laboratory

margaret.marshall@inl.gov

Delisa Rogers
Logistics and FInance
Center for Space
Nuclear Research, USRA
drogers@usra.edu

Wesley Deason
Publications
International Atomic
Energy Agency
wdeason07@gmail.com

Chris Morrison
Webmaster
Rensselaer Polytechnic
Institute
generalc.intergrity@gmail.com

Jarvis Caffrey
A/V Coordinator
NASA Marshall Space
Flight Center
jarvis.a.caffrey@nasa.gov

Track I: Radioisotope Power Systems

Technical Chair: Sal Oriti, NASA Glenn Research Center

June Sakrajsek	NASA - Glenn Research Center
Steve Johnson, PhD	Idaho National Laboratory
Becky Onuschak	DOE - NE 75
Carl Sandifer	NASA - Glenn Research Center
Jean-Pierre Fleurial	Jet Propulsion Laboratory
Ed Lewandowski	NASA - Glenn Research Center
Wayne Wong	NASA - Glenn Research Center
Richard Ambrosi, PhD	University of Leicester
Robert Wham	Oak Ridge National Laboratory
Tom Sutliff	NASA - Glenn Research Center

Track II: Fission Surface Power

Technical Chair: Patrick McClure, Los Alamos National Laboratory

Susan Voss	Global Nuclear Network Analysis
Max Briggs	NASA - Glenn Research Center
Tom Godfroy	NASA - Marshall Space Flight Center
Steve Clement	Los Alamos National Laboratory

Track III: Nuclear Thermal Propulsion

Technical Chair: Daniel Cavender, NASA Marshall Space Flight Center

Harold Gerrish	NASA - Marshall Space Flight Center
Michael Eades	The Ohio State University
Vishal Patel	Center for Space Nuclear Research
Jarvis Caffrey	NASA - Marshall Space Flight Center
Chance Garcia, PhD	NASA - Marshall Space Flight Center
Glen Doughty	NASA - Marshall Space Flight Center
Jim Werner	Idaho National Laboratory

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 GenCrop can be obtained by visiting the companies' websites at www.Rocket.com and www.GenCorp.com.

Monday February 22, 2016

8:00am - 9:00am	**Registration**	Registration Desk
	Session Preparation	
9:00am - 11:00am	**Plenary Session I**	Ballroom 1
	Welcome: Paul McConnaughey • Mike Houts, NASA Marshall Space Flight Center • Lee Mason, NASA Glenn Research Center • Tom Brown, NASA Marshall Space Flight Center	
11:00pm - 1:00pm	Lunch	On you own
1:00pm - 2:30pm	**Technical Sessions**	Ballrooms 1, 3, and 4
2:30pm - 3:00pm	Refreshments	Exhibitor Hall
3:00pm - 5:30pm	**Technical Sessions**	Ballrooms 1, 3, and 4
7:00pm - 9:00pm	**Opening Reception** Keynote Speaker: Ralph McNutt, Johns Hopkins Applied Physics Laboratory	US Space and Rocket Center

Tuesday February 23, 2016

8:30am - 11:00am	**Technical Sessions**	Ballroosm 1, 3, and 4
11:00pm - 1:00pm	Lunch	On your own
1:00pm - 2:30pm	**Technical Sessions**	Ballrooms 1, 3, and 4
2:30pm - 3:00pm	Refreshments	Exhibitor Hall
3:00pm - 5:30pm	**Technical Sessions**	Ballrooms 1, 3, and 4

Wednesday February 24, 2016

8:30am - 11:30am	**Technical Sessions**	Ballrooms 1, 3, and 4
11:30pm - 1:00pm	Lunch	On your own
1:00pm - 2:30pm	**Technical Sessions**	Ballrooms 1, 3, and 4
2:30pm - 3:00pm	Refreshments	Exhibitor Hall
3:00pm - 5:30pm	**Technical Sessions**	Ballrooms 1, 3, and 4
7:00pm - 9:00pm	**Dinner Banquet** Intro: Roger Myers, Aerojet Rocketdyne Keynote Speaker: Steve Jurczyk, NASA HQ	Von Braun Center

Thursday February 25, 2016 - Tour of NASA Marshall Space Flight Center

7:30am - 8:00am	Travel from Embassy Suites to MSFC (shuttle provided)
8:00am - 8:20am	Additive Manufacturing
8:20am - 8:40pm	Composite Manufacturing
8:40am - 9:00am	Shuttle
9:00am - 9:20am	ECLSS
9:20am - 9:40am	SLS Weld Tools
9:40am - 10:00am	Shuttle
10:00am - 10:20am	NTP Fuel Lab
10:20am - 10:40am	Shuttle
10:40am - 11:00am	East Test Area
11:00am - 11:20am	Shuttle
11:20am - 11:40am	ISS HOSC
11:40am - 12:00pm	Shuttle
12:00pm - 12:20pm	NTREES
12:20pm - 12:40pm	Travel to Embassy Suites from MFSC (shuttle provided)

Monday February 22, 2016

Track I: Radioisotope Power Systems
Mission Studies: Part I

1:00 pm - 2:30 pm	6005	**Re-Inventing the Light Bulb,** *A. Rajguru (University of Southern California), M. Molnar (Missouri University of Science and Technology), and P. Rexing (Missouri University of Science and Technology)*	Ballroom 1
	6084	**Saturn Spacecraft Power: Trading Radioisotope, Solar, and Fission Power Systems,** *S.R. Oleson (NASA GRC), L. Kohout (NASA GRC), P. Schmitz (Vantage Partners, LLC), and R. Lorenz (Johns Hopkins University)*	
	6038	**Timelines for Supporting a Nuclear-Enabled NASA Mission: Does a Temporal Phase Mismatch Between NASA and DOE Exist?,** *S.G. Johnson (Idaho National Laboratory), C.C. Dwight (Idaho National Laboratory), K. Lively (Idaho Natianal Laboratory), and Y. Lee (Jet Propulsion Laboratory)*	

Track III: Nuclear Thermal Propulsion
Project and Mission Architecture

1:00 pm - 1:30 pm	6080	**Development and Utilization of Nuclear Thermal Propulsion,** *M. Houts and S. Mitchell (NASA MSFC)*	Ballroom 3

Track III: Nuclear Thermal Propulsion
Test Facility and Regulatory Considerations

1:30 pm - 2:30 pm	6009	**Approach to Licensing and Permitting Nuclear Test Facilities and Launch Approval for a Nuclear Safety Review and Launch Approval,** *J. Werner (Idaho National Laboratory), A. Weitzberg, and A. Belvin (Department of Energy)*	Ballroom 3
	6083	**Axisymmetric Analysis of a Hydrogen Containment Process for Nuclear Thermal Engine Ground Testing,** *T-S. Wang, E.T. Stewart, and F. Canabal (NASA MSFC)*	

Track I: Radioisotope Power Systems
Fuel Production: Part I

1:00 pm - 2:30 pm	6047	**Idaho National Laboratory Radioisotope Power Systems Nuclear Operations: Preparations, Documentation, Readiness Assessments and Conduct of Operations Supporting a Nuclear-Enabled NASA Mission,** *K.L. Lively, E.S. Clarke, and R.P. Gomez (Idaho National Laboratory)*	Ballroom 4
	6015	**The Plutonium-238 Supply Project,** *R.M. Wham, D.W. DePaoli, R.W. Hobbs, E.D. Collins, E.D. Benker, R.S. Owens, and R.J. Vedder (Oak Ridge National Laboratory)*	
	6046	**Production of Polonium-209 Using Nuclear Reactor as Radioisotope Fuel for Space Nuclear Power,** *J. Nishiyama (Tokyo Institute of Technology)*	

Track I: Radioisotope Power Systems
Mission Studies: Part II

3:00 pm - 5:30 pm	6052	**Assessment of Future New Frontiers Mission Concepts Utilizing the MMRTG and eMMRTG Radioisotope Thermoelectric Generators,** *R.L. Cataldo (NASA GRC), and D.F. Woerner (Jet Propulsion Laboratory)*	Ballroom 1
	6023	**RPS Program Status,** *J.A. Hamley, T.J. Sutliff, C.E. Sandifer II, and J.F. Zakrajsek (NASA GRC)*	
	6033	**Triton Hopper: Exploring Neptune's Captured Kuiper Belt Object,** *S.R. Oleson and G. Landis (NASA GRC)*	
	6045	**Radioisotope Power Systems (RPS) for Emerging Power Needs fo Deep Space Small-Sats, CubeSats and Deployed Payloads,** *Y.H. Lee, B.K. Bairstow, and J.E. Riedel (Jet Propulsion Laboratory)*	
	6059	**Power Generation Alternatives for Deep Space Exploration in the Solar System,** *P.M. Beauchamp, J. Elliott, J.A. Cutts, and JPL A-Team (Jet Propulsion Laboratory)*	

Track II: Fission Power Systems
Reactor Physics and Fuel

3:00 pm - 5:00 pm	6006	**LEU CERMET Based Fission Surface Power Source for a Martian Habitat - Reactor Design,** *A. Kumar (Center for Space Nuclear Research), K. Schillo (University of Alabama), K. Harris (Utah State University), Y.M. Hew (Stanford University), and S.D. Howe (Center for Space Nuclear Research)*	Ballroom 3
	6014	**Moderator Configuration Options for Low-Enriched Uranium Fueled Kilowatt-Class Space Nuclear Reactors,** *L.D.H Mencarini (Instituto de Estudos Avancados) and J.C. King (Colorado School of Mines)*	
	6017	**Conceptual Design of a Heat Pipe Cooled Nuclear Reactor Power System for Mars Base,** *C. Yao (China Institute of Atomic Energy), G. Hu (China Institute of Atomic Energy), J. Xie (China Institute of Atomic Energy), Y. Liu (China Institute of Atomic Energy), C. Xu (China Institute of Nuclear Information and Economy), and L. Ha (China Institute of Nuclear Information and Economy)*	
	6090	**Reactor Design of the Kilowatt Reactor Using Stirling Technology (KRUSTY),** *D.I. Poston (Los Alamos National Laboratory), M. Gibson (NASA GRC), T. Godfroy (NASA MSFC), and P. McClure (Los Alamos National Laboratory)*	

Track I: Radioisotope Power Systems
Fuel Production: Part II

3:00 pm - 5:00 pm	6026	**Development of Chemical Processes for Production of Pu-238 from Irradiated Neptunium Targets,** *D.W. DePaoli, D.E. Benker, L.H. Delmau, J.D. Burns, and R.M. Wham (Oak Ridge National Laboratory)*	Ballroom 4
	6078	**The Separation of AM-241 from Aged Plutonium Dioxide for Use in Radioisotope Power Systems,** *M.J. Sarsfield (National Nuclear Laboratory), M.J. Carrott (National Nuclear Laboratory), C. C. Majer (National Nuclear Laboratory) C. Mason (National Nuclear Laboratory), C. Cambell (National Nuclear Laboratory), J. Holt (National Nuclear Laboratory), T. Griffiths (National Nuclear Laboratory), C. Carrigan (National Nuclear Laboratory), H. Fenwick (National Nuclear Laboratory), B. McLuckie (National Nuclear Laboratory), C. Gregson (National Nuclear Laboratory), T. Tinsley (National Nuclear Laboratory), and K. Stephenson (European Space Agency)*	
	6001	**Continuous Improvement Initiatives for the Radioisotope Power Systems Program at Oak Ridge National Laboratory,** *K.R. Veach Jr. (Oak Ridge National Laboratory)*	
	6039	**Progress on the Sol-Gel Microsphere Technology Demonstration for Pu-238 Heat Sources,** *J. Katalenich and S. Sinkov (Pacific Northwest National Laboratory)*	

Tuesday February 23, 2016

Track I: Radioisotope Power Systems
Thermoelectric Conversion: Part I

8:30 am - 11:00 am	6064	**Optimization of High Temperature Zintl Materials for the p-Leg of Thermoelectric Space Power Generation,** *S.M. Kauzlarich (University of California), J.H. Grebenkemper (University of California), Y. Hu (University of California), D. Barrett (Univeristy of California), E. Wille (University of California), and S. Bux (Jet Propulsion Laboratory)*	Ballroom 1
	6029	**High Efficiency Graphene Superlattices Based Thermoelement for Radioisotope Thermoelectric Generator Applications,** *S. K. Mishra, C.P. Kaushik, B. Dikshit, and A. Kumar (Bhabha Atomic Research Centre)*	
	6041	**An Update on the eMMRTG Skutterudite-Based Thermoelectric Technology Maturation Project,** *T. Caillat (Jet Propulsion Laboratory), I. Chi (Jet Propulsion Laboratory), S. Firdosy (Jet Propulsion Laboratory), C.-K. Huang (Jet Propulsion Laboratory), K. Smith (Jet Propulsion Laboratory), J. Paik (Jet Propulsion Laboratory), P. Gogna (Jet Propulsion Laboratory), K. Yu (Jet Propulsion Laboratory), J.-P. Fleurial (Jet Propulsion Laboratory), R. Bennett (Teledyne Energy Systems), and S. Keyser (Teledyne Energy Systems)*	
	6043	**A Technology Roadmap for Thermoelectric-Based Space and Terrestrial Power Systems,** *J.-P. Fleurial and T. Hendricks (Jet Propulsion Laboratory)*	
	6049	**Progress on Development of Skutterudite Thermoelectrics for Space Power Applications,** *R. Bennett (Teledyne Energy Systems), T. Hammel (Teledyne Energy Systems), S. Keyser (Teledyne Energy Systems), T.C. Holgate (Teledyne Energy Systems), and T. Caillat (Jet Propulsion Laboratory)*	

Track II: Fission Power Systems
Power Conversion and Associated Technologies: Part I

8:30 am - 11:00 am	6004	**Mass Optimization of Supercritical CO2 Brayton Cycle Power Conversion System for a Mars Surface Fission Power Reactor,** *K.E. Harris (Utah State University), Y.M. Hew (Stanford University), K.J. Schillo (University of Alabama), A. Kumar (Texas A&M University), and S.D. Howe (Center for Space Nuclear Research)*	Ballroom 3
	6007	**Design-Based Model of a Closed Brayton Cycle for Space Power Systems,** *G.B. Ribeiro, L.N.F. Guimaraes, and F.A.B. Filho (Institute for Advanced Studies)*	
	6068	**Alkali Metal Heat Pipes for Kilopower,** *C. Tarua, W.G. Anderson, and D. Beard (Advanced Cooling Technologies)*	
	6069	**Multiphysics Analysis of Liquid Metal Annular Linear Induction Pumps,** *C.O. Maidana and J.E. Neiminen (Maidana Research)*	
	6074	**Fission Surface Power Technology Demonstration Unit Test Results,** *M.H. Briggs (NASA GRC), M.A. Gibson (NASA GRC), S. Geng (NASA GRC), and J. Sanzi (Vantage Partners)*	

Track III: Nuclear Thermal Propulsion
Reactor Design: Part I

8:30 am - 11:00 am	6048	**Comparison of LEU and HEU Cermet Nuclear Thermal Propulsion Systems at 16,000 lbf Thrust,** *M. Eades (The Ohio State University), W. Deason (Center for Space Nuclear Research), and C.R. Joyner II (Aerojet Rocketdyne)*	Ballroom 4
	6025	**Comparison of Neutronic Properties of CERMET and Composite Nuclear Thermal Rocket Cores Utilizing Low-Enriched Uranium,** *A. Thody, T. Franklin, and A. Klein (Oregon State University)*	
	6050	**A LEU Cermet Point Design: The Space Capable Cryogenic Thermal Engine (SCCTE),** *M. Eades (The Ohio State University), V. Patel (Center for Space Nuclear Research), and W. Deason (Center fro Space Nuclear Research)*	
	6086	**Low-Enriched Uranium Nuclear Thermal Rocket Design Considerations,** *V. Patel (Center for Space Nuclear Research)*	
	6072	**A Point Design for a LEU Composite NTP System: Superb Use of Low-Enriched Uranium (SULEU),** *P. Venneri (Ultra-Safe Nuclear Corporation) and M. Eades (The Ohio State University)*	

Track I: Radioisotope Power Systems
Thermoelectric Conversion: Part II

1:00 pm - 2:30 pm	6040	**Development of a Sliding and Compliant Cold Side Thermal Interface for the a Thermopile Inside a Terrestrial Mini-RTG,** *N.R. Keyawa, P. Bahrami, G. Molina, V. Cormarkovic, S. Firdosy, R. Ewell (Jet Propulsion Laboratory)*	Ballroom 1
	6073	**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. Paik, D. Uhl, J. Ni, K. Smith, G. Nakatsukasa, J.-P. Fleurial (Jet Propulsion Laboratory)*	
	6030	**Development of High Efficiency Complex Zintl Phases for Thermoelectric Space Power Generation Applications,** *S. Bux (Jet Propulsion Laboratory), B. Li (Jet Propulsion Laboratory), Y. Hu (University of California), A. Zevalkink (Jet Propulsion Laboratory), S. Chanakian (Jet Propulsion Laboratory), D. Uhl (Jet Propulsion Laboratory), S. Kauzlarich (University of California), and J.-P. Fleurial (Jet Propulsion Laboratory)*	

Track II: Fission Power Systems
Power Conversion and Associated Technologies: Part II

1:00 pm - 2:30 pm	6075	**Completion of a 12kWe Stirling Converter for Fission Power Systems,** *J.C. Stanley (Sunpower), J.G. Wood (Sunpower, E. Holliday(NASA GRC), S.M. Geng (NASA GRC)*	Ballroom 3
	6081	**First Approach to the Design of Annular Linear Induction Pumps using First Principles,** *J.E. Nieminen and C.O. Maidana (Maidana Research)*	
	6087	**Ultra-Compact Heat Rejection System,** *J.J. Breedlove (Creare), T.M. Conboy (Creare), M. Gibson (NASA GRC)*	

Track III: Nuclear Thermal Propulsion
Reactor Design: Part II

1:00 pm - 2:30 pm	6051	**WORPH: An Open Source Code for NTR Infinite Lattice Studies Using MCNP and Serpent,** *M. Eades (The Ohio State University) and P. Venneri (KAIST)*	Ballroom 4
	6037	**Space Propulsion Optimization Code Benchmark Case: SNRE,** *V. Patel (Center for Space Nuclear Research), M. Eades (The Ohio State University), C.R. Joyner II (Aerojet Rocketdyne)*	
	6071	**Characterization of Xenon Induced Reactivity Changes in Low-Enriched Nuclear Thermal Propulsion Cores,** *P. Venneri (Ultra-Safe Nuclear Corporation) and M. Eades (The Ohio State University)*	

Track I: Radioisotope Power Systems
Stirling Conversion

3:00 pm - 5:30 pm	6020	**Stirling Research Laboratory Activities at NASA Glenn Research Center,** *S. Oriti (NASA GRC)*	Ballroom 1
	6061	**Advanced Stirling Convertor ASC-E3 Project Summary,** *J. Collins, K. Wilson, and M.A. Dunlap (Sunpower)*	
	6062	**Advanced Stirling Convertor (ASC) Design and Technology Assessment White Paper,** *J. Collins and K. Wilson (Sunpower)*	
	6076	**Radioisotope Thermoacoustic Power Conversion for Spacecraft,** *D.E. Lee, M. Petach, and E. Tward (Northrop Grumman Aerospace Systems)*	
	6055	**Status of Stirling Power System Modeling Capabilities,** *J. Metscher (NASA GRC), T. Reid (NASA GRC), P.C. Schmitz (Power Computing Solutions)*	

Track II: Fission Power Systems
Power Conversion and Associated Technologies: Part III

3:00 pm - 4:00 pm	6088	**Turbo-Brayton Power Converter for Spaceflight Applications,** *J.J. Breedlove, T.M. Conboy, M.V. Zagarolo (Creare)*	Ballroom 3
	6063	**Maturing Technologies for Stirling Space Power,** *S.D. Wilson (NASA GRC)*	

Track III: Nuclear Thermal Propulsion
Reactor Design: Part III

3:00 pm - 4:00 pm	6044	**Preliminary Analysis of Low-Enriched Uranium (LEU) Ultra High Temperature Nuclear Thermal Rockets Capable of 1100s Specific Impulse,** *K. Benensky (University of Tennessee), M.-J. Wang (Virginia Polytechnic Institute), J. Nieminen (University of Southern California), M. Eades (The Ohio State University), and S. Howe (Center for Space Nuclear Research)*	Ballroom 4
	6056	**A Six Component Model for Dusty Plasma Nuclear Fission Fragment Propulsion,** *R.L. Clark (Grassmere Dynamics) and R.B. Sheldon (RBSheldon Consulting)*	

Track I: Radioisotope Power Systems
Cermet as a Fuel Simulant: Part I

4:00 pm - 5:30 pm	6034	**Influence of the Gd(III) Cation on the Oxygen Exchange Behavior of CeO2,** *C.E. Whiting, D.P. Kramer, and C.D. Barklay (University of Dayton)*	Ballroom 3
	6036	**Impact of Carbon on the Oxygen Potential of a High Temperature System Containing CeO2 as PuO2 Surrogate,** *C.E. Whiting, H. Knachel, D.P. Kramer, and C.D. Barklay (University of Daytona)*	
	6079	**Sintering and Characterisation of Cerium Dioxide as a Surrogate for Americium-241,** *M.J. Sarfield (National Nuclear Laboratory), H. Fenwick (National Nuclear Laboratory), P. Glenville (National Nuclear Laboratory), D.P. Kramer (University of Dayton), E.J. Watkinson (University of Leicester), R.M. Ambrosi (University of Leicester), H.R. Williams (University of Leicester), C.D. Barklay (University of Daytona), K. Stephenson (European Space Agency), and T. Tinsley (National Nuclear Laboratory)*	

Wednesday February 24, 2016

Track I: Radioisotope Power Systems
Materials and Systems Testing: Part I

8:30 am - 11:30 am	6031	**Neutron Irradiation of Bi2Te3 Based Thermoelectric Modules for Radioisotope Space Power Systems Applications,** *R. Mesalam (University of Leicester), H.R. Williams (University of Leicester), R.M. Ambrosi (University of Leicester), D.P. Kramer (University of Dayton), C.D. Barklay (University of Daytona), J. Garcia-Canadas (Universitat Jaume I), and K. Stephenson (European Space Agency)*	Ballroom 1
	6085	**Effect of Sub-Sized Speciman Geometry and Orientation on High Strain-Rate Tensile Impact Ductilities of DOP-25 Iridium,** *B.R. Friske and C.A. Carmichael Jr. (Oak Ridge National Laboratory)*	
	6035	**Modeling the Gas Phase Chemistry Inside an RTG,** *C.E. Whiting (University of Dayton), E.J. Watkinson (University of Leicester), C.D. Barklay (University of Dayton), D.P. Kramer (University of Dayton), H.R. Williams (University of Leicester), and R.M. Ambrosi (University of Leicester)*	
	6053	**Characterization the Thermal Conductivity of CBCF: A Review and Recent Advances,** *N.C. Gallego, G.R. Romanoski, R.B. Dinwiddie, W.D. Porter, J. Wang, and G.B. Ulrich (Oak Ridge National Laboratory)*	
	6054	**Dynamics Modeling and Heat Flow Optmization of an Enhanced MMRTG,** *D. Woerner (Jet Propulsion Laboratory)*	
	6058	**Advanced Hybrid SiO2 Aerogel for eMMRTG Flight Module,** *Y. Song (Teledyne Energy Systems), R. Bennett (Teledyne Energy Systems), T. Hammel (Teledyne Energy Systems), S. Keyser (Teledyne Energy Systems), J-A. Paik (Jet Propulsion Laboratory), S. Jones (Jet Propulsion Laboratory), and T. Caillat (Jet Propulsion Laboratory)*	

Track II: Fission Power Systems
Space Nuclear Power Programs

8:30 am - 11:00 am	6002	**Power Management and Distribution System for a Marian Fission Surface Power Reactor,** *Y.M. Hew (Stanford University), K.E. Harris (Utah State University), K.J. Schillo (University of Alabama), A. Kumar (Texas A&M University), and S.D. Howe (Center for Space Nuclear Research)*	Ballroom 3
	6011	**Charger-1: Nuclear Fusion Propulsion Facility for Improved Deep Space Exploration,** *E.R. Gish, C.L. Matzkind, D.L. and Coad (The Boeing Company)*	
	6028	**Democritos: Development Logic for a Demonstrator Preparing Nuclear-Electric Spacecraft,** *S. Oriol (CNES), F. Masson (CNES), T. Tinsley (National Nuclear Laboratory), R. Stainsby (National Nuclear Laboratory), Z. Hodgson (National Nuclear Laboratory), E. Detsis (ESF), J-C. Worms (ESF), A. Solodukhin (Keldysh Research Center), A. Semenkin (Keldysh Research Center), F. Jansen (Thalese Alenisa Space Italia), W. Bauer (Thales Alenia Space Italia), M.C Tosi (DLR), S. Ferraris (DLR), F. Lassoudiere (Airbus-Safran Launchers), and M. Muszynski (Airbus-Safran Launchers)*	
	6057	**Nuclear Systems Kilopower Project Update,** *D.T. Palac (NASA GRC), M.A. Gibson (NASA GRC), L.S. Mason (NASA GRC), M.G. Houts (NASA MSFC), P. McClure (Los Alamos National Laboratory), and R.C. Robinson (Y-12 National Security Complex)*	
	6070	**Y-12 National Security Complex Casting and Machining Capabilities, and their Recent Application to Nuclear and Emerging Technologies for Space Programs,** *W.T. Rogerson Jr, (Y-12 National Security Complex)*	

Track III: Nuclear Thermal Propulsion
Engine System and Component Development: Part I

8:30 am - 11:30 am	6010	**Nuclear Thermal Propulsion Technology Demonstration Plan,** *G. Dought (NASA MSFC), J. Werner (Idaho National Laboratory), S. Borowski (NASA GRC), R. Sefick (NASA GRC), and A. Weitzberg*	RBallroom 4
	6077	**An Examination of the Engine Cycle TRENDS for a HEU and LEU NTP,** *C.R. Joyner II (Aerojet Rocketdyne), D.J. Levack (Aerojet Rocketdyne), and T. Jennings (Aerojet Rocketdyne)*	
	6019	**Nuclear Thermal Propulsion Integrated Injector-Manifold Development,** *T. Belcher (University of Texas - El Paso), R. Hetterich (Lehigh University), M. Reilly (Georgia Institute of Technology), T. Scogin (Georgia Institute of Technology), and J. Santecchia (Arizona State University)*	
	6018	**Aluminum-Beryllium Composit Trade Study for Space Nuclear Applications,** *R. Hetterich (Lehigh University), T. Belcher (University of Texas - El Paso), M. Reilly (Georgia Institute of Technology), T. Scogin (Georgia Institute of Technology), and J. Santecchia (Arizona State University)*	
	6008	**Potential for Additive Manufacture in Nuclear Thermal Propulsion,** *O.R. Mireles, C. Garcia, Z. Jones (NASA MSFC)*	
	6032	**Radiation Shielding for Nuclear Thermal Propulsion, J.***A. Caffrey (Oregon State University)*	

Track I: Radioisotope Power Systems

Cermet as Fuel Simulant: Part II

1:00 pm - 2:30 pm	6013	**Further Developments in CeO2 and Nd2O3 Sintering Trials as Analogues for Americium Oxide,** *E.J. Watksinson (University of Leicester), R.M. Ambrosi (University of Leicester), D.P. Kramer (University of Dayton), H.R. Williams (University of Leicester), M. Reece (Queen Mary University of London), K. Chen (Queen Mary University of London), H. Ning (Queen Mary University of London), C.E. Whiting (University of Dayton), C.D. Barklay (University of Dayton), D. Weston (University of Leicester), M. Sarsfield (National Nuclear Laboratory), K. Stephenson (European Space Agency), and T. Tinsley (National Nuclear Laboratory)*	Ballroom 1
	6016	**CeO2 - Ceramic Surrogate for Pu-238?,** *D.P. Kramer, C.O. Sjoblom, S.M. Goodrich, C.D. Barklay, and C.E. Whiting (University of Dayton)*	
	6027	**Development of Cerium-Neodymium Oxide Surrogates for Americium Oxides,** *E.J. Watkinson (University of Leicester), M.J. Sarsfield (National Nuclear Laboratory), R.M. Ambrosi (University of Leicester), H.R. Williams (University of Leicester), D. Weston (University of Leicester), N. Marsh (University of Leicester), C. Haidon (University of Leicester), K. Stephenson (European Space Agency), and T. Tinsley (National Nuclear Laboratory)*	

Track II: Fission Power Systems

Reactor Analytical Studies: Part I

1:00 pm - 2:30 pm	6003	**Thermal Hydraulics Analysis of a Low-Enriched Uranium Cermet Fuel Core for a Mars Surface Power Reactor,** *K.J. Schillo (University of Alabama), A. Kumar (Center for Space Nuclear Research), K.E. Harris (Utah State University), Y.M. Hew (Stanford University), S.D. Howe (Center for Space Nuclear Research)*	Ballroom 3
	6060	**A Gigawatt Space Power System Using Dusty Plasma Fission Fragment Reactor,** *R.B. Sheldon(RBSheldon Consulting) and R.L. Clark (Grassmere Dynamics)*	
	6067	**Status of the Development of Low Cost Radiator for Surface Fission Power - II,** *C. Tarau (Advanced Cooling Technologies), T. Maxwell (Advanced Cooling Technologies), W. G. Anderson (Advanced Cooling Technologies), C. Wagner (Advanced Cooling Technologies), M. Wrosch (Vanguard Space Technologies), and M.H. Briggs (NASA GRC)*	

Track III: Nuclear Thermal Propulsion

Engine System and Component Development: Part II

1:00 pm - 2:30	6091	**A Multi-Dimensional Heat Transfer Model of a Tie-Tube and Hexagonal Fuel Element for Nuclear Thermal Propulsion,** *C. Gomez, E. Stewart, and O.R. Mireles (NASA MSFC)*	Ballroom 4
	6092	**Review of a Preliminary Fluid-Thermal Model of Hydrogen Flow in a Fuel Rod Tube of Nuclear Thermal Propulsion Rocket Engine Core,** *M. Rocker (NASA MSFC)*	
	6093	**Cryogenic Fluid Management Technology and Nuclear Thermal Propulsion,** *B.D. Taylor (NASA MSFC), J. Caffrey, (Oregon State University) A. Hedayat (NASA MSFC), J. Stephens (NASA MSFC), and R. Polsgrove (NASA MSFC)*	

Track I: Radisotope Power Systems

Material and System Testing: Part II

6024	**Multi-Mission Radioisotope Thermoelectric Generator Experience on Mars,** *J. Herman, R. Hall, P. Stella, E. Wood, T.I. Valdez, A. Mitchell (Jet Propulsion Laboratory)*	
6021	**Advanced Stirling Radioisotope Generator EU2 Anomaly Investigation,** *E.J. Lewandowski (NASA GRC)*	
6065	**Performance Testing of the EU/QU MMRTG,** *C.D. Barklay (University of Dayton), B.A. Tolson (UES), C.W. Sjoblom (University of Dayton), and R.J. Harris (University of Dayton)*	
6066	**Optimized Alkali Metal Backup Cooling System Tested with a Stirling Convertor,** *C. Tarau, C.L. Schwendeman (Advanced Cooling Technologies), N.A. Schifer (NASA GRC), and W.G. Anderson (Advanced Cooling Technologies)*	
6042	**Pyroschock Dynamic Loading Impacts on Thermoelectric Module Assemblies and Bi-Couples in Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs),** *T. Hendricks, D.J. Neff, N.R. Keyawa, B.J. Nesmith, P. Bahrami, A. Derkevorkian, A.R. Kolaini (Jet Propulsion Laboratory)*	

Track II: Fission Power Systems

Reactor Analytical Studies: Part II

3:00 pm - 4:00 pm	6082	**Pulsed Fission Fusion Propulsion - Current Developments**	Ballroom 3
	6089	**Shielding Options for Kilopower Mars Surface Reactors, D.***I. Poston (Los Alamos National Laboratory), S. Eustice (Los Alamos National Laboratory), L.S. mason (NASA GRC), and M. Rucker (NASA JSC)*	

Track III: Nuclear Thermal Propulsion

Engine System and Component Development: Part III

3:00 pm - 4:00 pm	6012	**Electric Pump System Trade Study for NTP Start-Up and Shut-Down Operations,** *J. Santecchia (Arizona State University), R. Hetterich (Lehigh University), T. Belcher (University of Texas - El Paso), M. Reilly (Georgia Institute of Technology), T. Scogin (Georgia Institute of Technology)*	Ballroom 4
	6094	**Optimization of NTP System Truss to Reduce Radiation Shield Mass,** *L.L. Scharber, A. Kharofa, and J.A. Caffrey (NASA MSFC)*	

Paul McConnaughey, PhD
Associate Director
NASA Marshall Space Flight Center

Dr. Paul K. McConnaughey is the associate director, technical, supporting the Office of the Center Director at NASA's Marshall Space Flight Center in Huntsville, Alabama. Named to the position in August 2015, McConnaughey provides expert technical advice and assistance to Marshall Center Director Patrick Scheuermann in support of the entire body of engineering, science and propulsion work conducted at Marshall. He performs special studies; advises and assists in policy review; manages and reports on center-wide metrics; and develops new technical benchmarking strategies. He works closely with senior managers in all these endeavors, ensuring Marshall programs and projects are timely, technically sound and serve the goals and requirements of the agency and the nation. McConnaughey previously served as the chief engineer in the Exploration Systems Development Division beginning in 2012, where he was the lead technical authority on all technical and engineering matters, while providing the associate administrator for the Human Exploration and Operations Mission Directorate and the deputy associate administrator for Exploration Systems Development with assessments of the impact, effectiveness and efficiency of NASA's exploration systems investments. He joined Marshall in 1986 as a mathematician in the Systems Dynamics Laboratory. Within three years, he advanced to supervisory positions, including team lead, branch chief and division chief. In 1998, McConnaughey was named NASA deputy manager for the Military Spaceplane Technology Office, where he worked on space vehicle technologies of joint interest to NASA and the U.S. Air Force.

He was reassigned as technical assistant to the director of the Engineering Directorate in 1999, where he concurrently served a detail to the Office of the Director of the Space Transportation Directorate. From 2000 to 2004, McConnaughey was the director of the Engineering Directorate's Structures, Mechanical, and Thermal Department. In 2004, he was reassigned to the position of deputy manager of the Spacecraft and Vehicle Systems Department, directing the research, development, design and integration of state-of-the-art spacecraft and vehicle systems and exploration missions. From 2007 to 2011, he was selected Marshall's chief engineer, overseeing Marshall's Technical Excellence initiative. In 2011, he was named associate director for technical management within the Engineering Directorate.For his service to NASA, he has received three NASA Exceptional Service Medals, a NASA Outstanding Leadership Medal, a Center Director's Commendation and a Certificate of Appreciation. McConnaughey also received the Presidential Rank Award for Meritorious Executive in 2011, the second-highest award conferred by the president of the United States.McConnaughey earned his bachelor's degree from Oregon State University in Corvallis, and a master's degree and a doctorate from Cornell University in Ithaca, New York.He is married to Angela Jackman, and has three daughters -- Shannon McConnaughey of Seattle, Washington; Kelly McConnaughey of Browning, Montana; and Tracy McConnaughey of Auburn, Alabama.

Mike Houts, PhD
Nuclear Research Manager
NASA Marshall Space Flight Center

Dr. Houts has a PhD in Nuclear Engineering from the Massachusetts Institute of Technology. He was employed at Los Alamos National Laboratory for 11 years where he served in various positions including Team Leader for Criticality, Reactor, and Radiation Physics and Deputy Group Leader of the 70 person Nuclear Design and Risk Analysis group. Dr. Houts currently serves as Nuclear Research Manager for NASA's Marshall Space Flight Center, where he has been employed for 14 years. He is also the principal investigator for NASA's Nuclear Thermal Propulsion (NTP) project. Recent awards include a NASA Exceptional Engineering Achievement Medal, a NASA Space Flight Awareness Honoree award, and a NASA MSFC Director's Commendation Honor Award.

Lee Mason
Chief of the Thermal Energy Conversion Branch
NASA Glenn Research Center

Mr. Mason is a nationally recognized expert in space power and propulsion systems with 29 years of professional experience at NASA Glenn Research Center (GRC) in Cleveland Ohio. His current position is Chief of the Thermal Energy Conversion Branch in the Power Division at GRC. His branch is responsible for the development of Stirling radioisotope generators and advanced reactor power systems for science and human exploration missions. The branch oversees the GRC Stirling Research Lab with 13 separate test stands that have accumulated over 800,000 operating hours on free-piston Stirling engines. Mr. Mason has written over 100 technical publications on space power and propulsion and generated several patent applications related to space nuclear power. Mr. Mason has been awarded the NASA Exceptional Achievement Medal (2006), the Rotary National Stellar Award (2010), and the NASA Outstanding Leadership Medal (2014). He holds a B.S. in Mechanical Engineering from the University of Dayton and a M.S. in Mechanical Engineering from Cleveland State University.

Tom Brown, PhD
Technical Fellow
NASA Marshall Space Flight Center

Dr. Brown began his NASA career at Marshall Space Flight Center (MSFC) in 1999 as an aerospace engineer in the Space Transportation Directorate, performing propulsion systems analysis and integration. Initially working design, analysis, and integration of the X-34 Main Propulsion System and the Fastrac/MC-1 rocket engine, Dr. Brown's activities quickly expanded into a broad range of propulsion technology development efforts. Dr. Brown served as Chief Engineer for several of these efforts during both the Second Generation Reusable Launch Vehicle Program and the Next Generation Launch Technology Program. Specific projects included Main Propulsion and Auxiliary Propulsion Systems Technology Project, and the ISTAR, Rocket Based Combined Cycle technology project.

In 2005 Dr. Brown became the manager of the Propulsion Structural, Fluids and Thermal Analysis Division at MSFC, which was responsible for a variety of detailed engineering analyses supporting Space Shuttle propulsion systems, propulsion technology projects, and new propulsion development efforts. In 2007 Dr. Brown completed a developmental rotation to the NASA Glenn Research Center (GRC) where he served as the Acting Deputy Manager of the GRC Advanced Capabilities Project Office. Later, Dr. Brown served as the manager of the Propulsion Systems Design and Integration Division at MSFC, supporting systems level design, analysis and assessments related to safe operation of existing propulsion systems, and design, development of new propulsion elements.

Most recently Dr. Brown served as a Technical Advisor to the Director of Propulsion at MSFC, where he assisted in internal technology investment planning, and served in Agency and cross government level assignments such as chair of the Green Propellant Infusion Mission Standing Review Board and representative on the Joint Army, Navy, NASA, Air Force (JANNAF) subcommittees on propulsion - Executive Committee.

Dr. Brown has over 24 years of mechanical and aerospace engineering experience in thermo-fluids and propulsion. Prior to working at NASA, Dr. Brown held engineering positions at Jacobs Corporation and Sverdrup Technology. He holds a U. S. Patent and has published over 30 refereed/journal publications, book sections and conference proceedings related to fundamental combustion, advanced measurement techniques, propulsion technology and propulsion systems analysis and integration.

Dr. Brown received his doctorate and master's degrees in mechanical engineering from Vanderbilt University in Nashville, Tennessee, and his bachelor's degree in physics from Allegheny College in Meadville, Pennsylvania.

Ralph McNutt, PhD
Chief Scientist
Johns Hopkins University, Applied Physics Laboratory

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

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

Roger Myers, PhD
Executive Director
Aerojet Rocketdyne

Dr. Roger Myers is the Executive Director of Advanced In-Space Programs at Aerojet Rocketdyne. In this role, he oversees programs and strategic planning for next-generation in-space missions and architectures, propulsion, power and integrated systems. Prior to this appointment in mid-2013, Dr. Myers was the executive director of Electric Propulsion and Integrated Systems, and served as Deputy Lead of Space and Launch Systems and General Manager of Aerojet Rocketdyne's Redmond Operations, the world's leading supplier of spacecraft propulsion systems and thrusters. Prior to joining Aerojet Rocketdyne in 1996, he worked at NASA's Glenn Research Center in the On-Board Propulsion Team. He has led dozens of development and flight programs and published over 80 papers on electric and chemical propulsion technology and in-space transportation architectures.

In addition, Dr. Myers serves as chair of the Washington State Joint Center for Aerospace Technology Innovation and President of the Electric Rocket Propulsion Society (ERPS). He also serves on the Board of Directors of both the ERPS and the Aerojet Rocketdyne Foundation. He is a Fellow of the American Institute of Aeronautics and Astronautics (AIAA), was elected to the Washington State Academy of Sciences in 2012, won the AIAA Wyld Propulsion Award in 2014 and was elected to the Board of Trustees for the Seattle Museum of Flight in 2015. He has served on several committees for the National Research Council.

Dr. Myers holds a Bachelor of Science degree in Aerospace Engineering, summa cum laude, from the University of Michigan. He received his Ph.D. in Mechanical and Aerospace Engineering from Princeton University.

Steve Jurczyk
Associate
Administrator
NASA Space
echnology and
Mission DIrectorate

Jurczyk has spent most of his 25-year career in aerospace with NASA in various systems engineering, management, and senior leadership positions at NASA Headquarters, Langley, and NASA's Goddard Space Flight Center. He contributed to the development of several space-based remote sensing systems supporting earth science research including the Upper Atmosphere Research Satellite, Landsat 7, and the Clouds and Aerosol Lidar and Infrared Pathfinder Observations mission. As Director of Systems Engineering and later Director for Research and Technology at Langley, he led the organization's engineering contributions to many successful flight projects including the Mach 7 and 10 flights of the Hyper-X jet engine powered vehicle, the Shuttle Program return-to-flight, the successful flight test of the Ares 1-X vehicle, and flight test of the Orion Launch Abort System.

He is a recipient of the NASA Outstanding Leadership Medal and the Presidential Rank Award of Meritorious Executive.

Jurczyk is a graduate of the University of Virginia where he received a Bachelor of Science and a Master of Science in Electrical Engineering. He currently lives in Williamsburg, Va. with his wife and two daughters. He is an elder in the Williamsburg Presbyterian Church where he is active in mission and youth activities, and enjoys running and cycling.

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

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

The National Aeronautics and Space Administration (NASA) 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 mission within our solar system and beyond.

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

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

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

Continuous Improvement Initiatives for the Radioisotope Power Systems Program at Oak Ridge National Laboratory

K. R. Veach, Jr.

Oak Ridge National Laboratory, 1 Bethel Valley Rd., Oak Ridge, TN 37831
865-574-1692; veachkrjr@ornl.gov

Abstract. The Oak Ridge National Laboratory (ORNL) Radioisotope Power Systems (RPS) Materials Production and Technology Program quality assurance activities in support of the Department of Energy (DOE) are a critical part of the program and infrastructure that enables DOE to develop, qualify, and provide RPS for use in terrestrial applications and space exploration missions. The goal of this program is to provide safe, reliable, and cost effective RPS as needed for specific sponsor missions, and to participate in research and development activities in areas such as fabrication technology and performance evaluation of materials and components in support of the RPS Program.

The RPS program hardware production activities are conducted in facilities that have implemented comprehensive conduct of operations systems. These systems have been formulated to address specific concerns and ensure excellence in the conduct of operations related to ORNL processes, facilities, products, and services. Processes to monitor performance, identify weaknesses and deficiencies, share lessons learned, and establish and implement corrective actions are part of the quality improvement process. These processes are defined in select surveillances which are scheduled, planned, performed, and documented to ensure effective implementation of program quality requirements.

Quality improvements in day-to-day program operations are recognized and implemented when needed. Changes in processes are controlled and documented through the document revision process. Problems that transcend a particular program task are communicated to program participants. Assessments, including surveillances and audits, are used as sources of information concerning scientific, business, and operational performance by management, staff, and clients and provide mechanisms for continuous improvement. Audits, assessments, management reviews, surveillances, walk-throughs, and other evaluations are conducted as monitoring activities to evaluate the quality of selected work subject to appropriate acceptance criteria contained in the technical and QA implementing procedures utilized by the program to control activities with the potential to impact the quality of planned work. Surveillances and other evaluations are established, planned, and conducted for accomplishing the activities to which they apply. The surveillance results and any associated corrective actions are documented in reports to appropriate management. Quality Improvement activities and processes interface with QA requirements intended to provide assurance that program performance, potential risks, and information garnered from both event-related and assessment-related results are managed effectively.

Keywords: Assessments, audits, management review, quality improvement, surveillances

---

Power Management and Distribution System for a Martian Fission Surface Power Reactor

Yayu M. Hew[1a], Kurt E. Harris[2], Kevin J. Schillo[3], Akansha Kumar[4], Steven D. Howe[5]

[1] *Department of Aeronautics and Astronautics Engineering, Stanford University, Stanford, CA 94305*
[2] *Department of Mechanical & Aerospace Engineering, Utah State University, Logan, UT 84322*
[3]*Department of Mechanical & Aerospace Engineering, University of Alabama in Huntsville, Huntsville, AL 35899*
[4]*Department of Nuclear Engineering, Texas A&M University, College Station, TX 77840*
[5]*Talos Power LLC, Idaho Falls, ID 83402*
817-896-9274; ymhew@stanford.edu

Abstract. This paper presents a power management and distribution (PMAD) system for a growing Martian colony. The colony is designed for a 15-year operation lifetime, and will accommodate a population that grows from 6 to 126 crew members. To provide sufficient electric power for the colony, a nuclear fission surface power (FSP) system is proposed with a total capacity of 1MWe. The system consists of three 333 kWe fission reactors, which are separated at a distance of 300 m from the habitat area to provide power budget flexibility, additional shielding safety and redundancy in the event of a meteorite impact. Trade studies over various power distribution methods, including DC/AC transmission, laser power transmission, radio frequency (RF) power transmission, and fiber optics power transmission, are conducted. The DC transmission with 2000VDC is found to provide the best power density (kW/kg), and transmission efficiency for the given configuration. An adequate grounding system is also designed to protect the crew members and instruments from electrification in the colony. The grounding system consists of local grounding rods, local grounding grids, and a soil-enhancement plan to resolve the grounding challenge presented by the dry Martian surface. The energy storage options have also been studied using a rechargeable battery, thermal energy reservoir, and regenerative fuel cell. The regenerative fuel cell using the recycled lander propellant tanks has been found to have the best energy density and scalability among all the options investigated. The thermal energy reservoir, while having the worst storage efficiency (<30%), can be constructed using local in-situ resource utilization (ISRU) materials, and is considered to be a promising long term option if its efficiency can be improved. The three reactors will be turned on in stages according to the power budget projection based on the rate of population growth. Using the three reactors , the rechargeable battery on the rovers, and the energy storage unit, a daily load following a 12-hr cycle can be achieved, and the power variation will be less than 10% during normal operation. Several main load-following scenarios are studied and accommodated, including an extended dust storm (> 50 sols), night time, day time, and transient peak power operation. A contingency power operation budget is also considered in event that all the reactors fail. The energy storage unit can support the reactor operation for up to 10 days for the initial two years of the colony's operation, and the habitat can support the crew for more than 6 months. The system has a power distribution efficiency of 85%, a storage efficiency of 50%, and a total mass of 13 Mt. The mass density for the FSP system is 103.64 kg/kWe, which includes the reactors, shielding, and PMAD for a 1 MWe system.

Keywords: Grounding, PMAD, optimization, Energy Storage, and Load-Following

Thermal Hydraulics Analysis of a Low-Enriched Uranium Cermet Fuel Core for a Mars Surface Power Reactor

Kevin J. Schillo[1], Akansha Kumar[2], Kurt E. Harris[3], Yayu M. Hew[4], Steven D. Howe[5]

[1]Department of Mechanical & Aerospace Engineering, University of Alabama in Huntsville, Huntsville, AL 35899
[2]Center for Space Nuclear Research, Idaho National Laboratory, Idaho Falls, ID 83401
[3]Department of Mechanical & Aerospace Engineering, Utah State University, Logan, UT 84322
[4]Department of Aeronautics and Astronautics Engineering, Stanford University, Stanford, CA 94305
[5]Talos Power LLC, Idaho Falls, ID 83402
813-597-1708; kjs0011@uah.edu

Abstract. A fission reactor utilizing low-enriched uranium cermet fuel and supercritical carbon dioxide as coolant was designed to provide electrical power for a manned Mars base. The reactor was designed to generate 1.67 MWth for a fifteen year operational lifetime, and the new electric output was 333 kWe. The core has alternating rows of fuel elements and a breeder blanket, with nineteen coolant channels in the fuel element and a single coolant channel in the breeder blanket. Zirconium hydride was selected as a neutron moderator, and had the lowest operating temperature of all the materials that would be used in the core. The ZrH therefore represented the limiting factor in the core thermal hydraulics analysis. The objective of this study was to find the maximum inlet and outlet temperatures of the S-CO2 that could be obtained while also keeping all of the reactor materials within an acceptable temperature range. Maximizing these temperatures would provide the highest performance for a power conversion system. A separate neutronics analysis found the core would have a conservatively estimated maximum power peaking factor of 1.6. In this study, a single fuel element and a breeder channel were simulated with the thermal power generated by this maximum peaking factor. This represented the greatest amount of thermal power that the core would experience. Finding the coolant conditions that kept this section of the core below the maximum permissible temperature would ensure that the rest of the core would also remain within an acceptable temperature limit. Throughout the reactor's operational lifetime, the fissile material in the LEU cermet fuel would be depleted while the breeder blanket would generate additional fissile material. As such, during the lifetime of the reactor, the fuel element would generate less thermal power as a function of time, and the breeder blanket would generate a greater amount of power as a function of time. Thermal hydraulics simulations were conducted at the different power levels the fuel element and breeder blanket would generate throughout the fifteen-year lifecycle. The simulation analysis was done using COMSOL Multiphysics.

Keywords: supercritical, thermal, hydraulics, CO2, Mars

Mass Optimization of a Supercritical CO2 Brayton Cycle Power Conversion System for a Mars Surface Fission Power Reactor

Kurt E. Harris[1], Yayu M. Hew[2], Kevin J. Schillo[3], Akansha Kumar[4], Steven D. Howe[5]

[1]Department of Mechanical & Aerospace Engineering, Utah State University, Logan, UT 84322
[2]Department of Aeronautics and Astronautics Engineering, Stanford University, Stanford, CA 94305
[3]Department of Mechanical & Aerospace Engineering, University of Alabama in Huntsville, Huntsville, AL 35899
[4]Department of Nuclear Engineering, Texas A&M University, College Station, TX 77840
[5]Center for Space Nuclear Research, Idaho National Laboratory, Idaho Falls, ID 83401
435-535-1414; k.harris@aggiemail.usu.edu

Abstract. In NASA's Design Reference Architecture 5.0 (DRA 5.0), fission surface power systems (FSPS) are described as "enabling for the human exploration of Mars". This study investigates the design of a power conversion system (PCS) based on supercritical CO2 (S-CO2) Brayton configurations for a growing Martian colony. Various configurations utilizing regeneration, intercooling, and reheating are analyzed. A model to estimate the mass of the PCS is developed and used to obtain a realistic mass-optimized configuration. This mass model is conservative, being based on simple concentric tube counterflow heat exchangers and published data regarding turbomachinery masses. For load following and redundancy purposes, the FSPS consists of three 333 kWe reactors and PCS to provide a total of 1MWe for 15 years. The optimal configuration is a S-CO2 Brayton cycle with 70% regeneration and one stage of intercooling. Analyses are mostly performed in MATLAB, with certain data provided by a COMSOL model of part of a low-enriched uranium (LEU) ceramic metallic (CERMET) reactor core.

Keywords: Mars, FSP, CO2, Brayton, mass

Re-inventing the Light Bulb

Rajguru Adarsh[1], Molnar Mikayla[2] and Rexing Philip[2]

[1]Department of Astronautical Engineering, University of Southern California, 854B Downey Way, RRB 225
Los Angeles, California 90089-1192
[2]Department of Nuclear Engineering, Missouri University of Science and Technology, 1870 Miner Cir, Rolla, MO 6540
(213) 819-4536; arajguru@usc.edu

Abstract. This paper proposes a novel concept of lighting a Mars Habitat using a radioisotope power source. The study was done at the Center for Space Nuclear Research (CSNR) during its summer 2015 internship program. The study was part of investigating a radioisotope power source solution to support the critical life support systems of a human Mars habitat for 6 crewmembers. Adequate, reliable and energy efficient lighting & heating of the habitat were a primary concern. Hence, in order to address that the Radioisotope light bulb concept was developed. The paper presents the design, heat transfer analysis, thermal radiosity analysis, structural analysis, radiation analysis and electric power conversion mechanism of the radioisotope light bulb. An Americium Oxide core in a Tungsten Rhenium Cermet was considered as the power source core. A Tantalum coating around the core heats up to temperatures of 1480 K enabling the material to glow at a “warm white light” spectrum, which is appropriate and psychologically convenient for a healthy work environment inside the habitat. Based on the assumption of high quality thermal insulation of the habitat, a passive heat rejection system from the radioisotope light bulb into the habitat was designed and analyzed to achieve a steady state temperature of the Tantalum coating at the required 1480 K. This heat transfer analysis was done in COMSOL. The passive heat rejection system was incorporated in the thermal control system design of the habitat in order to maintain the required nominal temperature for the crew. For “lights off” condition, a ThermoPhotoVoltaic (TPV) cells design was evaluated that would cover over the light bulb. The light from the radioisotope will be converted into electric power via the TPV cells, which would then be channeled into the Power Management And Distribution (PMAD) system of the habitat for storage (via charging batteries) or running any electrical appliances. An MCNP model was created to study the radiation from the light bulb. The MCNP model helped in polishing the design to meet acceptable radiation dosage for the human crew during the course of the mission. Lighting & heating analysis for operating hydroponics in a Mars habitat were performed to broaden the application of the radioisotope light bulb.

Keywords: Radioisotope, Americium, Plutonium, Photovoltaics and Lighting.

LEU CERMET Based Fission Surface Power Source for a Martian Habitat – Reactor Design

Akansha Kumar[1], Kevin J. Schillo[2], Kurt E. Harris[3], Yayu M. Hew[4], Steven D. Howe[5]

[1] Center for Space Nuclear Research, Idaho National Laboratory, Idaho Falls, ID 83401
[2]Department of Mechanical & Aerospace Engineering, University of Alabama in Huntsville, Huntsville, AL 35899
[3]Department of Mechanical & Aerospace Engineering, Utah State University, Logan, UT 84322
[4]Department of Aeronautics and Astronautics Engineering, Stanford University, Stanford, CA 94305
[5]Center for Space Nuclear Research, Idaho National Laboratory, Idaho Falls, ID 83401
979-492-1256; akansha @tamu.edu

Abstract. A surface power source is necessary for sustaining a crew and habitat on Mars for a short term stay as well as long term scaling of the colony. Fission based surface power source (FSP) in particular is scalable, green, safe, and economical. This work proposes a nuclear fission based reactor design that provides a power of 333 kWe for a lifetime of 15 years with no fuel reloading and shuffling.. Three such reactors will be used to supply a total power load of 1 MWe to the habitat. The design uses 15% isotopic enriched U-235 based CERMET fuel, and uranium dioxide fuelled blankets. S-CO2 is used as a coolant, which converts the heat generated by the reactor to electricity using a closed Brayton cycle. CERMET fuel is used in the form of hexagonal shaped element with 19 coolant channels and a ZrH moderator. The reactor uses B4C based control drums for control and safety. ZrC is used as an insulator, and ensures that the ZrH moderator does not reach an unacceptably high temperature. The coolant channels have a cladding of tungsten to prevent the release of fission gas from the fuel into the coolant. Beryllium reflectors are used to moderate and reflect neutrons back into the active core. The active core has a bull’s eye configuration, in which there are alternate fuel and blanket circular rows. Radial and axial enrichment zoning studies have been performed to reduce the power peaking factors. A basic safety assessment has been performed by determining the temperature and void coefficient of reactivity of fuel and coolant, respectively. Shielding studies were performed by determining the neutron and gamma dose rate at the outer surface of the reactor. Shielding materials that were investigated consisted of concrete, B4C, and tungsten. The reactor is a 1.7 by 1.5 m cylinder with no structural elements. This research presents a very viable reactor design that uses materials currently tested on other types of reactors. Nuclear reactor modeling, neutronics, shielding, and depletion analysis were done using MCNP6.

Keywords: FSP, thermal, supercritical, CO2, Mars

Design-Based Model of a Closed Brayton Cycle for Space Power Systems

Guilherme B. Ribeiro, Lamartine N. F. Guimarães and Francisco A. Braz Filho

Institute for Advanced Studies, Department of Aerospace Science and Technology, São José dos Campos, Brazil
+55 012 39475484; gbribeiro@ieav.cta.br

Abstract. Nuclear power systems tuned to space electric propulsion differs strongly from usual ground-based power systems regarding the importance of overall size and weight. For propulsion power systems, size/weight are essential drivers that should be minimized during conception processes. Considering that, this paper aims the development of a design-based model of a closed Brayton cycle that applies the thermal conductance of the main components in order to predict the energy conversion performance, allowing its use as preliminary tool for the heat exchangers and the radiator panel sizing. The centrifugal-flow turbine and compressor characterization were achieved using algebraic equations from literature data. The binary mixture of He-Xe with molecular weight of 40 g/mole is applied and the impact of the components sizing in the energy efficiency is evaluated in this paper, including the radiator panel area. Moreover, an optimization analysis based on the final area/size of these components is performed.

Keywords: Simulation, Brayton, Optimization

Potential for Additive Manufacture in Nuclear Thermal Propulsion

Omar R. Mireles[1], Chance Garcia[1], Zachary Jones[1]

[1]NASA Marshall Space Flight Center, Huntsville, AL 35401
(256) 544-6327; omar.r.mireles@nasa.gov

Abstract. Nuclear Thermal Propulsion (NTP) is one technology under investigation to provide rapid-transit for human missions to destinations beyond low earth orbit. Rocket engine manufacturing faces significant challenges stemming from high complexity, low production rate, and reliability requirements under extreme conditions. There is a significant effort underway to leverage additive manufacture (AM) technologies to decrease lead time and cost of rocket engines. A preliminary study was conducted to identify specialized NTP components that could potentially be produced via AM. NTP component examples include 1) turbo pumps housing and rotating components, 2) regenerative cooled nozzle, 3) B_4C neutron shields, 4) a combination injector-manifold or “injectifold”, 5) ZrC insulator sleeves/slats, and a number of other potential components. In addition, technical aspects of the AM process are discussed including design for AM, starting powder requirements, build layout, support generation, metallic and non-metallic build parameter development. Real-time In-Situ Process Monitoring (ISPM) uses empirical build data in conjunction with a solidification kinetics models to predict residual stresses, geometric distortion, surface finish, defects, microstructure, and material properties. Post processing such as stress relieve, HIP, shot-peen, anneal, machining prepares components for system integration. Finally, NDE such as x-ray tomography (micro-CT) is used to create a 3D spatial porosity and flaw distribution maps. The as-built part model undergoes analysis to predict properties and operational performance with an associated statistical tolerance comparison to least-material condition (LMC) design requirements. These results provide a degree of confidence for hot-fire tests and eventual flight certification.

Keywords: Nuclear, Thermal, Propulsion, Additive, Manufacture, 3D, Printing, Component.

Approach to Licensing and Permitting Nuclear Test Facilities and Launch Approval for a Nuclear Safety Review and Launch Approval

James Werner[1], Abraham Weitzberg[2], Anthony Belvin[3]

[1]Department of Energy Idaho National Laboratory, Idaho Falls, ID 83401
[2]Consultant, Woodland Hills, CA 91367
[3]Department of Energy Office of Nuclear Energy, NE-75, Germantown, MD 20874
208-526-8378 ; james.werner@inl.gov

Abstract. This paper reviews the basis and authority regarding the design, development, and demonstration of space nuclear technology and systems. Congress initially and formally vested authority for the design, development, test, evaluation, and demonstration of space nuclear technology and systems that utilize special nuclear material to the U.S. Atomic Energy Commission (AEC) by the Atomic Energy Act of 1954. The AEC was to retain title and control of the space power and propulsion system at all times. Finally the AEC was to provide the necessary means to fulfil its responsibility with respect to the radiological health, safety, safeguards and security of the system and support facilities. This authority was transferred to the U.S. Energy Research and Development Administration pursuant to sections 104(b), (c) and (d) of the Energy Reorganization Act of 1974 (Pub. L. 93-438, 88 Stat. 1233 at 1237, 42 U.S.C. 5814) and retransferred to the Secretary of Energy pursuant to section 301(a) of the Department of Energy (DOE) Organization Act (Pub. L. 95–91, 91 Stat. 565 at 577–578, 42 U.S.C. 7151).

The development of fabrication and test facilities for these systems intended for some flight design also falls exclusively to DOE under the authority provided by these Acts. DOE has the authority to either utilize its own permitting and operational authority to operate and oversee fabrication and test facilities or use alternative licensing options such as through the NRC licensing pathway for fabrication and test facilities. It is recognized that all these activities, including planning, scheduling, and management will require close coordination and communication with the agency responsible, in this case DOE, for the system development and vehicle integration, the DOE will have the lead approval responsibility for conducting reactor system systems concept and technology development such as reactor fuels and materials, and nuclear test site activities and items concerning nuclear safety.

Licensing pathway options for test or demonstration reactors depend on the specific nature and purposes of the utilization facilities. Consideration of the specific mechanisms provided by existing governmental agencies for developing regulatory requirements for an advanced design (such as a nuclear thermal propulsion test facility) will reduce the overall regulatory risk associated with the project.

The purpose of this paper is to provide a summary overview of the various regulatory processes that are available for the licensing of an innovative reactor design (which could potentially be applied to a nuclear thermal propulsion test facility).

Keywords: E Safety, Licensing, Space Nuclear, Safety Basis.

Nuclear Thermal Propulsion Technology Demonstration Plan

Glen Doughty[1,] James Werner,[2], Stanly Borowski[3], Robert Sefick[3], Abe Weitzberg[4]

[1]NASA Marshall Space Flight Center, Hunstville, AL 35808
[2]Department of Energy Idaho National Laboratory, Idaho Falls, ID 83401
[3]NASA Glen Research Center Cleveland, OH 80401
[4]Consultant, Woodland Hills, CA 91367
256-544-4389; glen.e.doughty@nasa.gov

Abstract. A Design, Development, Test and Evaluation Plan (DDT&E) for Nuclear Thermal Propulsion engine was developed to show a cost effective pathway in demonstrating and developing a composite fuel reactor.

Purpose: The purpose of this work is to provide a DDT&E plan for an NTP demonstrator flight that has both NASA and DOE concurrence. The fundamental objective is to take all technologies to TRL 6 by the end of a successful demonstration flight. However because of cost and schedule constraints, only the ground test portion was completed. These tasks included:

- Develop top-level NTP Demonstrator Plan describing sequence of principal tasks needed to reach engine TRL 6 via ground testing. The Plan is laid out in swim lanes for ease of communication.
- Develop detailed task descriptions supporting the individual tasks shown in the swim lanes
- Develop WBS and SME cost estimate consistent with detailed tasks
- Identify Issues/Risks and Suggested Resolution Path

A Plan was developed that identified major work scope in various development phases from pre-phase A through Phase D&E which consisted of integrated testing of the reactor and engine components

This work was performed under Advanced Exploration Studies in FY15 as a precursor to the development of a NTP Technology Demonstrator Flight Plan to be developed in FY16 & FY 17.

Keywords: Nuclear Thermal Propulsion, ground test, WBS, Space Nuclear.

Charger-1: Nuclear Fusion Propulsion Facility for Improved Deep Space Exploration

Erin R. Gish, Courtney L. Matzkind, Dennis L. Coad

The Boeing Company, Advanced Space Propulsion, Huntsville, AL
(256) 772-1433 Erin.R.Gish@boeing.com

Abstract. To stay on the leading edge of space exploration and meet emerging interplanetary needs, it's crucial to invest in new technologies for safe, reliable deep space travel. Fusion propulsion provides the high specific impulse propulsion needed in vehicles with high payload mass fractions required for deep space missions. The Charger-1 facility has the potential to propel Boeing to the forefront of space exploration with fusion propulsion that will reduce mission times, provide new abort capabilities and limit crew exposure to harsh space environments. Simultaneously, it will promote research in materials, radiation science and magnetic nozzle technology that may be applicable across multiple platforms.

Originally called Decade Module 2 (DM2), Charger-1 was the last prototype serving as a test bed for the design and construction of the larger Decade Machine at Arnold AFB for nuclear weapons effects testing. This 500 kJ pulsed power facility is capable of 2MA discharges at 3TW of instantaneous power. For comparison, the electrical power in the entire global grid is 15 TW. Charger-1 is now at a UA Huntsville laboratory on Redstone Arsenal and is under construction supported by UAH, MSFC, and The Boeing Company.

The goal of this presentation is to highlight current advancements at the Charger-1 facility and the expected impact of this emerging technology across Boeing and the industry. Charger-1 will facilitate advancements in:

1) Increased repetition rate of large pulse power machines to 100 pulses/minute, allowing for multi-use applications, including in space based nuclear propulsion systems

2) Development of materials and propulsion systems that tolerate temperatures > 10 keV (>120,000,000 K)

3) Development/design of dynamic plasmas as both a fuel source and radiation shields

4) An x-ray and neutron source for advanced radiation testing

5) Development of new explosive containment structures to withstand giga to terajoule outputs characteristic of fusion thrust levels

6) Research in magnetic nozzles

7) Creation of new fusion-based electrical power source

The expected outcome is a prototype impulse engine utilizing scaled versions of the DM2 and an eventual full size interplanetary impulse engine that can be incorporated into an interplanetary space vehicle that propels Boeing to the forefront of deep space exploration.

Keywords: Nuclear Fusion, Z-Pinch, Advanced Space Propulsion

Electrical Propellant Pump system trade study for start up and shut down operation of the Nuclear Thermal Propulsion system design by NASA MSFC.

Joaquin Santecchia [1], Robert Hetterich [2], Travis Belcher [3], Matthew Reilly [4],
Tyler Scogin [5].

[1] *Arizona State University, Tempe, AZ 85281*
[2] *Lehigh University, Bethlehem, PA 18015*
[3] *University of Texas at El Paso, El Paso, TX 79978*
[4] *Georgia Institute of Technology, Atlanta, GA 30332*
[5] *Georgia Institute of Technology, Atlanta, GA 30332*

Abstract. NASA Marshall Spaceflight Center is currently in the early stages of developing a Nuclear Thermal Propulsion (NTP) system for deep space exploration. The design utilizes a turbo-pump driven by pre-heated propellant to transport liquid hydrogen propellant from the cryogenic storage tank to the reactor for cooling and propulsion. While this is an efficient system when the reactor is fully powered, it is limited during reactor start-up and shut-down due to high heat production and dissipation. In order to alleviate this limitation of the turbo-pump during start-up and shut-down cycles, small electric pumps in parallel to the NTP turbo-pump were developed. An auxiliary solar power unit (ASPU) was designed to provide power to the electric pump. The proposed system was designed to function on Earth and Mars AMO and it is recommended to continue further study and development.

Keywords: NTP, Nuclear Thermal Propulsion, NASA MSFC.

Further Developments in CeO_2 and Nd_2O_3 Sintering Trials as Analogues for Americium Oxide

Emily Jane Watkinson[1a], Richard M. Ambrosi[1a], Daniel P. Kramer[2], Hugo R. Williams[1b], Mike Reece[3], Kan Chen[3], Huanpo Ning[3], Christofer E. Whiting[2], Chadwick D. Barklay[2], David Weston[1b], Mark Sarsfield[4], Keith Stephenson[5], and Tim Tinsley.[4]

[1a]Department of Physics and Astronomy and [1b]Department of Engineering, University of Leicester, Leicester, LE1 7RH, UK
[2]University of Dayton Research Institute, Kettering Laboratories, 300 College Park, Dayton OH 45469-0172, USA
[3]Queen Mary University of London, School of Engineering and Materials Science, Mile End Rd, London, E1 4NS, UK
[4]National Nuclear Laboratory, Central Laboratory, Sellafield, Seascale, Cumbria, CA20 1PG, UK
[5]European Space Agency, ESTEC, Noordwijk, The Netherlands
+44-116-223-1033; ejw36@le.ac.uk

Abstract. An essential part of the European program to develop americium-based radioisotope power systems and heater units is fuel research. A key area is understanding how americium oxides behave under different environmental conditions, including those relevant to pellet sintering processes. The objective of this early work is to fabricate a pellet that is both physically and chemically stable and has sufficient handling strength. It is highlighted that the form of the americium oxide has yet to be decided. Non-radioactive oxides are being used as analogues to provide an indication of how americium oxides may sinter. In the past, CeO_2 and Nd_2O_3 have been used as analogues for AmO_2 and Am_2O_3 respectively. Sintering studies on these surrogates using 'cold press and sinter' and spark plasma sintering (SPS) are being conducted to assess the most viable processing route.

This study outlines the progress with the ceria sintering trials presented at NETS 2015 (paper #5041). The National Nuclear Laboratory has created batches of ceria with differing particle properties using an oxalate precipitation and then calcination. The results of a 'cold press and sinter' investigation will be presented, where the effect of differing CeO_2 particle properties on pellet sinterability will be described, including ceramography and mechanical properties.

Further analyses of the previously fabricated SPS ceria discs (NETS 2015 paper #5041) have been carried out. Firstly, powder x-ray diffraction with a reference compound has been conducted in an attempt to see if there is any evidence of reduction. Secondly, some of the discs have undergone Vickers hardness testing. A comparison of the latter with the results from cold pressed and sintered discs will be presented. Finally, some preliminary results on the spark plasma sintering studies of Nd_2O_3 will be presented.

Keywords: americium, cerium, neodymium, sintering, space applications.

Moderator Configuration Options for Low-Enriched Uranium Fueled Kilowatt-Class Space Nuclear Reactors

Leonardo de Holanda Mencarini[1,2] and Jeffrey C. King[2]

[1]Divisão de Energia Nuclear – Instituto de Estudos Avançados (IEAv), Trevo Coronel Aviador José Alberto Albano do Amarante, 1, 12228-001 São José dos Campos, SP, Brasil
[2]Nuclear Science and Engineering Program – Colorado School of Mines (CSM),
1500 Illinois St., Hill Hall, Golden, CO 80401
[lmencari, kingjc]@mines.edu

Abstract. The Brazilian Air Force, through its Institute for Advanced Studies (Instituto de Estudos Avançados, IEAv/DCTA), and the Colorado School of Mines (CSM) are studying the feasibility of a space nuclear reactor with a power of 1-5 kW_e and fueled with a Low Enriched Uranium (LEU) fuel. A LEU-fueled space reactor would avoid the security concerns inherent with Highly Enriched Uranium (HEU) fuel and would be attractive to signatory countries of the Non-Proliferation Treaty (NPT) or commercial interests. The HEU-fueled Kilowatt Reactor Using Stirling TechnologY (KRUSTY) designed by the Los Alamos National Laboratory serves as a basis for a similar reactor fueled with LEU fuel. Using the computational code MCNP6 to predict the reactor neutronics performance, the size of the resulting reactor fueled with 19.75 wt% enriched uranium-10 wt% molybdenum alloy fuel is adjusted to match the excess reactivity of KRUSTY. Then, zirconium hydride moderator is added to the core to reduce the size of the reactor. These computational simulations, with reflector thicknesses from 1 cm to 30 cm, determined the optimal reactor configuration in terms of total mass and dimensions while maintaining the same cold clean multiplication factor (k_{eff} = 1.035). This work presents the results of the configuration study, with special emphasis on the comparison between homogeneous and heterogeneous moderator systems. MCNP6™ burnup calculations provided lifetime estimates for the minimum mass unmoderated reactor, the minimum mass homogeneously moderated reactor containing 80 wt.% moderator, and the minimum mass heterogeneously moderated reactor containing 60 wt.% moderator optimized are presented in this paper.

Keywords: LEU-fueled space reactor, moderated system, computational simulations.

The Plutonium-238 Supply Project

R. M. Wham[1], D. W. DePaoli[1], R. W. Hobbs[1], E. D. Collins[1], D. E. Benker[1],
R. S. Owens[1], and R. J. Vedder[1]

[1]*Oak Ridge National Laboratory, Oak Ridge, TN 37831*
865-576-7783; whamrm@ornl.gov

Abstract. The current supply of plutonium-238 (^{238}Pu), used to power deep-space missions for the National Aeronautics and Space Administration (NASA), can support only a limited number of future missions. A new supply chain is planned using existing reactors at Oak Ridge National Laboratory (ORNL) and Idaho National Laboratory (INL) and existing chemical recovery facilities at ORNL.

Two reactors, the High Flux Isotope Reactor at ORNL and the Advanced Test Reactor at INL, can irradiate sufficient neptunium oxide (NpO_2) to produce ~1.5 kg of plutonium product per year. The hot cell facility in the ORNL Radiochemical Engineering Development Center can process approximately 1.5 kg of plutonium per year (based on five campaigns of approximately 100 targets per campaign, with each campaign yielding 0.3–0.4 kg of plutonium product).

Validation and testing activities are underway to provide data for scale-up to production. Target design qualification, target fabrication, and irradiation of targets have been accomplished. Chemical processing development tasks have been completed on selected flow sheet steps at a batch size close to that planned for full-scale production. This presentation describes the ^{238}Pu Supply Project, and highlights key areas that have been developed over the last four years.

Keywords: Plutonium-238; NASA; radioisotope thermoelectric generator

---

CeO_2 - Ceramic Surrogate for $^{238}PuO_2$?

D.P. Kramer, T.M. Pierson, C.O. Sjöblom, S.M. Goodrich,
C.D. Barklay, and C.E. Whiting

University of Dayton Research Institute, Dayton, OH 45469
937-229-1038;daniel.kramer@udri.udayton.edu

Abstract. There are significant costs and radiological difficulties of working directly with $^{238}PuO_{2.}$ $^{238}PuO_2$ in the form of ceramic pellets are employed in current United States produced Radioisotope Power Systems (RPS) which have been utilized for powering spacecraft/landers on various space missions (i.e. Cassini/Saturn, Curiosity/Mars, and New Horizons/Pluto). The $^{238}PuO_2$ pellets are produced utilizing several "classical" ceramic unit operations such as ball milling, sieving, hot pressing, and sintering. Due to the inherent significant difficulties associated with working with $^{238}PuO_2$, over the last several years there have been a number of ceramic based processing studies performed utilizing CeO_2 as a surrogate material for PuO_2. CeO_2 has been employed since it has many expected physical and chemical properties similar to PuO_2 in terms of crystal structure, general oxidation behavior, etc.

As with any surrogate material there are limitations on how well the selected material truly mirrors the actual material of interest. Besides the large radiological differences between CeO_2 (which is non-radioactive) and a $^{238}PuO_2$ fuel pellet (which is highly radioactive and which internally produces ~0.41W_{th}/gram), several other differences have recently been observed during ceramic pellet processing experiments which may limit the application of CeO_2 as a ceramic processing surrogate for $^{238}PuO_2$. A discussion of the application of CeO_2 as a $^{238}PuO_2$ surrogate will be presented.

Keywords: Hot Pressing, CeO_2, Sintering, Pellets, $^{238}PuO_2$

Conceptual Design of a Heat Pipe Cooled Nuclear Reactor Power System for Mars Base

Chengzhi Yao[1], Gu Hu[1], Jiachun Xie[1], Yuan Liu[2], Chunyang Xu[2], Lin Ha[2]

[1]*Department of Reactor Engineering Research & Design, China Institute of Atomic Energy, Beijing 102413, China*
[2]*China Institute of Nuclear Information and Economy, Beijing 102413, China*

Abstract. Nuclear reactor power system has the advantages of high power, long service life and environmental tolerance ability. It is an ideal energy solution option for Mars base and other deep space exploration missions. This paper analyzes the current status of energy that can be used for Mars base, and then presents a 40kWe nuclear reactor power system scheme for Mars surface. The power system is designed to use the lithium heat pipe cooling fast spectrum reactor, stirling engine thermoelectric conversion to produce 40kWe electricity for up to eight years. Waste heat is rejected by potassium heat pipe radiator. The power system scheme is analyzed from the aspects of reactor physics, shielding, thermal safety and structure. The results show that the nuclear reactor power system is reasonable and feasible. It has advantages of low mass, long lifetime, no pumped liquid coolant, and no single point of failure. Main parameters of the system are also given in this paper.

Keywords: Mars base; nuclear reactor power; thermoelectric conversion; stirling engine

---

Aluminum-Beryllium Composite Trade Study for Space Nuclear Applications

Robert Hetterich[1], Travis Belcher[2], Matthew Reilly[3], Tyler Scogin[3], and Joaquin Santecchia[4]

[1]*Lehigh University, Bethlehem, PA 18015*
(516)361-7813; rjh216@lehigh.edu
[2]*University of Texas at El Paso, El Paso, TX 79968*
[3]*Georgia Institute of Technology, Atlanta, GA 30332*
[4]*Arizona State University, Tempe, AZ 85287*

Abstract. With the current drive towards deep space exploration, NASA is investigating nuclear systems as a possible in-space propulsion system for missions beyond low earth orbit. Development of nuclear propulsion is creating a growing need to design engine components made of light-weight materials that still have desirable nuclear properties, such as aluminum-beryllium composites. In traditional aerospace applications aluminum-beryllium composites were used for their light-weight and stiffness, ignoring their nuclear properties. Unfortunately, the major drawback to beryllium is a health hazard due to inhalation of beryllium dust during machining and handling operations known as beryllium poisoning. This deficiency along with the lack of need for light, stiff components in conventional nuclear applications is the main reason that beryllium has seen little development in nuclear and aerospace systems. However, beryllium's light-weight and excellent ability to reflect neutrons combined with the strength and stiffness of aluminum makes aluminum-beryllium composites optimal to use in space-based nuclear applications. In this report a specific example of an aluminum-beryllium composite, AlBeMet® by Materion, was evaluated based on its physical properties for both nuclear and aerospace requirements. The potential advantages and disadvantages of aluminum-beryllium composites are discussed in the context of developing a component for NASA's Nuclear Thermal Propulsion (NTP) engine called an Injectifold. The Injectifold is a combined injector-manifold which directs hydrogen coolant/propellant to different locations in the reactor core while also acting as a neutron reflector. It is recommended that more detailed studies be performed to fully evaluate AlBeMet's physical properties and viability for space nuclear systems.

Keywords: Aluminum-Beryllium Composite, Injectifold, Nuclear Thermal Propulsion, AlBeMet

Nuclear Thermal Propulsion Integrated Injector-Manifold Development

Travis Belcher[1], Robert Hetterich[2], Matthew Reilly[3], Tyler Scogin[3], and Joaquin Santecchia[4]

[1]*University of Texas at El Paso, El Paso, TX 79968*
(281)904-0553; travisb117@gmail.com
[2]*Lehigh University, Bethlehem, PA 18015*
[3]*Georgia Institute of Technology, Atlanta, GA 30332*
[4]*Arizona State University, Tempe, AZ 85287*

Abstract. As research in technology for missions beyond Earth's orbit continues, Nuclear Thermal Propulsion (NTP) is potentially one method to enable deep space propulsion. NTP engines are still in an early stage of research and development, with many new and complicated components that have not yet been developed. One such component is a combined injector-manifold or “Injectifold”, which receives H_2 propellant from several components and distributes it for cooling and other duties within the reactor. Having a detailed design and analysis of the Injectifold is a vital part in the development of the engine, but the Injectifold has numerous requirements that are different from standard injectors or manifolds for existing chemical engines. In this work, an Injectifold model was developed using SolidWorks for mechanical design and COMSOL for CFD analysis. A prototype section was manufactured using 3D sterolithography and subjected to cold flow testing using nitrogen as a surrogate propellant gas. It is expected that the design for the Injectifold will continue to iterate in the future, as more tests are carried out and hard data is gathered.

Keywords: Injectifold, Nuclear Thermal Propulsion, Injector-manifold, In-space propulsion

---

Stirling Research Laboratory Activities at NASA Glenn Research Center

Salvatore Oriti[1]

[1]*Thermal Energy Conversion Branch, NASA Glenn Research Center, Cleveland, OH 44135*
Salvatore.M.Oriti@nasa.gov

Abstract. NASA Glenn Research Center (GRC) has been supporting the advancement of dynamic conversion for space power systems for several decades. A Stirling Research Laboratory (SRL) was established at GRC to evaluate performance of a multitude of Stirling machines. The lab is capable of several activities, such as: unattended extended operation, environmental simulation, performance mapping, and specialized tests as needed. The SRL is currently operating 14 Stirling convertors in unattended extended mode. Data acquisition systems and analysis software have been tailored to continuously gather performance data and observe long-term conversion performance trends. This set of convertors includes several models, four units produced during the SRG110 project, and 10 units produced during the ASRG project. The total runtime of these convertors has reached 580,000 hours. The longest single-unit runtime has reached over 95,000 hours; almost 11 years. The SRL has also has the unique ability to respond to specialized ad-hoc test needs such as the investigation of the ASRG EU2 failure. The ongoing operations in the SRL will be summarized in this paper.

Keywords: Radioisotope Power Systems, Stirling, Energy Conversion.

Advanced Stirling Radioisotope Generator EU2 Anomaly Investigation

Edward J. Lewandowski[1]

[1]*Thermal Energy Conversion Branch, NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135*
Edward.J.Lewandowski@nasa.gov

Abstract. NASA GRC completed the assembly of the ASRG Engineering Unit 2 (EU2) in 2014 using hardware from the now terminated ASRG flight development project. The ASRG EU2 consisted of the first pair of Sunpower's ASC-E3 Stirling convertors mounted in an aluminum generator housing, and Lockheed Martin's Engineering Development Unit (EDU) 4 controller. After just 328 hours of operation, the first power fluctuation occurred on one of the convertors. Over the next 849 hours of operation, the power fluctuations became more frequent on both convertors and larger in magnitude, eventually leading to shutdown of the EU2 in January, 2015. An anomaly investigation was chartered to determine root cause of the power fluctuations and other anomalous observations, to the extent possible. A team with members from GRC, Sunpower, and Lockheed Martin conducted a thorough investigation. Investigation steps included:

- Creation of a fishbone diagram to identify possible causes in convertor, controller, housing, and test rack
- Disassembly and detailed inspection of the generator housing assembly, convertors, and components
- Detailed analysis of EU2 test data
- Finite element analysis and simulation to investigate possible causes
- Additional testing at the component and convertor level to investigate possible causes.

Findings from the disassembly identified proximate causes of the anomalous observations. Using data collected from the 8-month investigation, the team identified a likely root cause of the anomalies. Discussion of the team's assessment of the primary possible failure theories and conclusions is provided. Recommendations were made for future Stirling generator development to address the findings from the anomaly investigation. Additional findings uncovered by the investigation are also discussed.

Keywords: Stirling convertor, Stirling radioisotope generator

---

RPS Program Status

John A. Hamley[1], Thomas J. Sutliff[1], Carl E. Sandifer II[1], and June F. Zakrajsek[1]

[1]*NASA Glenn Research Center, Cleveland, OH 44135*
(216) 977-7430, john.a.hamley@nasa.gov

Abstract. NASA's Radioisotope Power Systems (RPS) Program continues to plan, mature research in energy conversion, and partners with the Department of Energy (DOE) to make RPS ready and available to support the exploration of the solar system in environments where the use of conventional solar or chemical power generation is impractical or impossible to meet potential future mission needs. Recent program's responsibilities include providing investment recommendations to NASA stakeholders on emerging thermoelectric and Stirling energy conversion technologies and insight on NASA investments at DOE in readying a generator for the Mars 2020 mission. This presentation provides an overview of the RPS Program content and status and the approach used to maintain the readiness of RPS to support potential future NASA missions.

Keywords: radioisotope, generator, Mars, Stirling, thermoelectric

Multi-Mission Radioisotope Thermoelectric Generator Experience on Mars

Jennifer Herman, Ronald Hall, Paul Stella, Eric Wood, Thomas I. Valdez, Andrew Mitchell

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena CA 91109

Abstract. The Mars Science Laboratory (MSL) Curiosity rover has been operating on Mars using the F1 Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) for over one and one-half Mars years (over three Earth years). During this extended period, Curiosity has provided a wealth of information about operating with an MMRTG in the Mars surface environment. This paper will discuss MMRTG performance over the life of the mission as affected not only by expected radioisotope degradation, but also by the thermal environment, including seasonal, wind, and time-of-sol effects. Also discussed will be the issues related to MMRTG internal shorts: detection, impacts on operations, and clearing the shorts.

Keywords: RTG, MMRTG, Mars, Surface, Operations, MMRTG internal short

---

Comparison of Neutronic Properties of CERMET and Composite Nuclear Thermal Rocket Cores Utilizing Low Enriched Uranium

Austin Thody[1], Tyler Franklin[1], Andrew Klein[1]

[1]School of Nuclear Science and Engineering, Corvallis, OR 97331
541-737-2343, thodya@oregonstate.edu

Abstract. A nuclear thermal rocket (NTR) delivers efficiencies on the order of three times greater than modern chemical rocket engines. A NTR can deliver payloads to locations in a shorter period of time, possibly shortening an 8 month Martian transit to just three months. NTR technology has been developed and tested in the United States for many decades. This study evaluates two core fuel configurations designed to produce approximately 111 kN of thrust and a specific impulse of at least 900s utilizing Low Enriched Uranium (LEU). One configuration modeled was a Low Enriched Uranium Ceramic Metal (LEU CERMET) core optimized for a fast neutron spectrum. The particular CERMET fuel used in this analysis was a 50-50 mixture of Tungsten and Uranium Oxide. The other core configuration was a Low Enriched Uranium graphite composite fuel (LEU Composite) designed for a thermal neutron spectrum. The Monte-Carlo N-Particle (MCNP) code was used to construct models of the cores and provide an analysis of criticality, reactor performance, and safety. Using the MCNP models, the LEU Composite and LEU CERMET cores were compared and the results of the two MCNP designs evaluated. The LEU composite core model required a larger core radius to achieve criticality, while the CERMET core model is smaller it is also denser and capable of operation at a higher temperature. Though a unique trait to the CERMET core model is that the introduction of a moderator, forces the design into a subcritical state. Both designs have positive attributes though determining which is superior depends on design requirements.

Keywords: LEU, Nuclear, Thermal, Rocket, Composite, CERMET

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

David W. DePaoli, Dennis E. Benker, Lætitia H. Delmau, Jonathan D. Burns, and Robert M. Wham

Nuclear Security and Isotope Technology Division, Oak Ridge National Laboratory,
1 Bethel Valley Road, MS-6423, Oak Ridge, TN 37831
865-574-6817;depaolidw@ornl.gov

Abstract. Oak Ridge National Laboratory (ORNL) is currently working on the plutonium-238 (Pu-238) supply project to reestablish the capability to produce plutonium dioxide (PuO_2) for use in radioisotope power systems for deep space applications. Neptunium-237 oxide currently stored at Idaho National Laboratory is to be fabricated into targets for irradiation at the High Flux Isotope Reactor (HFIR) and the Advanced Test Reactor (ATR). The processing of the irradiated targets will be performed in equipment installed in the hot cells and glove boxes at ORNL's Radiochemical Engineering Development Center. The product PuO_2 will be shipped to Los Alamos National Laboratory. Neptunium will be recovered and recycled for use in target fabrication.

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

Based on results obtained in testing, production will be increased during the next ~ 5 years to reach a rate of 1500 g/y of plutonium containing > 85% Pu-238.

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

---

Development of Cerium-Neodymium Oxide surrogates for Americium Oxides.

Emily Jane Watkinson[1a], Mark J. Sarsfield[2], Richard M. Ambrosi[1a], Hugo R. Williams[1b], David Weston[1b], Nick Marsh[1c], Cheryl Haidon[1c], Keith Stephenson[3], Tim Tinsley[2]

[1a]Department of Physics and Astronomy and [1b]Department of Engineering, [1c] Department of Geology, University of Leicester, Leicester, LE1 7RH, UK
[2] National Nuclear Laboratory, Central Laboratory, Sellafield, Seascale, Cumbria, CA20 1PG ,UK
[3] European Space Agency, ESTEC, Noordwijk, The Netherlands
+44-116-223-1033; ejw36@le.ac.uk

Abstract. Understanding the behavior of americium oxides under conditions pertinent to ceramic pellet fabrication is an essential part of the research program, for European americium-based RPSs and RHUs. The National Nuclear Laboratory is leading the fuel research and is considering a range of americium oxide forms including $AmO_{2-(x/2)}$.

At the temperatures required to sinter americium oxides into dense ceramic pellets, the material loses oxygen and becomes substoichiometric ($AmO_{2-(x/2)}$). As the amount of oxygen in americium oxide changes from AmO_2 to Am_2O_3, crystal phase changes occur and the oxidation state of the americium becomes a mixture of Am^{IV} and Am^{III} within the oxide lattice. The high radiotoxicity of americium-241 makes the element expensive and difficult to work with making the use of simulants necessary where possible. Non-radioactive simulants such as $CeO_{2-(x/2)}$ are unstable due to high reactivity with oxygen, however it was envisaged that a mixed Ce/Nd oxide solid solution, namely $Ce_{1-x}Nd_xO_{2-(x/2)}$, would be stable in air. This was proposed as a surrogate at NETS 2015 where initial results into its synthesis were presented.

The preferred methodology to create americium oxide is via oxalate precipitation from an americium nitrate solution followed by calcination of the americium oxalate to the oxide. Objectives of this research are to determine: a) if the proposed synthesis route could create a $Ce_{1-x}Nd_xO_{2-(x/2)}$ material, for a targeted x-value, as a stable surrogate for $Am^{IV}{}_{1-x}Am^{III}{}_xO_{2-(x/2)}$; b) the impact of oxalate precipitation variables on oxalate particle properties. Material has been created, and a detailed characterization of the material, including powder x-ray diffraction, Raman spectroscopy and quantitative x-ray fluorescence results, will be discussed. The impact of oxalate precipitation temperature on particle shape and particle size is examined. As oxalate particles are decomposed to oxides, it is important to understand how the precipitation process can affect particle shape and size and, therefore, the material sinterability. Finally, the Ce Nd oxide's suitability as a surrogate for $AmO_{2-(x/2)}$ with a targeted x value i.e. O/Am ratio will be discussed.

Keywords: americium, cerium, neodymium, oxide, space applications.

Democritos: Development logic for a demonstrator preparing nuclear-electric spacecraft.

Mr. Stéphane Oriol, Mr. Frédéric Masson [1]
Mr. Tim Tinsley, Dr Richard Stainsby, Mrs Zara Hodgson [2]
Dr. Emmanouil Detsis, Dr. Jean-Claude Worms [3]
Dr Alexander Solodukhin, Dr. Alexander Semenkin [4]
Dr. Frank Jansen, Mr. Waldemar Bauer [5]
Mrs Maria Cristina Tosi, Mrs Simona Ferraris, [6]
Mr. Francois Lassoudiere, Mr. Michel Muszynski, [7]

[1a]CNES, launcher directorate, 52 rue Jacques Hillairet, 75612 Paris Cedex, France
[2]National Nuclear Laboratory, United Kingdom
[3]ESF, France
[4] Keldysh Research Center, Russia
[5]Thales Alenia Space, Italia
[6]DLR, Germany
[7] Airbus-Safran Launchers, France

Contacts: stephane.oriol@cnes.fr, tim.tinsley@nnl.co.uk, edetsis@esf.org

Abstract. The Democritos project aims at preparing demonstrators for a mega-watt class nuclear-electric spacecraft. 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: National Nuclear Laboratory (U.K.), DLR (Germany), The Keldysh Research Center (Russia), Thales Alenia Space Italia (Italy), Airbus-Safran Launchers (France), ESF (France) and CNES (France). IEAV (Brazil) has joined as an observer. Democritos is the follow-up of the Megahit project.

We will present here the development logic for a ground demonstrator, whose target is to test end-to-end nuclear-electric propulsion, with nuclear core replaced by a conventional heater. We will first justify the need for a ground demonstrator, and we will outline our reference vision: the general architecture, and the definition of each sub-system, together with the technologies considered. We will then detail the test objectives and the requirements for the test bench.

We target to test a 200 kWe conversion loop (closed Brayton cycle), linked to lesser power heat-pipe radiator and electrical thrusters. As the ground demonstrator should be modular, several technologies could be tested for each subsystem (kit approach), in particular for electrical thrusters. Our assessment is that it is possible, with technology and test benches already available in Europe and in Russia, to conduct a first test campaign in 2023 with a good representativeness of the spacecraft.

Keywords: Nuclear, electric, space propulsion, Democritos.

High Efficiency Graphene Superlattices based Thermoelement for Radioisotope Thermoelectric Generator Applications

Shakti Kumar Mishra[1], C P Kaushik[1], Biswaranjan Dikshit[2], and Amar Kumar[1]

[1]Waste Management Division and [2]Laser and Plasma Technology Division, Bhabha Atomic Research Centre, Trombay, Mumbai, India 400085
Tel Ph. No. - (+91) 9870086848, (+91) 022 2559 6705; shaktimishra15@gmail.com ; shakti@barc.gov.in

Abstract. The present day's Radio Isotope Thermoelectric Generators are found to be based on segmented thermoelectric unicouples. Due to lower seebeck coefficient of the thermoelement the maximum thermal to electrical efficiency is limited up to 15%. This study deals with the replacement of the existing segmented thermoelectric unicouples with the graphene superlattices to increase the conversion efficiencies significantly. The graphene superlattices nanostructure with periodically arranged metallic electrodes over graphene is deposited on a silicon dioxide substrate. When a defect barrier is introduced in the graphene superlattices and a gate voltage is applied to the metallic electrodes, a great thermoelectric effect is observed to take place near the defect mode. It causes a large seebeck voltage generated between the graphene contact electrodes. Initially the gate voltage is supplied from an external voltage source and later switched over to seebeck potential when it reaches to a stable voltage range. The detailed power balance in terms of gate driving power loss and thermo electric power generated is explained in the paper. The detailed calculations of the seebeck coefficient and thermopower generation are based on a transfer matrix approach. The paper describes the practical feasibility studies of graphene superlattices based RTGs and evaluation of its overall efficiency in contrast to the existing RTGs under the same conditions of temperature gradient & surface area of heat source. Due to higher efficiency, this technique will explore the use of alternative low cost radioisotopes like Americium-241 to replace highly scarce plutonium-238 from today's RTGs without compromising the power output & overall weight.

Keywords: Graphene superlattices, Radioisotope Thermoelectric Generator, Defect barrier, Segmented Thermoelectric Unicouples.

Development of High Efficiency Complex Zintl Phases for Thermoelectric Space Power Generation Applications

Sabah Bux[1], Billy Li[1], Yufei Hu[2], Alexandra Zevalkink[1], Sevan Chanakian[1], David Uhl[1], Susan Kauzlarich[2], Jean-Pierre Fleurial[1]

[1a] Jet Propulsion Laboratory/California Institute of Technology, 4800 Oak Grove Drive, MS: 277-207, Pasadena, CA,
[2]Department of Chemistry, University of California, Davis, One Shields Drive, Davis, CA

818 393 7067; Sabah.K.Bux@jpl.nasa.gov

Abstract. Since the 1960s, the state-of-the-art thermoelectric power systems for space applications has typically been based up on either SiGe alloys or PbTe. Although reliable and robust, the thermal to electric conversion efficiency of these systems remains fairly low at only 6.5% with an average thermoelectric figure of merit, ZT, of about 0.55. A factor of 2 improvements in the thermoelectric conversion efficiency is needed to support future space missions. In recent years, complex Zintl phases such as n-type $La_{3-x}Te_4$ and p-type $Yb_{14}MnSb_{11}$ have emerged as new high efficiency, high temperature thermoelectric materials with peak ZTs of 1.2 at 1275K. The high performance of these materials is attributed to their combination of favorable characteristics such as: semi-metallic behavior due to small band gaps, low glass-like lattice thermal conductivity values due to structural complexity and reasonably large Seebeck values near their peak operating temperatures. Previously we have demonstrated that when these materials are segmented with the lower temperature filled skutterudites (475-875K) that 15% thermal to electric conversion efficiency can be obtained, a factor of 2 improvement over the state of the art couple technologies. Recent work by JPL and collaborating institutions have led to discovery of additional, new, complex p-type Zintl phases which also possess high dimensionless thermoelectric figures of merit (ZT): $Yb_{14}Mg_{1.05}Sb_{11}$ (ZT of 1.2 at 1273 K), Sr_3GaSb_3 (ZT of 0.9 at 1000 K), and $Yb_{1.05}Zn_2Sb_2$ (ZT of 1.1 at 775 K) that could serve as alternate p-type leg materials to the filled skutterudites with comparable conversion efficiency. The p-type Zintl phases could potentially have several advantages over the previous generation couple such as potentially improved chemical and mechanical compatibilities, which could facilitate device development/fabrication and help minimize degradation rates during operation. We will present an overview of recent research efforts at JPL and collaborating institutions on thermoelectric properties of these new p-type Zintls phases as well as validated of the performance of these materials through a proof-of principle TE couple at 473-1273 K. The experimental and predicted performance of the couple in terms of electrical resistance, output voltage, current, power output and efficiency will also be presented and discussed.

Keywords: Thermoelectrics, Zintl phases, devices.

Neutron Irradiation of Bi_2Te_3 Based Thermoelectric Modules for Radioisotope Space Power System Applications

Ramy Mesalam[1a,*], Hugo R. Williams[1a], Richard M. Ambrosi[1b], Daniel P. Kramer[2], Chadwick D. Barklay[2], Jorge García-Cañadas[3], Keith Stephenson[4]

[1a]Dept. of Engineering and [1b]Dept. of Physics & Astronomy, University of Leicester, Leicester, LE1 7RH, UK
[2]University of Dayton Research Institute, 300 College Park Dayton, OH 45469-0102
[3]Dept. of Industrial Engineering Systems and Design, Universitat Jaume I, E-12071 Castellón, Spain
[4]European Space Agency, ESTEC TEC-EP, Keplerlaan 1, 2201AZ Noordwijk, The Netherlands
[*]+44 (0) 116 252 1307; rm467@le.ac.uk

Abstract. The European Radioisotope Thermoelectric Generator (RTG) development programme has selected americium-241 as a fuel. Initial design studies and a successful laboratory breadboard experimental campaign have demonstrated that bismuth telluride based thermoelectric modules are a viable power conversion option with proven commercial manufacturing routes. The performance of the thermoelectric modules following exposure to neutron radiation is of significant interest due to the likely application of RTGs in deep space vehicles or planetary landers requiring prolonged periods of operation. Based on the operational conditions expected to be observed by the thermoelectric modules within a 200 W_{th} americium-241 RTG design, it has been estimated that the hot side of the thermoelectric devices will be exposed to an integrated flux of ~to $5x10^{13}$ neutrons/cm^2. The effect of this neutron dose on thermoelectric material and module performance were investigated experimentally via an acute (~2 hour) exposure in a research reactor at The Ohio State University – Nuclear Reactor Lab (OSU-NRL). In this study, thermoelectric modules with different leg length and microstructure (directionally solidified and polycrystalline) were investigated. After irradiation, a gamma spectrometer was employed to determine if any of the elements in the thermoelectric modules activated prior to shipping. The pre and post effects of thermal-neutron irradiation on the bismuth telluride based thermoelectric modules have been examined using impedance spectroscopy as a module characterisation technique. The effect of annealing and the implications for overall system performance will be reported.

Keywords: RTG, Bismuth Telluride, Impedance Spectroscopy

Radiation Shielding for Nuclear Thermal Propulsion

Jarvis A. Caffrey[1,2]

[1]NASA Marshall Space Flight Center, Huntsville, AL 35812
[2]College of Nuclear Science and Engineering, Oregon State University, Corvallis, OR 97331
(256)544-8464; jarvis.a.caffrey@nasa.gov

Abstract. Design and analysis of radiation shielding for nuclear thermal propulsion has continued at Marshall Space Flight Center. A set of optimization tools are in development, and strategies for shielding optimization will be discussed. Considerations for the concurrent design of internal and external shielding are likely required for a mass optimal shield design. The task of reducing radiation dose to crew from a nuclear engine is considered to be less challenging than the task of thermal mitigation for cryogenic propellant, especially considering the likely implementation of additional crew shielding for protection from solar particles and cosmic rays. Further consideration is thus made for the thermal effects of radiation absorption in cryogenic propellant. Materials challenges and possible methods of manufacturing are also discussed.

Keywords: Nuclear, shielding, radiation

Triton Hopper: Exploring Neptune’s Captured Kuiper Belt Object

Steven R. Oleson and Dr. Geoffrey Landis

NASA John H. Glenn Research Center,
Cleveland Ohio 44135 216-977-7426,
Steven.R.Oleson@NASA.gov

Abstract. Neptune's moon Triton is a fascinating object, a dynamic moon with an atmosphere, and geysers. Triton is unique in the outer solar system in that it is most likely a captured Kuiper belt object (KBO)—a leftover building block of the solar system. When Voyager flew by it was the coldest body yet found in our solar system (33 K) and had volcanic activity, geysers, and a thin atmosphere. It is covered in ices made from nitrogen, water, and carbon- dioxide, and shows surface deposits of tholins, organic compounds that may be precursor chemicals to the origin of life.

Exploring Triton will be a challenge well beyond anything done in previous missions; but the unique environment of Triton also allows some new possibilities for mobility. We developed a conceptual design of a Triton Hopping probe that both analyzes the surface and collects it for use to propel its hops. The Hopper would land near the South Pole in 2040 where geysers have been detected. Depending the details of propulsion chosen the Hopper should be able to jump over 300 km in 60 hops or less, exploring the surface and thin atmosphere on its way. This craft will autonomously carry out detailed scientific investigations on the surface, below the surface (drilling) and in the upper atmosphere to provide unprecedented knowledge of a KBO turned moon and expanding NASA’s existing capabilities in deep space planetary exploration to include Hoppers using different ices for propellant.
Triton is roughly 2700 km in diameter with a surface of mostly frozen nitrogen, mostly water ice crust and core of metal and rock. Its gravity is half that of Earth’s Moon and its atmosphere is 1/70,000th of Earths or 0.3% of Mars.


Figure 1. Triton Hopper Artist Concept

The mission concept studied investigated the full surface and atmospheric phenomenon: chemical composition of surface and near subsurface materials, the thin atmosphere, volcanic and geyser activity. Measurements of all these aspects of Triton’s unique environment can only be made through focused in situ exploration with a well-instrumented craft. And this craft will be provided revolutionary mobility, nearly global, using in-situ ices as propellants. While other concepts have looked at gathering gases at Mars to propel a hopper, long periods of time are needed to gather the thin CO2 atmosphere. Several gases, mainly nitrogen are on the surface in a readily dense ice form and just need to be picked up, vaporized and used for propellant.

This paper will describe the mission options to get to Triton, a notional descent system and the design of a hopper to explore large parts of Triton. Trades on propellant gathering and propulsion will be explained.

Keywords: Radioisotope Power, Triton, Neptune

Influence of the Gd(III) Cation on the Oxygen Exchange Behavior of CeO_2

Christofer E. Whiting*, Daniel P. Kramer, and Chadwick D. Barklay

University of Dayton – Research Institute, 300 College Park, Dayton, OH 45469
**Corresponding Author: (937) 229-2570, chris.whitin@udri.udayton.edu*

Abstract. Oxygen exchange is important in processing RTG fuel because it helps reduce the highly penetrating neutron radiation produced by the fuel. Understanding the mechanisms and kinetics of this reaction will help make sure the RPS program can apply the oxygen exchange reaction in an efficient and well-informed manner at all times, and minimize cost and resources spent on any oxygen exchange development work. Previous studies using CeO_2 and $^{238}PuO_2$ have shown that the oxygen exchange reaction can be influenced by up to three different reaction mechanisms: an internal chemical reaction, the surface mobility of active species and/or defects, and the surface exchange of gas phase oxygen with the lattice. Since these reaction mechanisms have only been partially characterized, obtaining a more thorough understanding of the variables that influence these mechanisms will improve our ability to apply the oxygen exchange reaction in a well-informed manner. One area of study that could prove informative is how the oxygen exchange reaction is influenced by oxygen vacancies. In order to observe how fixed oxygen vacancies influence the reaction rate, several oxygen exchange experiments were performed on 10% Gd doped CeO_2 (i.e., $Ce_{0.9}Gd_{0.1}O_{1.95}$). CeO_2 is a common non-radioactive surrogate for PuO_2, and doping CeO_2 with trivalent cations is a common practice for introducing oxygen vacancies. Preliminary analysis of the results indicates that the reaction rates are slower, and the activation energy for the internal chemical reaction is larger. This corroborates previous conclusions indicating that the internal chemical reaction is not limited by oxygen mobility or diffusivity. It also suggests that either the presence of significant oxygen vacancies or the trivalent dopant increases the energy required to begin the process of oxygen exchange. More detailed analysis of the data obtained from these experiments was performed, and the results will be discussed.

Keywords: Gd Doped CeO_2, Oxygen Exchange, Kinetics.

Modeling the Gas Phase Chemistry Inside an RTG

Christofer E. Whiting[1*], Emily Jane Watkinson[2a], Chadwick D. Barklay[1], Daniel P. Kramer[1], Hugo R. Williams[2a] and Richard M. Ambrosi[2b]

[1] University of Dayton – Research Institute, 300 College Park, Dayton, OH 45469-0172, USA
[2a] Department of Engineering and [2b] Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, UK
** Corresponding Author: (937) 229-2570, chris.whiting@udri.udayton.edu*

Abstract. Understanding the gas phase chemistry inside an RTG is beneficial because: 1) it will aid in predicting the reactivity of chemical impurities and contaminants, 2) allow more accurate thermal modeling of the gas phase, 3) help predict potential chemical reactions with other RTG components, and 4) more accurately predict the properties of the fuel pellet. One of the well-known properties of CeO_2, PuO_2, and AmO_2 is their ability to release oxygen and become slightly substoichiometric (i.e., PuO_{2-x}) at high temperatures and low oxygen potentials. When in an RTG-like environment, oxygen released from these materials can interact with the graphite found in the safety envelope and form CO and CO_2. Precise quantities of these gases are controlled by the temperature of the system, temperature of the solid oxide, and the oxygen potential within the system. Previously, a model was developed that took a closed, isothermal system containing carbon and the oxide of interest and predicted the gas phase chemistry. This model utilized the well-understood thermodynamics of the interactions between C, CO, CO_2, and the oxygen potential along with several semi-empirical equations that define the relationship between temperature, oxygen potential, and the substoichiometric oxide. While this previous model was a good first step, an RTG is not isothermal. Introducing a thermal gradient into the model requires more than just modifications to some of the equations; it also requires a better understanding of an RTG's kinetic and thermodynamic environment. Recent experiments using CeO_2 as a surrogate have helped provide this information, allowing the previous model to be modified. This improved model will be benchmarked against the CeO_2 empirical data in order to validate the model's accuracy. Then, assuming that PuO_2 and AmO_2 based RTGs operate on the same kinetic and thermodynamic principles, the behavior of these two RTG fuels will be modeled. This improved model will provide a significantly more thorough understanding of an RTG's gas phase chemistry.

Keywords: RTG Chemistry, Plutonium(IV) Oxide, Americium(IV) Oxide, Oxygen Potential.

Impact of Carbon on the Oxygen Potential of a High Temperature System Containing CeO_2 as a PuO_2 Surrogate

Christofer E. Whiting*, Howard Knachel, Daniel P. Kramer, and Chadwick D. Barklay

University of Dayton – Research Institute, 300 College Park, Dayton, OH 45469
**Corresponding Author: (937) 229-2570, chris.whitin@udri.udayton.edu*

Abstract. Chemistry inside the GPHS system is surprisingly complex, yet an accurate understanding of this chemistry is required to fully predict the behavior of the species present inside an RTG. Fortunately, all of the major chemical forces that influence the GPHS chemistry can be linked together through the oxygen potential. Accurately predicting the oxygen potential, therefore, becomes the key to unlocking the chemical behavior of the GPHS system. A major reason why predicting the oxygen potential inside of a GPHS is so challenging is because PuO_2, when exposed to high temperatures and low oxygen potentials, can release oxygen and become slightly reduced (i.e., PuO_{2-x}). Oxygen released from the PuO_2 can then react with nearby carbon to form a specific ratio of CO and CO_2 that will be controlled by the temperature of the system and the chemical potential generated by the PuO_{2-x}. Inside a sealed RTG, like an MMRTG, all of these chemical reactions and forces will eventually reach equilibrium. Understanding how the oxygen potential behaves during reduction and at equilibrium requires a more accurate understanding of the kinetic and thermodynamic environment. To that end, an experimental system has been constructed using CeO_2, a PuO_2 surrogate that behaves similarly when exposed to high temperatures and low oxygen potentials, in order to better understand the forces and boundary conditions that drive the oxygen potential. These experiments show that the composition of the gas phase is controlled by the system temperature, the C/CO/CO_2 equilibrium thermodynamics, and the chemical potential produced by the CeO_{2-x}. It will also be shown that the thermal gradient present in the system induces a chemical potential gradient. The thermal gradient does not, in fact, cause a major chemical composition gradient due to changes in the equilibrium thermodynamics. Using this information, an equation is derived that will allow the determination of the oxygen potential at any point of interest given the temperature of the carbon, the temperature at the point of interest, and the pressure of CO or CO_2 in the system. Kinetic experiments indicate that rate of reaction is very slow, and in order to reach equilibrium, the system may need to react for days, or longer. These slow reaction kinetics appear to be tied to the reaction of CO_2 with carbon, indicating that the reaction rate can be increased by increasing the partial pressure of CO_2 and/or surface area of the carbon.

Keywords: GPHS Chemistry, CeO_2, Carbon Redox Chemistry, Oxygen Potential.

Space Propulsion Optimization Code Benchmark Case: SNRE Model

Vishal Patel[1,2], Michael Eades[1,3], Claude Russell Joyner II[4]

[1]Center for Space Nuclear Research, 995 University Blvd., Idaho Falls, ID 83401
[2]Department of Nuclear Engineering, Texas A&M University, College Station, TX 77843
[3]2Nuclear Engineering Program, The Ohio State University, Columbus, OH 43201
[4]Aerojet Rocketdyne, P.O. Box 109680, West Palm Beach, Florida 33410, USA
832-334-9762; vkp93@tamu.edu

Abstract. The Small Nuclear Rocket Engine (SNRE) was modeled in the Center for Space Nuclear Research's (CSNR) Space Propulsion Optimization Code (SPOC). SPOC aims to create nuclear thermal propulsion (NTP) geometries quickly to perform parametric studies on design spaces of historic and new NTP designs. The SNRE geometry was modeled in SPOC and a critical core with a reasonable amount of criticality margin was found. The fuel, tie-tubes, reflector, and control drum masses were predicted rather well. These are all very important for neutronics calculations so the active reactor geometries created with SPOC can continue to be trusted. Thermal calculations of the average and hot fuel channels agreed very well. The specific impulse calculations used historically and in SPOC disagree so mass flow rates and impulses differed. Modeling peripheral and power balance components that do not affect nuclear characteristics of the core is not a feature of SPOC and as such, these components should continue to be designed using other tools. A full paper detailing the available SNRE data and comparisons with SPOC outputs will be submitted as a follow-up to this abstract.

Keywords: Nuclear Thermal Propulsion & MCNP & SNRE

Timelines for Supporting a Nuclear-enabled NASA Mission: Does a Temporal Phase Mismatch Between NASA and DOE Exist?

Stephen G. Johnson[1], Carla C. Dwight[1], Kelly Lively[1] and Young Lee[2]

[1]*Idaho National Laboratory, Idaho Falls, ID 83415*
[2] *NASA Jet Propulsion Laboratory, 4800 Oak Grove Dr. Pasadena Ca 91109-8001,*
208-533-7496; Stephen.johnson@inl.gov

Abstract. The timelines developed and previously implemented for supporting a nuclear-enabled NASA mission launch will be examined for the Department of Energy and National Aeronautical and Space Administration components in support of an anticipated New Frontiers class mission. These timelines are both reasonably well defined and implemented in the past. However, mission execution experiences have indicated that some temporal phase issues between DOE and NASA could arise depending on key decision points and mission funding profiles. These possible temporal issues will be clearly identified and discussed, using a notional NASA New Frontiers class mission. Two scenarios will be discussed from a radioisotope power systems perspective: (1) a 1-unit multi-mission radioisotope thermoelectric generator (MMRTG) enabling a New Frontiers mission and (2) a 3-unit MMRTG enabled New Frontiers mission. The primary objective of this paper will be to inform prospective mission customers who might be affected by the various timelines with commonalities and conflicts between the two processes in order to call for an early resolution of identified temporal phase mismatch(es) if possible.

Keywords: New Frontiers mission, timeline, MMRTG, DOE, NASA

Progress on the Sol-Gel Microsphere Technology Demonstration for Pu-238 Heat Sources

Jeffrey A. Katalenich and Sergey Sinkov

Pacific Northwest National Laboratory, Richland, WA 99354
(509) 375-2244; jeffrey.katalenich@pnnl.gov

Abstract. A technology demonstration project is being pursued at the Pacific Northwest National Laboratory (PNNL) to develop sol-gel techniques for the dust-free processing of plutonium-238 oxide ($^{238}PuO_2$) used in heat and power sources. The project aims to replace current powder processing and ball milling operations with a solution-based gelation method that produces very few fine particulates. Minimizing the amount of fines produced is especially attractive for plutonium processing due to the extreme dispersibility and contamination hazards associated with $^{238}PuO_2$ fines. Efforts at PNNL have included establishing sol-gel production and processing capabilities in both radiological and non-radiological spaces. A stepped approach is being pursued whereby cerium oxide is used as a nonradioactive surrogate prior to work with plutonium. A non-radioactive sol-gel microsphere capability is being used to produce cerium oxide microspheres for initial efforts to press microspheres into pellets. Additionally, the process will be validated with Pu-239 prior to using Pu-238 in order to discriminate between chemical and radiological effects on the process. The ability to produce, process, and analyze plutonium oxide microspheres has been installed in a radiological glove box and is being commissioned for operation. A chemical flowsheet for preparing plutonium microspheres is being developed using 20 grams of Pu-239. Planned work includes the production and analysis of Pu-239 and Pu-238 oxide microspheres as well as pressing small plutonium oxide pellets.

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

Development of a Sliding and Compliant Cold Side Thermal Interface for a Thermopile Inside a Terrestrial Mini-RTG

Nicholas R. Keyawa, Poyan Bahrami, Gabriel Molina, Velibor Cormarkovic,
Samad Firdosy, Richard Ewell

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
Phone: +1-818-354-4355, E-mail: Nicholas.r.keyawa@jpl.nasa.gov

Abstract. Radioisotope Thermoelectric Generators (RTGs) could be an ideal power source for potential applications in remote areas on Earth that require little to no maintenance and stable electrical power over the course of decades. As thermoelectric technology improves, RTG designs are pushing the boundaries in how small they can become in order to meet applications that would require a few watts of electrical power in tight and compact areas. Due to the compact nature of these Mini-RTG concepts, an innovative cold-side thermal interface is required for the thermoelectrics in order to provide a sufficient thermal heat sink to optimize the performance of the generator. During assembly, the insertion of the thermoelectrics into the Mini-RTG would require that the cold-side thermal interface slide while maintaining good thermal contact once fully inserted and assembled. In addition, the cold-side thermal interface needs to provide compliance in order to minimize load stresses in the thermoelectrics due to environment vibrations and shocks from potential dropping/handling. In order to assess the performance of the cold-side thermal interfaces, an Electrical Power Demonstrator for a Mini-RTG concept was designed and fabricated to mimic the thermal performance of a 1/8th section of the generator. In addition, a Thermal Contact Resistance Measurement (TCRM) Fixture was designed and developed to more rapidly assess the thermal performance of various cold-side thermal interface candidates. The cold-side interface is required to operate at around 170C, and provide a temperature delta of less than 20C between the cold side of the thermopile and the contact wall, assuming about 2.2 W/cm^2 of heat transfer through the thermopile. Two potential cold side thermal interfaces were tested: a stainless steel flat spring, and a carbon velvet thermal pad. Each interface was tested using the EPD and TCRM fixture. For testing with the EPD, various aerogel insulation and thicknesses were explored, in addition to operation in both high vacuum and argon cover gas. Results indicate that the carbon velvet thermal pad is the more promising cold-side thermal interface. For future work, the physical properties of the carbon velvet thermal pad are to be tweaked to optimize the thermal performance for this unique potential Mini-RTG application. In addition, bonding techniques of the carbon velvet thermal pad to the cold side of the thermopile are to be further developed.

Keywords: Cold side thermal interface, thermopile, Mini-RTG concept, carbon velvet thermal pad, electrical power demonstrator, thermal contact resistance

---

An Update on the eMMRTG Skutterudite-Based Thermoelectric Technology Maturation Project

T. Caillat[1], I. Chi, S. Firdosy[1], C. –K. Huang[1], K. Smith[1], J. Paik[1], P. Gogna[1],
K. Yu[1], J.- P. Fleurial[1], R. Bennett[2], and S. Keyser[2]

[1]*Jet Propulsion Laboratory/Caltech, MS 277-207, 4800 Oak Grove Drive, Pasadena CA, 91107*
[2]*Teledyne Energy Systems, Inc., 10707 Gilroy Road, Hunt Valley, MD 21301*
818-354-0407 ; thierry.caillat@jpl.nasa.gov

Abstract. The overall objective Skutterudite Technology Maturation (STM) project is to advance JPL-developed skutterudite (SKD) technology to an enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) flight unit development readiness by end of FY2018. Conversion efficiency values on the order of 9% have been demonstrated for SKD-based un-segmented couples when operating at a hot-junction of 600C and a cold-junction of 200C. This represents ~ a 25% improvement over the conversion efficiency of PbTe/TAGS MMRTG couples at beginning-of-life (BOL). The STM project has entered its third year at the beginning of FY16. During the first two years of the project, the Jet propulsion Laboratory (JPL) and Teledyne Energy Systems Inc. (TESI) have collaborated to transfer the technology to TESI, to develop the manufacturing capabilities for SKD TE materials and couples at TESI, and to demonstrate their performance and initiate a lifetime performance prediction. Great progress has been made towards those goals and this paper will summarize this progress as well as the remaining challenges to fully mature this technology.

Keywords: eMMRTG, skutterudite, thermoelectric.

Pyroshock Dynamic Loading Impacts on Thermoelectric Module Assemblies and Bi-Couples in Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs)

Terry J. Hendricks, David J. Neff, Nicholas R. Keyawa, Bill J. Nesmith, Poyan Bahrami, Armen Derkevorkian, Ali R. Kolaini

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Abstract. Pyroshock environments created by shock separation devices in the close proximity to the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) generated undesired dynamic responses during MMRTG testing on the Mars Science Laboratory (MSL) project. Pyroshock-driven dynamic responses during the MMRTG qualification unit and engineering unit dynamic tests caused the power output from each system to temporarily decrease by 2-4%, and then fully recover within 10's of minutes after the shock signature subsided. An effort is underway to understand the root causes of these temporary MMRTG 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, an update on recent findings from MMRTG pyroshock high-frequency dynamic analyses and thermoelectric (TE) bi-couple test results are presented to highlight the potential root-cause mechanisms leading to the power loss and recovery pathways. The dynamic analyses have shown that critical MMRTG internal electrical and thermal interfaces are disrupted and potentially rapidly disconnected (within milliseconds) during the transient shock loads. Bi-couple dynamic load testing shows that their electrical and thermal interfaces then do not reversibly recover for relatively long periods of time (10s of seconds), which leads to MMRTG bi-couple voltage and power losses. The pyroshock dynamic analyses show that this disruption/recovery scenario can be projected to occur across multiple couples of the 768-couple MMRTG due to incident and reflected shock waves throughout a TE module bar assembly. The impact of shock wave propagation on MMRTG structural compression components and interfaces, subsequently altering the electrical circuit networks, electrical contact interfaces, thermal networks and interfaces within the MMRTG, is then evaluated and quantified through electrical and thermal modeling to predict potential MMRTG-wide power losses, all of which is correlated and tied to system fault tree pathways to identify and prioritize likely causes and recovery mechanisms. This work reviews the latest TE bi-couple testing results obtained from new bi-couple dynamic load testing at representative MMRTG bi-couple temperatures (T_h = 510°C, T_c = 210°C), based on the pyroshock-driven TE module bar dynamic response results. These new dynamic load test results have qualitatively replicated the power loss and recovery profiles and observations originally seen in the MMRTG engineering unit testing under pyroshock environments, and provided new understanding into its potential causes and recovery profile. This study suggests that the combination of computational and experimental techniques is providing new insights to track and predict MMRTG pyroshock effects and impact magnitudes. This paper will also discuss current plans to design and execute a TE-module-assembly pyroshock test to demonstrate pyroshock-driven effects on power at the TE module assembly-level. The TE-module-assembly pyroshock test will simulate the 3-dimensional pyroshock wave propagation into and through the TE module assembly and measure the resultant dynamic effects (i.e., local accelerations and displacements) on TE bi-couples and module power output. 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, bi-couple dynamic loading

---

A Technology Roadmap for Thermoelectric-Based Space and Terrestrial Power Systems

Jean-Pierre Fleurial[1] and Terry Hendricks[1]

[1] Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109
jean-pierre.fleurial@jpl.nasa.gov : 818-354-4144

Abstract. Thermoelectric (TE) power sources have consistently demonstrated their extraordinary reliability and longevity for deep space missions as well as for some unique terrestrial applications where unattended operation in remote locations is required. They are static devices with a high degree of redundancy, no electromagnetic interferences, with well documented "graceful degradation" characteristics and a high level of modularity and scalability. They are also tolerant of extreme environments (temperature, pressure, shock and radiation). The development of new, more efficient materials and devices is the key to improving existing space power technology and expanding into efficient, cost-effective systems using high grade heat sources, generated through fossil fuel combustion or from waste exhaust streams in transportation, industrial and military applications. The Thermoelectric Technology Development Project (TTDP), one of two technology development projects of NASA's Radioisotope Power Systems (RPS) Program, has established a roadmap for the advancement and maturation of higher performance TE materials and devices. We describe this roadmap and how these technologies might be infused into next generation RPS with significantly higher conversion efficiencies and specific power, and could facilitate the development of highly modular system architectures thanks to highly versatile common device building blocks. We also discuss how these technology investments have helped renew interest in potential terrestrial applications using high grade heat sources (above 800 K), and we highlight some recent efforts, near term opportunities, and the unique challenges in terrestrial applications whose solutions can further benefit and promote RPS program goals.

Keywords: Radioisotope, Fission, Power Generation, Thermoelectric, Module.

Preliminary Analysis of Low Enriched Uranium (LEU) Ultra High Temperature Nuclear Thermal Rockets Capable of 1100s Specific Impulse

Kelsa Benensky[1,5], Meng-Jen Wang[2,5], Juha Nieminen[3,5], Michael Eades[4,5], and Steven Howe[6]

[1]*Department of Nuclear Engineering, University of Tennessee, Knoxville, TN 37996*
[2]*Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061*
[3]*Department of Astronautical Engineering, University of Southern California, Los Angeles, CA 90089*
[4]*Nuclear Engineering Program, The Ohio State University, Columbus, OH 43210*
[5]*The Center for Space Nuclear Research, 995 University Blvd., Idaho Falls, ID 83401*
[6]*Talos Power LLC, 480 Sunnyside Rd., STE 4, Idaho Falls, ID 83402*

Abstract. The current reference design for a nuclear thermal rocket (NTR) requires a specific impulse (I_{sp}) of 900 seconds, corresponding to six month transit times to Mars. Development of high performance nuclear thermal propulsion (NTP) fuel forms capable of withstanding ultra-high temperatures would enable year-long round-trip missions to Mars with four month transit times. With the addition of enriched hafnium carbide (HfC), solid-solution carbide fuel forms have the potential of operating at temperatures greater than 3400 K and could allow for low-enriched uranium (LEU) engine designs with specific impulse values of greater than 1100 s. This presentation will discuss the operating potential, design methodology, and neutronic studies completed to support the development of a HfC solid-solution NTP fuel form and corresponding engine.

Keywords: Nuclear Thermal Propulsion, Fuel Elements, Hafnium Carbide, Tri-Carbide, Solid Solution Carbide, Low Enriched Uranium

---

Radioisotope Power Systems (RPS) for Emerging Power Needs of Deep Space SmallSats, CubeSats and Deployed Payloads

Young H. Lee[1], Brian K. Bairstow[1], and Joseph E. Riedel[1]

[1] *NASA Jet Propulsion Laboratory, California Institute of Technology*
4800 Oak Grove Dr. Pasadena Ca. 91109-8001,
818-354-1326; young.h.lee@jpl.nasa.gov

Abstract. Small-sized Radioisotope Power Systems (RPS) could very likely be an enabling technology for future small spacecraft exploration of the outer planets, including investigating possible habitable environments of the moons of Jupiter and Saturn. Though NASA has flown many spacecraft equipped with RPS to enable their missions, the total mass of each spacecraft has been well in excess of 1,000 kg. The emergence of CubeSat technology is pointing the way to a future featuring very small spacecraftwith low cost, but very high capabilities. However, solar system exploration beyond Mars may prove very challenging for the use of such small vehicles without the use of radioisotope power.

This paper examines several potential power architectures utilizing small-sized RPS. The performance of these architectures is matched to the anticipated needs of SmallSats and CubeSats in the outer solar system, where solar power becomes impractical for such small craft. This analysis highlights a gap in existing power systems that could address this emerging power need. In particular, this paper describes possible RPS-based power solutions for small vehicles that require much less than 100 W_e.

Keywords: RPS, Small RPS, Power Needs, SmallSat, CubeSat, Deployed Payloads

Production of Polonium-209 Using Nuclear Reactor as Radioisotope Fuel for Space Nuclear Power

Jun Nishiyama

Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology
2-12-1-N1-19 Ookayama, Meguro-ku, Tokyo 152-8550, Japan
Telephone: +81-3-5734-3849, E-mail: jun-nishiyama@nr.titech.ac.jp

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 specific power (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. In the previous work, the production rate of Po isotopes with proton accelerators was evaluated using the PHITS code with a simple geometry. As the results, the beam current of 14 A with 40 MeV proton energy was required for annual production of 1kg ^{209}Po. However, this requirement for accelerator is quite large in comparison with the current accelerator technology. In this study, the production rate using the reaction chain of ^{209}Bi (n, γ)^{210}Bi (β decay) ^{210}Po (n, 2n)^{209}Po was estimated. 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 rate, calculations for the reaction rate of Bi and Po isotopes in Lead-Bismuth cooled fast reactors were performed using the MVP code. The TENDL nuclear data library was used for neutron reaction cross section of the Po isotopes. The calculation results showed that the amount of Po-210 in the equilibrium state was 1.4 (kg/m^3) assuming the averaged neutron flux level of 10^{16} (1/cm^2/s). In this situation, annual production per unit volume was $5.4 \times 10^{-4} R_{c/l}$ (kg/m^3/y), where $R_{c/l}$ is the volume ratio of Lead-Bismuth coolant in the core and in the loop. This result strongly depended on the core design. Especially, the neutron flux upper the threshold energy of the ^{210}Po (n, 2n)^{209}Po reaction (7.7 MeV) was very significant parameter.

Keywords: Polonium-209, Polonium-208, Plutonium-238, Radioisotope Fuel, RTG, Lead-Bismuth cooled fast reactor.

Idaho National Laboratory Radioisotope Power Systems Nuclear Operations: Preparations, Documentation, Readiness Assessments and Conduct of Operations Supporting a Nuclear-enabled NASA Mission

Kelly L. Lively, Eric S. Clarke, Robert P. Gomez

Idaho National Laboratory, Idaho Falls, ID 83415 208-533-7388;
Kelly.Lively@inl.gov

Abstract. The Radioisotope Power Systems (RPS) Program, located at Idaho National Laboratory (INL), is responsible for assembling, testing, and delivering plutonium oxide-fueled RPSs for use in powering missions in remote, harsh environments such as deep space. An informative presentation will be given discussing the preparations, documents, readiness assessments, human capital and conduct of operations involved in performing nuclear operations to support providing these systems to end users for the Department of Energy (DOE). DOE is the start-up authority for performing nuclear operations. Readiness for start-up is determined through independent assessment against established acceptance criteria to ensure activities can be performed safely and within a well-defined nuclear safety envelope. There is also an RPS Program approval element requiring additional readiness review before nuclear operations can begin. The programmatic readiness review is performed to ascertain readiness to proceed with nuclear operations from the perspective of product quality. The assessments and reviews are conducted in series in the following order of progression: Management Self Assessment (MSA), Contractor Readiness Assessment (CRA), DOE Readiness Assessment (DOE RA) and lastly, the Programmatic Production Readiness Review (PRR). The CRA, DOE RA, and PRR requires an independent technical review team. Twelve assessment criteria are reviewed and a selection of the criteria is identified for review on a graded approach. Typically, the assessments/review criteria requires, at a minimum, review of operating instructions to ensure technical safety requirements are adequately identified, review of training records to ensure personnel are adequately trained to perform the specified work scope, personnel are interviewed to determine adequacy of level of knowledge for work scope, and a high-fidelity performance of the operation to ensure the operating instructions and conduct of operations are adequate to perform the work scope. As each assessment/review is conducted a formal report delineating any issues in the form of findings, observations, and noteworthy practices will be issued. Before start-up approval is obtained all issues must be resolved to the satisfaction of the individual teams. Start-up notification is formally communicated by memorandum from DOE. Programmatic approval is documented in a Segmented Readiness Review where vested Program representatives in the RPS community (to include DOE NE 75 and DOE ID representatives) ensure personnel, documentation, and materials are in place to perform the activity. The four assessments/reviews can be completed in a 16-week period of time, provided ample resources and a relatively small work scope is identified. RPS assembly and testing operations to support the Mars 2020 Mission, the next planned space mission using a nuclear power system, will require about of year of assessments/reviews before the nuclear operations are performed.

Keywords: INL, Operations, Assessments, DOE

Comparison of LEU and HEU Cermet Nuclear Thermal Propulsion Systems at 16,000 lbf thrust

Michael Eades[1,2], Wesley Deason[1], C. R. Joyner II1[3]

[1]Center for Space Nuclear Research, 995 University Blvd., Idaho Falls, ID 83401
[2]Nuclear Engineering Program, The Ohio State University, Columbus, OH 43201
[3]Aerojet Rocketdyne, P.O. Box 109680, West Palm Beach, Florida 33410, USA
740-262-2804; eades.15@osu.edu

Abstract. There has been recent interest in Low Enriched Uranium (LEU) Nuclear Thermal Propulsion (NTP) systems, but few studies showing how they directly compare to Highly Enriched Uranium (HEU) NTP systems in terms of performance. Presented is a comparison of cermet nuclear thermal propulsion point designs using Low Enriched Uranium (LEU) and Highly Enriched Uranium (HEU) at 16,000 lbf thrust. The point designs called are labeled TRIBLE-LEU and TRIBLE-HEU (Tiny Rocket Investigating Balanced Launch Economics). The TRIBLE-LEU and TRIBLE-HEU studies were developed using the SPOC (Space Propulsion Optimization Code), for a similar mission and with similar design constants. By keeping many of the factors leading into the design of TRIBLE-LEU and TRIBLE-HEU consistent, a fair and meaningful comparison between LEU and HEU cermet systems can be accomplished. It was found that TRIBLE-LEU and TRIBLE-HEU had comparable mass, Isp, and pressure drop. In addition, the unique technological issues that associated with LEU cermet and separately a HEU cermet system are discussed.

Keywords: Nuclear Thermal Propulsion, HEU, LEU, 16k lbf, Low Enriched Uranium, High Enriched Uranium, SPOC

Progress on Development of Skutterudite Thermoelectrics for Space Power Applications

Russell Bennett[1], Thomas Hammel[1], Steven Keyser[1], Tim C. Holgate[1], Thierry Caillat[2]

[1]Teledyne Energy Systems Inc., Hunt Valley, MD 21031
[2]Jet Propulsion Laboratory, Pasadena, CA 91109
410-891-2302, Russell.bennett@teledyne.com

Abstract: Skutterudite thermoelectric couple technology developed at the Jet Propulsion Laboratory is being transferred to Teledyne through a NASA technology transfer program. The goal is to develop a thermoelectric couple which can replace the PbTe/TAGS couples in the MMRTG and create an enhanced MMRTG (eMMRTG) which will provide greater performance with minimum risk and system changes. This eMMRTG power system will offer improved beginning-of-life performance with even larger improvements at end-of-mission. Significant progress has been made on materials production and scale-up. Thermoelectric couples have been fabricated and tested and couple power test results show excellent agreement with predictions. Overall development progress will be presented.

Keywords: Thermoelectric, RTG, power, eMMRTG

A LEU Cermet Point Design: The Space Capable Cryogenic Thermal Engine (SCCTE)

Michael Eades[1,2], Vishal Patel[1,3] Wesley Deason[1]

[1]Center for Space Nuclear Research, 995 University Blvd., Idaho Falls, ID 83401
[2]Nuclear Engineering Program, The Ohio State University, Columbus, OH 43201
[3]Department of Nuclear Engineering, Texas A&M University, College Station, TX 77843
740-262-2804; eades.15@osu.edu

Abstract. The Space Capable Cryogenic Thermal Engine (SCCTE), a Low Enriched Uranium (LEU) W-UO_2 cermet fuel, $ZrH_{1.8}$ moderated Nuclear Thermal Propulsion (NTP) Concept. The SCCTE project was undertaken by collaboration with NASA Marshall Space Flight Center (MSFC) and Center for Space Nuclear Research (CSNR) to investigate the applicability of LEU cermet NTP technology for a human Mars mission in the 2030's time frame. SCCTE was designed with Space Propulsion Optimization Code (SPOC) and large design studies conducted high performance computing resources. The result of the large design studies found an optimum rocket design point for the 35,000 lbf thrust SCCTE with an Isp of 894 s and a reactor mass of 2558 kg. Presented in this work is an overview of the SCCTE design, background on the design methodology, and of technical issues associated with LEU cermet systems.

Keywords: Nuclear Thermal Propulsion, HEU, LEU, 16k lbf, Low Enriched Uranium, High Enriched Uranium, SPOC

WORPH: An Open Source Code for NTR Infinite Lattice Studies Using MCNP and Serpent

Michael Eades[1], Paolo Venneri[2]

[1]Nuclear Engineering Program, The Ohio State University, Columbus, OH 43201
[2]Department of Nuclear & Quantum Engineering, KAIST, Daejeon, Republic of Korea
740-262-2804; eades.15@osu.edu

Abstract. WORPH (Well Organized Reactor Physics) is an open source MATLAB code for infinite lattice studies applied to common Nuclear Thermal Rocket (NTR) geometries. WORPH generates inputs for the established Monte Carlo reactor analyses codes MCNP and Serpent. Infinite Lattice calculations are much less computationally intensive than full core calculations, but are still able to identify and quantify many phenomena. Users of WORPH are able to easily modify key reactor parameters such as fuel geometry, fuel type, fuel to moderator ratio, tie tube, geometry, moderator type, and cross section selection. Furthermore, WORPH has features to parse and visualize results. WORPH is freely available and written in a user friendly MATLAB environment with the intention that it can be used in the future by students and researchers. In addition, infinite lattice studies require less computational resources and are well suited for students that do not have access to high performance computer resources.

Keywords: Reactor Physics, Infinite Lattice, Nuclear Thermal Propulsion, Open Source

Assessment of Future New Frontiers Mission Concepts Utilizing the MMRTG and eMMRTG Radioisotope Thermoelectric Generators

Robert.L.Cataldo[1], David F. Woerner[2]

[1] *NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135,*
[2] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91009*
Robert Cataldo, (216) 977-7082, robert.l.cataldo@nasa.gov

Abstract. The NASA Science Mission Directorate (SMD) is contemplating offering radioisotope power systems (RPS) for the next New Frontiers solicitation (known as NF-4). The release of the Step 1 NF-4 Announcement of Opportunity (AO) is currently planned for late 2016, with a projected mission launch in the 2022-2024 time frame based on past mission Phase A-D schedule timelines. Two New Frontiers missions have been launched to date: Pluto New Horizons (PNH) in January 2006, and the Juno mission to Jupiter in August 2011; the OSIRIS-Rex mission to sample an asteroid is scheduled for launch in September 2016. PNH is the only NF mission to utilize a RPS for spacecraft power. This choice was due primarily to the limited intensity of sunlight at Pluto; Juno and OSIRIS-Rex are both solar-powered spacecraft, due to their mission designs and science/operational needs. PNH is powered by a General Purpose Heat Source-Radioisotope Thermoelectric Generator (GPHS-RTG, designated as F-8), which was originally designed and built for the Galileo, Ulysses, and Cassini missions. The currently available RPS is the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG); one MMRTG is powering the Curiosity Mars rover and another is the baseline power system for the Mars 2020 rover mission. The MMRTG is designed to operate in both Mars' environment and in the vacuum of space. NASA is developing a concept called the enhanced MMRTG (eMMRTG) that would utilize new, more efficient thermoelectric materials and energy conversion technology, and could provide an approximate 25% increase in initial power output over the MMRTG. Therefore, if RPS were to be offered in the NF-4 AO, the number of RTGs required to satisfy the mission power requirements must be estimated to adequately plan related resources should an RPS-powered mission be selected. To that end, an assessment of end-of-mission (EOM) power required by the focused mission concepts in New Frontiers, targeting seven potential mission destinations, was performed. This report estimates and discusses the power needs for potential applications, considering both the MMRTG and eMMRTG for these New Frontiers-focused mission concepts.

Keywords: Radioisotope Thermoelectric Generator, New Frontiers, Mission Power Requirements

---

Characterizing the Thermal Conductivity of CBCF: a Review and Recent Advances

Nidia C. Gallego, Glenn R. Romanoski, Ralph B. Dinwiddie, Wallace D. Porter,
Hsin Wang, and George B. Ulrich

Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN
37831 865-241-9459; gallegonc@ornl.gov

Abstract. Carbon-Bonded Carbon-Fiber (CBCF) insulation is an important component in radioisotope thermoelectric generators. Thermal conductivity in vacuum is a critical property of this material for qualification as well as for its application. The accepted practice for determining the thermal conductivity of CBCF is to measure the thermal diffusivity, α, by the flash method and then using the bulk density, ρ, and specific heat, C_p, to compute the thermal conductivity, $K = \rho \cdot \alpha \cdot C_p$. A recent revision of the guideline to measure the thermal diffusivity of CBCF ensured conformance to ASTM E1461-13 "Standard Test Method for Thermal Diffusivity by the Flash Method." The revised guideline also allows for flexibility on the required vacuum levels, as long as the vacuum level reading for a given instrument falls within the plateau or pressure-independent region of the thermal diffusivity. In addition, the use of a loss number for validation of measurements was replaced with an equipment performance verification step using a Standard Reference Material, and adjustment of pulse conditions to ensure the input power does not drive the detector out of the linear range. A historical account of the important findings made regarding the measurement of thermal diffusivity (and calculated thermal conductivity) of CBCF insulation during the past 35 years (1980 – 2015) will also be presented.

Keywords: Thermal conductivity, carbon bonded carbon fiber, CBCF.

Dynamics Modeling and Heat Flow Optimization of an Enhanced MMRTG

David Woerner

Power and Sensor Systems Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109,
Office: 818-393-2000; david.f.woerner@jpl.nasa.gov

Abstract. JPL, NASA, and Teledyne Energy Systems, Inc and Aerojet Rocketdyne have been engineering a potentially enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) in consultation with the US Department Of Energy (DOE) over the last 3 years. The eMMRTG concept is a derivative of the successful MMRTG; the Mars Science Laboratory (MSL) rover Curiosity is powered by an MMRTG. The eMMRTG concept incorporates new thermoelectric couples and makes some relatively modest changes to a proven design. These changes promise a boost of Beginning Of Life power of at least 25% and a boost at End Of Design Life of greater than 50%.

In the last year, work on the eMMRTG design included modeling the dynamics of an eMMRTG in a representative launch, random vibration environment and an analysis of the heat flow into the thermoelectric couples with a goal to optimize heat flow and thereby improve modeled temperatures and remove uncertainties. These tasks largely completed an update of the MMRTG dynamics model to eMMRTG design and lent confidence in the newly built model's ability to support thermal design trades. This paper will review the findings and resultant recommendations for future work.

Keywords: enhanced MMRTG, MMRTG, RTG, Multi-Mission.

Status of Stirling Power System Modeling Capabilities

Jonathan Metscher[1], Terry Reid[1], Paul C. Schmitz[2]

[1]Thermal Energy Conversion Branch, Power Division, NASA Glenn Research Center, Cleveland, OH 44135
[2]Power Computing Solutions, Inc., Avon Lake, OH 44012
216-433-6870, jonathan.f.metscher@nasa.gov

Abstract. The Thermal Energy Conversion Branch at NASA's Glenn Research Center (GRC) conducts a wide array of modeling efforts to support the development of Stirling power systems. Models are a simplified representation of a system that enables performance to be analyzed and aid in the development and testing of hardware. Stirling convertors such as Sunpower's Advanced Stirling Convertor (ASC) are modeled using the Sage modeling software. Sage is a specialized software package for 1-D modeling of Stirling-cycle engines and coolers, as well as linear alternators. Sage simulation results provide steady state performance predictions and is computationally faster than other 2-D or 3-D modeling methods. This allows Sage models to be used early in the design process of Stirling convertors to conduct component level trade studies and design optimization. Sage models are also used to provide convertor performance predictions to larger generator level thermal models. Models are further refined with test data leading to more accurate performance predictions, which are useful for simulating possible operational scenarios. Matlab and the additional toolbox Simscape (part of Matlab/Simulink) are also used for Stirling convertor modeling. Sage models are coupled with Matlab to provide scripted simulations and automatic data analysis. Simulink is a graphical mathematical modeling tool while Simscape is a multi-domain physical network modeling tool based on Bond graphs. The Simscape modeling environment enables 1-D dynamic modeling of physical systems using a library of fundamental physical components that are used as building blocks to develop more complex physical models. Custom components specific to Stirling modeling have also been made using the Simscape modeling language, enabling the development of a Stirling generator model. This modeling capability allows system characteristics such as conductivity, heat capacity, Stirling convertor performance, etc., to be parameterized such that trades can be performed on the generator design. It additionally allows the study of transient behavior of the convertor in controller failure scenarios as well as behavior of the generator in the event of a convertor failure. The modular capability of the Simulink/Simscape environment allows the convertor to be studied in a variety of generator configurations. ANSYS Fluent is a 3-D computational fluid dynamics (CFD) software that utilizes the fundamental equations of fluid dynamics and heat transfer to produce detailed temperature distributions of Stirling power systems as well as in depth convertor performance predictions. CFD models are used to investigate the effect of geometric parameter variations on convertor performance and to predict a convertor's sensitivity to changes in operating conditions. CFD simulations provide both static and dynamic performance results that aid in understanding measured convertor data in more depth. Fluent models can be combined with other ANSYS products such as ANSYS Maxwell, a 2-D/3-D electromechanical modeling software, to perform multi-disciplined analyses. Linear alternators used in Stirling convertors are modeled with Maxwell for performance and efficiency predictions and aid in development of alternators capable of operating at higher temperatures.

Keywords: Stirling, Advanced Stirling Convertor, ASC, Sage, Simscape

A Six Component Model for Dusty Plasma Nuclear Fission Fragment Propulsion

Rodney L. Clark[1], Robert B. Sheldon[1,2]

[1]Grassmere Dynamics, LLC, Gurley, AL35748-8909
[1,2]RBSheldon Consulting, Huntsville, AL 35803
256-6538592; rbs@rbsp.info

Abstract. A dusty plasma nuclear fission fragment rocket employs a cloud of nanometer-sized dust of fissionable material inside a magnetized moderator from which the fission fragments emerge to form the high velocity exhaust. The negatively charged dust, free electrons, and positively charged ions form a 3-component "dusty plasma" that can be confined and manipulated as charged fluid. The fission fragments exit the ~100nm dust with velocities approaching 5% the speed of light, giving this rocket an ISP~500,000 seconds, as discussed in previous papers. Despite 1-10 GW power densities, this ultra-high ISP results in very little thrust, which is only ideal for a starship drive. The thrust can be increased by expanding the size of the dusty plasma core, however, collisions with the dust lower the ISP to ~70,000s and the dust begins to vaporize. In this paper we explicitly backfill the dusty plasma with neutral hydrogen gas to provide a mass-loading of the fission fragment exhaust that increases the thrust, making a variable-ISP rocket. The neutral gas also heats and transfers thermal energy to the dust, which must be accounted for in this design. We model this novel rocket with a six-component dusty plasma, finding the temperature equilibrium between fissile dust, hydrogen gas, free electrons, free protons, fission fragments, and photons. For certain operating regimes, the dusty plasma rocket is competitive with nuclear thermal rockets, but by throttling the hydrogen, can transition to a fuel-saving high-ISP engine for interplanetary missions. We considered the possibility of using the fission fragments to heat a deuterium-tritium gas mixture to fusion temperatures, but several hurdles must be overcome for this fission-fusion concept to work.

Keywords: Fission fragment nuclear rocket, dusty plasma, thermal equilibrium, variable ISP

Nuclear Systems Kilopower Project Update

Donald T. Palac, Marc A. Gibson, Lee S. Mason[1], Michael G. Houts[2], Patrick McClure[3], R. Chris Robinson[4]

[1]*NASA Glenn Research Center, Cleveland, OH 44135*
(216) 977-7094, d.palac@nasa.gov
[2] *NASA Marshall Space Flight Center, Huntsville, AL 35812*
[3]*Los Alamos National Laboratory, Los Alamos, NM 87545*
[4] *Y-12 National Security Complex, Oak Ridge, TN 37831*

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 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 two elements. The primary element is the Kilopower Prototype Test, also called the Kilopower Reactor Using Stirling Technology (KRUSTY) Test. This element consists of the development and testing of a fission ground technology demonstrator of a 1 kW_e fission power system. A 1 kW_e system matches requirements for some robotic precursor exploration systems and future potential deep space science missions, and also allows a nuclear ground technology demonstration in existing nuclear test facilities at low cost. The second element, the Mars Kilopower Scalability Study, consists of the analysis and design of a scaled-up version of the 1 kW_e reference concept to 10 kW_e for Mars surface power projected requirements, and validation of the applicability of the KRUSTY experiment to key technology challenges for a 10 kW_e system. If successful, these two elements will lead to initiation of planning for a technology demonstration of a 10 kWe fission power capability for Mars surface outpost power.

The main purpose of the Nuclear Systems Kilopower Project is the development and testing of a fission power system technology demonstration based on a 1 kW_e space fission power system concept. A 1 kW_e Kilopower system will use four pairs of Stirling engines, with each pair generating 250 W_e. All technology objectives can be achieved by a ¼ power demonstration 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 reflector and shielding for nuclear testing. Non-nuclear testing of a simulated system will be conducted to validate component and system design prior to the nuclear test, and to allow development and demonstration of nuclear experiment procedures. A non-nuclear electrically-heated demonstration of sodium heat pipe heat transfer from an electrically heated stainless-steel core simulator has been conducted at GRC, establishing adequate heat transfer of the critical core-to-heat-pipe interface. A second non-nuclear test will include replacement of the stainless steel core with an electrically heated non-fissionable Depleted Uranium (DU) core, and addition of Stirling engine power conversion and heat rejection in a configuration identical to the planned nuclear test. Once the balance of plant has been tested and the reactor core has been fabricated, the KRUSTY nuclear experiment will be assembled and tested at the Device Assembly Facility at the Nevada National Security Site.

Keywords: Space Fission Power, Space Nuclear Power.

Advanced Hybrid SiO_2 Aerogel for eMMRTG Flight Module

Ying Song[1], Russell Bennett[1], Tom Hammel[1], Steven Keyser[1],
Jong-Ai Paik[2], Steve Jones[2], and Thierry Caillat[2]

[1] *Teledyne Energy Systems, Inc., Hunt Valley, MD 21031*
[2] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109*
(410) 891-2304; Ying.Song@Teledyne.com

Abstract. All spacecraft, satellites, and landers require the use of thermal insulations considering the extreme environments encountered in space and on extraterrestrial bodies. Silica aerogel has been intensively investigated and reviewed as a potential thermal insulation candidate for space application due to its unique properties such as exceptionally porous structure, high specific surface area, light weight, and extremely low thermal conductivity. It may effectively reduce heat losses and provide sublimation suppression at the surface of the thermoelectric (T/E) materials. Supercritical extraction has been a conventional method to approach the synthesis of silica aerogel. However, its drying process requires high temperature and high pressure that not only costs much energy but also limit its application. Ambient drying technique is one of the alternative processes of aerogel synthesis that introduce the possibility of using aerogel as thermal insulation in a wide variety of instance where supercritically dried aerogel cannot be used. Particularly, its advantages are in site production using the cast-in ability of silica aerogel in T/E devices. However, the use of ambiently dried aerogel has been challenging because of its brittleness and shrinkage. After TESI adapted JPL's technology to synthesize silica aerogel at ambient conditions, further modification and optimization work have been conducted to improve the aerogel structure and performance. A new hybrid generation of SiO_2 aerogel through ambient drying process has been successfully developed and assessed at TESI. The mechanical strength and thermal stability have been significantly enhanced while the low thermal conductivity is still retained to fulfill thermal insulation requirements. In this presentation, the development work will be presented. More details in characterization and performance of the advanced hybrid SiO2 aerogel will be reviewed and discussed.

Keywords: Hybrid Silica aerogel, ambiently dried, thermoelectrics, RTG

Power Generation Alternatives for Deep Space Exploration in the Solar System

Patricia M. Beauchamp[1], John Elliott[1], James A. Cutts[1] and the JPL A-Team[1]

[1] *NASA Jet Propulsion Laboratory, California Institute of Technology,*
4800 Oak Grove Dr. Pasadena Ca. 91109-8001
818-354-0529; patricia.m.beauchamp@jpl.nasa.gov

Abstract. Missions to the outer planets utilize radioisotope power systems (RPS) when they enable, or significantly enhance, the ability of the mission to meet its scientific and operational goals. Recently two missions such as *Juno*, and the proposed *Europa* mission to the Jupiter system, (5.2AU) have both turned to solar power. Moreover, proposals have been made to use solar power as far as Saturn (9.6 AU) and more imaginative advanced mission concepts have been developed for using solar power out to Pluto (40 AU). But what are the practical limits and constraints of the different power sources and how will new technology affect the trade space for future orbiter and flyby missions?

Power for *in situ* missions involves a different set of trades. For Mars, mobility, scaling relationships and target location all factor into that trade. Solar power was a practical solution for Spirit/Opportunity. However, for the larger Curiosity vehicle, RPS was selected to provide adequate power to drive the larger vehicle and offer resilience to dust storm degradation and other operational constraints.

While the power trades for landers are generally more permissive for solar power, there are circumstances where the solar input is attenuated or periodically or permanently occulted, such as the atmospheres of Titan and Venus. What new technologies could impact the trade space for landers?

Exploring planetary bodies with atmospheres, e.g. Venus, Titan, and Mars, presents some special challenges for solar power usage and also requires RPS to be designed to tolerate atmospheric environments as opposed to the vacuum of space. The greatest challenges may be posed at Venus. Solar power is practical for balloons operating within the upper clouds. But how deep into the atmosphere can it be used? Are there other options for generating power at Venus that exploit thermal gradients or velocity shears in the atmosphere? And more importantly, how long can a power source operate at Venus surface conditions (450°C and ~92 bar CO_2)? Can solar panels operate effectively at the attenuated light levels on the hot surface? What RPS options are compatible with the Venus surface environment?

For some *in situ* applications, stored energy may be the right solution. While scientific measurements and communication may required modest amounts of power, the lifetime of the vehicle may be limited by the power needed to heat the battery and payload compartment to its minimum operating temperatures. In this context, the development of low temperature batteries and electronics can be enabling. How long for example could such a vehicle operate at Europa with stored energy? And how would it fare at Titan?

As exploration proceeds throughout the solar system with more complex missions, power becomes an increasingly critical issue. Understanding the limitations and requirements of power systems is critical. On-going progress with existing space power technologies and potential development of new technologies could change the traditional power trade space that has existed between radioisotope power, solar power, and energy storage/ generation devices. A science driven study looked at the possible mission scenarios and what ranges of technologies could accomplish planetary missions in the future. This paper describes a potential power generation roadmap for solar system exploration that could guide the development of new technologies.

Keywords: Power Generation Roadmap, Power Systems, Power Trades, Space Explorations

A Gigawatt Space Power System using Dusty Plasma Fission Fragment Reactor

Robert B. Sheldon[1,2], Rodney L. Clark[1]

[1]*Grassmere Dynamics, LLC, Gurley, AL35748-8909*
[1,2]*RBSheldon Consulting, Huntsville, AL 35803*
256-6538592; rbs@rbsp.info

Abstract. A dusty plasma nuclear fission fragment reactor employs a cloud of nanometer-sized dust of fissionable material inside a magnetized moderator. The negatively charged dust, free electrons, and positively charged ions form a 3-component "dusty plasma" that can be confined and manipulated as charged fluid. The nanometer dust has such a large surface to volume ratio, that it is capable of remaining solid at 3000K while radiating 10-100 GW of radiant power, as discussed in previous work. This ``nuclear light bulb" power source solves the intractable problems of previous designs: confining charged dust rather than hot gas; eliminating the need for quartz windows; and not requiring gas cooling. Unlike previous designs the radiation is in the near-infrared, so that conversion to electricity is inefficient. While Brayton-cycle power converters are often advertised as a space power solution, they require additional radiators and additional mass. Several recent technologies, however, can convert NIR into electric power at improved efficiency and with no moving parts. We model the conversion efficiency of a space system consisting of radiators, moderator, direct fission-fragment converter, and IR converter panels as a viable solution to the growing need for MW space power systems.

Keywords: Fission fragment nuclear reactor, dusty plasma, mass to power ratio, infrared power conversion

---

Advanced Stirling Convertor
ASC-E3 Project Summary

Josh Collins, Kyle Wilson, and Mary Anne Dunlap[1]

[1] *Sunpower, Inc. 2005 East State Street, Suite 104, Athens, OH 45701*
740-594-2221;josh.collins@ametek.com

Abstract. Sunpower's Advanced Stirling Convertor (ASC) development began as a NASA Research Announcement contract in 2003. The ASC demonstrated high power conversion efficiency which made it an attractive option for potential use in future Radioisotope Power Systems (RPS). In 2006, per NASA and DOE direction, the ASC was adopted for use in the Advanced Stirling Radioisotope Generator (ASRG) integrated Federal Project. The ASC design was subsequently tailored to progressively include generator-specific interfaces and specifications. Three engineering unit builds have been completed since 2006 totaling 20 units. Each build – ASC-E (four convertors), ASC-E2 (eight), and ASC-E3 (eight) – included production units delivered to NASA GRC for use in performance, extended operation, life certification, reliability, tactical, and verification testing. The focus of this paper is the ASC-E3 project at Sunpower.

The primary purposes of ASC-E3 engineering units were to serve as production pathfinders, provide test units to GRC that were representative of full Flight quality hardware, and provide units suitable for use in early ASRG system integration efforts. In a collaborative effort between NASA GRC, DOE, Lockheed Martin, and Sunpower, the ASC-E3 project plan incorporated a phased approach to demonstrating full Flight processing at Sunpower. The first pair of convertors was primarily used to demonstrate the Flight design performance, finalize and qualify Flight processes, demonstrate production capability within Sunpower's new facility, and exercise the Flight quality system. The second pair of convertors validated ASC performance, built upon the lessons learned from the first pair, incorporated testing and processing to Flight approved documentation, and introduced processing within a Class 8 clean room. The third and fourth pairs of convertors were to build upon lessons learned producing the second pair of convertors and be produced according to the full Flight build documentation, test sequence and quality system. Prior to the initiation of the third pair, the ASRG program was terminated due to budgetary constraints. Despite ASRG termination, the importance of high conversion efficiency for potential future RPS was recognized by NASA. The third and fourth pairs of ASC-E3 convertors were produced for NASA GRC under a restructured project plan. Minimal changes were made to the Flight Quality Project Plan and Product Specification in order to maintain the intent, rigor, pedigree, and processing of the Flight project. The final ASC-E3 convertor will be delivered to NASA GRC in December 2015. This paper will summarize the accomplishments, performance achieved, and challenges overcome during the ASC-E3 contract.

Keywords: Sunpower, ASC-E3, Stirling, convertor, RPS

Advanced Stirling Convertor (ASC) Design & Technology Assessment White Paper

Josh Collins and Kyle Wilson[1]

[1] Sunpower, Inc. 2005 East State Street, Suite 104, Athens, OH 45701
740-594-2221;josh.collins@ametek.com

Abstract. Sunpower's Advanced Stirling Convertor (ASC) development began as a NASA Research Announcement contract in 2003. The ASC demonstrated high power conversion efficiency which made it an attractive option for potential use in future Radioisotope Power Systems (RPS). In 2006, per NASA and DOE direction, the ASC was adopted for use in the Advanced Stirling Radioisotope Generator (ASRG) integrated Federal Project. The ASC design was subsequently tailored to progressively include generator-specific interfaces and specifications. Three engineering unit builds have been completed since 2006 totaling 20 units: ASC-E (four convertors), ASC-E2 (eight), and ASC-E3 (eight) – included production units delivered to NASA GRC for use in performance, extended operation, life certification, reliability, tactical, and verification testing.

In December 2014, NASA GRC requested Sunpower undertake an activity to develop, evaluate, and recommend changes to the existing ASC design that could enhance robustness and reliability of the convertor and that could be implemented in potential future convertor builds without significant development. For the purpose of this exercise, robustness is defined as tolerance to off-nominal operation without significantly reducing life of the convertor. Reliability is defined as nominal operation over the range of conditions prescribed in the Product Specification (e.g. Beginning of Mission and End of Mission, High and Low Reject). Additional consideration, though with less weighting, was given to design and processing changes that could increase manufacturability and/or reduce schedule, thereby reducing cost. A reasonable reduction in ASC performance is permitted in exchange for a significant increase in robustness and/or reliability.

The Sunpower ASC team - engineering, technician, quality, and management personnel – identified design changes after comprehensively reviewing the Sunpower ASC lessons learned log, build experiences, technical challenges, and customer feedback. Feedback and review was also requested of and provided by the NASA GRC team. Each potential change was ranked based on the criteria listed above. Those with the highest impact were selected for evaluation through analysis, fabrication and/or testing at the component, subassembly, and/or convertor level. Convertor-level testing was also employed to determine convertor effects as appropriate.

Sunpower efforts were divided into two phases and delivered as two report volumes. Volume 1, delivered in August 2015, focused on design changes within the existing 80W convertor and design changes that could be evaluated in a short period of time. Volume 2, which will be delivered in December 2015, focuses on design changes that required longer evaluation times, lessons learned from Volume 1, potential design changes which would require moderate levels of development prior to implementation, and generator level recommendations.

This paper will summarize the evaluation process and recommended design changes primarily focused on increasing robustness and reliability of the ASC design.

Keywords: Sunpower, ASC, Technology Assessment, Stirling

Maturing Technologies for Stirling Space Power

Scott D. Wilson

Thermal Energy Conversion Branch, Power Division, NASA Glenn Research Center, Cleveland, OH 44135 (216) 433-6681; scott.d.wilson@nasa.gov

Abstract. Stirling Radioisotope Power Systems (RPS) are being studied as an option to provide power on future space science missions where robotic spacecraft will orbit, flyby, land or rove and may use less than a quarter of the plutonium needed by the currently available RPS to produce about the same power. The Radioisotope Power System Program Office (RPSPO) managed Stirling Cycle Technology Development Project (SCTDP) continues development of Stirling-based systems and subsystems, including hardware demonstrations of generator, convertor, and controller technologies. Also being developed under the Stirling Technology Research area, are less mature technologies with a focus on demonstration in representative environments to increase the technology readiness level. Matured technologies are evaluated for potential selection in future generator designs. Stirling Technology Research tasks focus on a wide variety of objectives, including increasing temperature capability to enable new environments, improving reliability or system fault tolerance, reducing mass and/or size, and developing alternative designs. Increased temperature capability on magnets and organic materials could enable new environments mission environments not previously considered for Stirling applications. Some of these material temperature limits are rated higher than others so a continual effort is made to identify new materials or formulations that exceed the previous limits. As temperature limits increase, so does the margin and reliability for anticipated environments. Examples of improving system fault tolerance are given in the development of a variable conductance heat pipes and an active vibration control system. To enable emergency heat removal from a heat source, a variable conductance heat pipe was demonstrated to reject enough heat to keep the heat source and Stirling temperatures below critical levels. Also, an active vibration reduction system was used to demonstrate vibration reduction to relatively low levels for a single convertor, characterizing baseline power and mass costs to an ASRG-like design. The goal of reducing size and mass has been successful for multi-layered insulation and radial heat pipe rejection designs. The improved efficiency of a multi-layered insulation package was verified in a vacuum test at high-temperature where it was found that overall insulation size could be reduced for equivalent performance. Typical Stirling heat rejection flanges involve removing heat through solid conduction paths that also serve as structural components. A radial heat pipe design has been demonstrated to provide equivalent performance with a 4x mass reduction over existing design. Alternative designs for convertors, controllers, and generators is important to explore technical and cost options for future, unknown trade spaces where some designs or cost models are more advantageous to the government than others. An alternative controller design, developed by APL and NASA GRC, has completed verification testing to evaluate electrical interactions between a generator, electrical controller, power bus, and representative spacecraft electrical loads. Also, an alternative building block generator design has been explored through simulation to provide benefit to system reliability through redundancy of the Stirling components used in the system while enabling missions to right size the power system based on spacecraft need. These tasks are being performed under the RPSPO's SCTDP, where Stirling Technology Research is being performed to develop Stirling-based systems and subsystems for future space science missions.

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

Optimization of High Temperature Zintl Materials for the *p*-Leg of Thermoelectric Space Power Generation

Susan M. Kauzlarich[1], Jason H. Grebenkemper[1], Yufei Hu[1], Dashiel Barrett, Elizabeth Wille[1], Sabah Bux[2]

[1]*Department of Chemistry, University of California, Davis, One Shields Drive, Davis, CA 95616*
[2]*Jet Propulsion Laboratory/California Institute of Technology,*
4800 Oak Grove Drive, MS: 277-207, Pasadena,CA, 91109
530 752 47457; smkauzlarich@ucdavis.edu

Abstract. Compounds of the $Yb_{14}MnSb_{11}$ structure type are the highest efficiency bulk *p*-type materials for high temperature thermoelectric applications, with reported zTs as high as ~1.3 at 1275 K. Further optimization of zT for this structure type is possible with alloying and replacement of various elements in the general formula, $A_{14}MSb_{11}$. Because of the small amount of M required compared with A and Sb, development of a simple route has been challenging. A simple synthetic route for $Yb_{14}MnSb_{11}$ has been developed utilizing a combination of ball milling and spark plasma sintering (SPS) to produce fully dense samples for measurement. Additional phases have been prepared via ball milling and heat treatment, followed by SPS to ensure fully dense pellets for measurements. These results provide a reliable method of bulk synthesis of this Zintl phase and open the way for discovery of new compounds with potential for even higher zT. The development of this approach along with new phases and their thermoelectric characterization up to 1200 K will be presented.

Keywords: Thermoelectrics, Zintl, high temperature materials processing, RTG.

Performance Testing of the EU/QU MMRTG

Chadwick D. Barklay[1], Boyd A. Tolson[2], Carl W.O. Sjöblom[1], and Richard J. Harris[1]

[1]*University of Dayton Research Institute, 300 College Park, Dayton, OH 45469*
[2]*UES, Inc. 4401 Dayton Xenia Rd., Dayton, OH 45432*

Abstract. The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) Lifecycle Testing Laboratory is operated by the University of Dayton Research Institute (UDRI), which is dedicated to conducting life-cycle testing of electrically heated versions of the MMRTG. Since there are only two MMRTG electrically-heated thermoelectric generators (ETG) available for testing, a Test Plan Development Working Group was established to determine and prioritize the performance testing that is being conducted with the Engineering Unit (EU) and Qualification Unit (QU) ETGs. This working group is comprised of subject matter experts from the U.S. Department of Energy (DOE), the National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC), NASA Jet Propulsion Laboratory (JPL), Idaho National Laboratory (INL), Oak Ridge National Laboratory (ORNL), UDRI, Aerojet Rocketdyne, and Teledyne Energy Systems. The highest priority testing was concluded by the working group to be: 1) To determine the impact of thermal cycling on thermoelectric components by characterizing the evolution of the thermoelectric/electrical properties of the EU as a result of thermal cycling the ETG through a Martian SOL repeatedly; and 2) to characterize the effect of a simulated cruise-phase environment on the QU by evaluating the change in performance of the ETG before and after a cruise-phase simulation. The results of these ongoing test campaigns will be discussed.

Keywords: MMRTG, Life-Testing, Diurnal Cycling

Optimized Alkali Metal Backup Cooling System Tested with a Stirling Convertor

Calin Tarau[1], Carl L. Schwendeman[1], Nicholas A. Schifer[2] and William G. Anderson[1]

[1]*Advanced Cooling Technologies, Inc., 1046 New Holland Ave., Lancaster, PA 17601*
[2]*NASA John H. Glenn Research Center, 21000 Brookpark Rd. MS 301-2 Cleveland, OH 44135*
717-295-6066; calin.tarau@1-act.com

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 by bypassing the heat during stops. 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 these 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 convertor. The semi-optimized system features a two-phase radiator and is significantly smaller and lighter than the prior prototype to reflect a higher level of flight readiness. The VCHP is designed to activate and remove heat from the GPHS during stoppage 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 convertor 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 measurements or procedures. This paper presents the design of the VCHP and its test results with a Stirling convertor at GRC. Tests were carried for multiple on and off cycles to demonstrate repeatability. The impacts associated with the addition of the VCHP to the system are also addressed in terms of mass and additional heat losses due to the presence of the VCHP.

Keywords: Variable Conductance Heat Pipe, Stirling Radioisotope Generator, Backup Cooling System, Alkali Metal Variable Conductance Heat Pipe,

---

Status of the Development of Low Cost Radiator for Surface Fission Power - II

Calin Tarau[1], Taylor Maxwell[1], William G. Anderson[1], Corey Wagner[1],
Matthew Wrosch[2], Maxwell H. Briggs[3]

[1]*Advanced Cooling Technologies, 1046 New Holland Ave. Lancaster PA 17601*
[2]*Vanguard Space Technologies, Inc., San Diego, CA 92126*
[3]*NASA Glenn Research Center, Cleveland, OH, 44135*
717-295-6066; calin.tarau@1-act.com

Abstract. NASA Glenn Research Center (GRC) is developing fission power system technology for future Lunar surface power applications. The systems are envisioned in the 10 to 100kWe range and have an anticipated design life of 8 to 15 years with no maintenance. NASA GRC is currently setting up a 55 kWe non-nuclear system ground test in thermal-vacuum to validate technologies required to transfer reactor heat, convert the heat into electricity, reject waste heat, process the electrical output, and demonstrate overall system performance. The paper reports on the development of the heat pipe radiator to reject the waste heat from the Stirling convertors. Reducing the radiator mass, size, and cost is essential to the success of the program. To meet these goals, Advanced Cooling Technologies, Inc. (ACT) and Vanguard Space Technologies, Inc. (VST) are developing a single facesheet radiator with heat pipes directly bonded to the facesheet. The facesheet material is a graphite fiber reinforced composite (GFRC) and the heat pipes are titanium/water Variable Conductance Heat Pipes (VCHPs). By directly bonding a single facesheet to the heat pipes, several heavy and expensive components can be eliminated from the traditional radiator design such as, POCO™ foam saddles, aluminum honeycomb, and a second facesheet. In a previous paper it was shown that the final design of the waste heat radiator is modular having independent GFRC panels for each heat pipe. This work reports testing results of both a single radiator module and an eight module radiator cluster. These tests were carried in both ambient and vacuum. While the single radiator module was tested in the ACT's vacuum chamber, the eight heat pipe module cluster was tested in NASA GRC's vacuum chamber because of size related reasons. The results for both articles show good agreement with the predictions and will be presented in the final paper.

Keywords: Heat Pipe Radiator, Surface Fission Power, Low Cost Radiator, Single Face Sheet Radiator

Alkali Metal Heat Pipes for Kilopower

Calin Tarau, William G. Anderson and Derek Beard

Advanced Cooling Technologies, 1046 New Holland Ave. Lancaster PA 17601
717-295-6066; calin.tarau@1-act.com

Abstract. Future space transportation and surface power applications will require small fission reactors for power generation. Under the Kilopower program, NASA GRC is developing a 1 to 10 kWe nuclear reactor for space and planetary applications. The heat generated by the reactor would be collected and transferred to a series of Stirling convertors or thermoelectric converters for power generation. This heat collection and transfer can be done by high-temperature alkali-metal heat pipes. Arterial heat pipes are the current default design for spacecraft nuclear reactors; however, de-priming of the artery during ground testing is a serious potential problem. Hybrid grooved and arterial self-venting heat pipes offer potential benefits over the standard arterial heat pipes: 1. The grooves cannot be de-primed, and 2. The self-venting pipes are less susceptible to de-priming, as well as having a lower mass. Unlike earlier alkali metal heat pipes, these heat pipes must be capable of operating in the following orientations: 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 vertical ground testing, the heat pipe wick will de-prime, and will need to re-prime for operation in space after launch. The self-venting arterial wick design was chosen for these heat pipes, since this design is known to automatically re-prime after de-priming. Moreover, previous work showed that arterial self-venting heat pipes offer higher performance than the hybrid grooved heat pipes. However the alkali metal heat pipes with these wicks have never been tested. Advanced Cooling Technologies, Inc. (ACT) developed alkali metal (sodium) heat pipes for space nuclear fission reactors under a NASA Glenn Research Center SBIR Program. Full scale alkali metal heat pipes were designed, fabricated, tested and delivered to NASA for further testing and integration into the depleted uranium based energy conversion system. Three heat pipes are self-venting arterial while other nine are thermosyphons. All the heat pipes are gas charged to facilitate startup. Moreover, two of the heat pipes have a larger gas reservoir that allows them to be shut down with the intention of simulating heat pipe failure in the system. This paper reports on development details and testing results of these heat pipes as well as on other components of the thermal management system of the kilopower system hot end.

Keywords: Alkali Metal Heat Pipes, Self-Venting Arterial Heat Pipes, Surface Fission Power, Space Fission Power

---

Multiphysics Analysis of Liquid Metal Annular Linear Induction Pumps

Carlos O. Maidana [1,2,3] and Juha E. Nieminen[1]

[1]MAIDANA RESEARCH, 2885 Sanford Ave SW #25601, Grandville, MI 49418 – United States
[2]Idaho State University, Department of Mechanical Engineering, Pocatello, ID 83209
[3]Chiang Mai University, Dept. of Mechanical Engineering, 239 Huay Kaew Rd., Muang District, Chiang Mai 50200, Thailand
E-mail: carlos.omar.maidana@maidana-research.ch | +1 2908 904-0401

Abstract. Liquid metal-cooled fission 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. The coupling between the electromagnetics and thermo-fluid mechanical phenomena observed in liquid metal thermo-magnetic systems for nuclear and space applications gives rise to complex engineering magnetohydrodynamics and numerical problems. It is known that electromagnetic pumps have a number of advantages over rotating mechanisms: absence of moving parts, low noise and vibration level, simplicity of flow rate regulation, easy maintenance and so on. However, while developing annular linear induction pumps, we are faced with a significant problem of magnetohydrodynamic instability arising in the device. The complex flow behavior in this type of devices includes a time-varying Lorentz force and pressure pulsation due to the time-varying electromagnetic fields and the induced convective currents that originates from the liquid metal flow, leading to instability problems along the device geometry. The determinations of the geometry and electrical configuration of liquid metal thermo-magnetic devices give rise to a complex inverse magnetohydrodynamic field problem were techniques for global optimization should be used, magnetohydrodynamics instabilities understood –or quantified- and multiphysics models developed and analyzed.

We present computational models developed to study liquid metal annular linear induction pumps using first principles and the results of our multi-physics analysis.

Keywords: EM pumps; liquid metal; MHD; Multiphysics; nuclear.

Y-12 National Security Complex Casting and Machining Capabilities, and their Recent Application to Nuclear and Emerging Technologies for Space Programs

William T. Rogerson, Jr., Ph.D.[1]

[1]Development Organization, Y-12 National Security Complex, P.O. Box 2009, Oak Ridge, TN 37831-8097
865-574-2059;Bill.Rogerson@cns.doe.gov

Abstract. The Y-12 National Security Complex is now managed by M&O Contractor Consolidated Nuclear Services, LLC, a Lockheed Martin and Bechtel management team, in a joint Contract that includes the Pantex Plant. These changes provide additional resources and expertise for accomplishing research and development work in support of a number of nuclear and emerging technologies for space projects.

This presentation will discuss the current Y-12 Development casting and machining capabilities, and discuss how projects are tested in an R&D environment with surrogate materials, and then moved to full production with appropriate nuclear materials at reduced production risk.

Additionally, recent related projects with NASA and University of Washington in St. Louis will be presented. The Y-12 National Security Complex (Y-12) is a key participant in Space Programs by providing the uranium fuel and other needed materials. Y-12 has a Technology Development Organization, which allows customers to fabricate parts and materials using surrogate materials in a research and development environment. These capabilities allow customers to assess varying process parameters to achieve desired material characteristics in a lower risk environment. This presentation will discuss both fabrication and analyses capabilities in the Technology Development Organization.

Keywords: Casting, Machining, Space Programs

Characterization of Xenon Induced Reactivity Changes in Low Enriched Nuclear Thermal Propulsion Cores

Paolo F. Venneri[1,2], Michael J. Eades[3]

[1]Ultra-Safe Nuclear Corporation, Los Alamos, NM, 87544
[2]Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, Daejeon, ROK, 34141
[3]Nuclear Engineering Program, The Ohio State University, Columbus, OH 43201
858-342-4837; pvenneri@ultrasafe-nuclear.com

Abstract. One of the primary methods by which low enriched uranium (LEU) can be successfully implemented into nuclear thermal propulsion (NTP) cores is to thermalize the neutron spectrum. This helps reduce the role of the epithermal neutrons in fission, reduces the average neutron path length, and increases the fission to absorption ratio in the fuel, ensuring that neutrons are more likely to fission within the active core. However, given the high power density of the core, the resulting build-up of Xenon-135 following full power operation is significant and can render the core inoperable for days after shutdown. In this study we have fully characterized for the SULEU and SCCTE cores (the current baseline LEU cores for graphite composite and tungsten CERMET fuel) and present a variety of methods by which it can be mitigated in the future.

Keywords: LEU-NTP, graphite composite, SPACE.

A Point Design for a LEU Composite NTP system: Superb Use of Low Enriched Uranium (SULEU)

Paolo F. Venneri[1,2], Michael J. Eades[3]

[1]*Ultra-Safe Nuclear Corporation, Los Alamos, NM, 87544*
[2]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, Daejeon, ROK, 34141*
[3]*Nuclear Engineering Program, The Ohio State University, Columbus, OH 43201*
858-342-4837; pvenneri@ultrasafe-nuclear.com

Abstract. This work presents the initial point design and development of the Superb Use of Low Enriched Uranium (SULEU) nuclear thermal propulsion core. The core design is base off the heritage NERVA design, retaining the graphite-composite fuel elements (the only difference being the enrichment level), the presence of the moderator elements in the core (albeit with a varied tacking configuration and an increase in the size of the moderator sleeve), and the core peripherals including the reflector, control drums, and axial components of the core. The core is unique at this point by the fact that is able to match the existing NASA DRA 5.0 mission requirements while having a similar mass as existing NTP core designs. The performance parameters achieved by this preliminary design are as follows. It has a mass of 2498 kg (excluding the shield), a nominal Isp of 898 seconds (calculated using the rigorous methodology implement in SPACE), a nominal thrust of 155.7 kN, and a peak fuel temperature of 2850 K. It should be noted that in order to achieve these performance values, the inlet pressure for the core is higher than other LEU-NTP designs, requiring 8 MPa at the core inlet and consequently higher pressure drop across the core of 3 MPa. Furthermore, SULEU, has a total fissile mass of ^{235}U that is well below that of other cores of the same class. In direct contrast with existing LEU-NTP cores, SULEU has only 18.1 kg of ^{235}U. This establishes it as the current best in class in terms of reduction of fissile material, particularly when compared with tungsten CERMET LEU-NTP cores. In this work we have done a basic neutronic and performance analysis of the core and identified various methods and areas where it can be further improved upon.

Keywords: LEU-NTP, graphite composite, SPACE.

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

S. Firdosy[1], T. Caillat[1], B.C-Y. Li[1], C.K. Huang[1], V. Ravi[1], J. Paik[1], D. Uhl[1], Jennifer Ni[1], K. Smith[1] , G. Nakatsukasa[1] and J.-P. Fleurial[1]

[1]*Department of 1Jet Propulsion Laboratory/Caltech, MS 277-207*
4800 Oak Grove Drive, Pasadena CA, 91107
818-393-0576, samad.a.firdosy@jpl.nasa.gov

Abstract. NASA has used Radioisotope Thermoelectric Generators (RTGs) to power spacecraft in support of space science and exploration missions for over 50 years. The Cassini Saturn orbiter, the New Horizons Pluto probe and the Mars Science Laboratory (MSL) rover are the most recent examples while the Voyager 1 spacecraft has been in operation for more than 38 years and is currently the farthest human-made object from earth (~ 12 billion miles from earth). These RTG flight systems rely on heritage thermoelectric converter device technologies, with beginning of life (BOL) efficiencies close to 6.5%. The NASA's Radioisotope Power Systems Program's Thermoelectric Technology Development Project (TTDP) is pursuing the advancement and maturation of materials and device technologies that could increase conversion efficiency and specific power by a factor of 2 to 4X over the current Multi-Mission RTG used by MSL. To this end, the Advanced Thermoelectric Converter (ATEC) project is focused on the development, fabrication and testing of power generating segmented device 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, beginning of life couple 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 at hot-junction temperatures of up 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. Progress status on 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

Fission Surface Power Technology Demonstration Unit Test Results

Maxwell H. Briggs, Marc A. Gibson, Steven Geng[1] James Sanzi[2]

[1]NASA Glenn Research Center, 21000 Brookpark Rd, Cleveland, OH 44135
[2]Vantage Partners, 21000 Brookpark Rd., Cleveland, OH 44135

Abstract. The Fission Surface Power (FSP) Technology Demonstration Unit (TDU) is a system-level demonstration of fission power technology intended for use on manned missions to Mars. The Baseline FSP systems consists of a 190 kW$_t$ UO$_2$ fast-spectrum reactor cooled by a primary pumped liquid metal loop. This liquid metal loop transfers heat to two intermediate liquid metal loops designed to isolate fission products in the primary loop from the balance of plant. The intermediate liquid metal loops transfer heat to four Stirling Power Conversion Units (PCU), each of which produce 12 kW$_e$ (48 kW total) and reject waste heat to two pumped water loops, which transfer the waste heat to titanium-water heat pipe radiators. The FSP TDU simulates a single leg of the baseline FSP system using an electrically heater core simulator, a single liquid metal loop, a single PCU, and a pumped water loop which rejects the waste heat to a Facility Cooling System (FCS).

Several component and sub-system tests were run prior to system level testing of the TDU. Liquid metal component testing revealed that the Annular Linear Induction Pump (ALIP) used to pump the liquid metal achieved 5% efficiency compared to an expected value of 10% at the nominal operating condition of 850 K, 1.75 kg/s, and 28 kPa liquid metal loop pressure drop. The reduced ALIP efficiency increases the power required to achieve a given flow rate, increasing the parasitic power loss, and decreasing system efficiency. A preliminary investigation revealed several design and process improvements that could be used in future pump designs to increase pump performance closer to expected values. However, there redesign and fabrication of a new pump was outside of the scope of the project, so the existing ALIP was used as-built for TDU testing. Liquid-metal sub-system checkout testing prior to system-level testing revealed an issue with one of the two ALIP power supplies. Replacement of the power supply was straight forward, but the TDU test schedule did not allow for the substantial lead time so liquid metal mass flow was limited to 1.2 kg/s throughout testing.

The Stirling PCU was designed and manufactured by Sunpower Inc. Component testing of the PCU, using electric heating showed that the PCU operating at nominal operating (850 K hot-end temperature, 375 K water temperature, 0.375 kg/s water flow rate, and 16 mm amplitude) produced 12.2 kW of power at a gross efficiency (electrical power output of the engines divided by electrical power input to the electric heaters) of 25.5%, compared to the specified values of 12.0 kW and 26% efficiency. After the conclusion of electrically heated testing, the electrically heated head was removed and replaced with a heater head that included a liquid metal heat exchanger for testing in the TDU. Since Sunpower does not have the capability to operate a pumped liquid metal loop, the TDU system-level test was the first time that the PCU was run in its final configuration.

When operated at the nominal operating conditions (modified for low liquid metal flow) the PCU produced 8.9 kW of power at an efficiency of 21.7% resulting in a net system power of 8.1 kW and a system level efficiency of 17.2%. The reduction in PCU power from levels seen during electrically heated testing is likely the result of insufficient heat transfer from the NaK heater head to the Stirling acceptor, which could not be tested at Sunpower prior to delivery to GRC. The maximum PCU power of 10.5 kW was achieved at the maximum liquid metal temperature of 875 K, minimum water temperature of 350 K, 1.1 kg/s liquid metal flow, 0.39 kg/s water flow, and 15.0 mm amplitude at an efficiency of 23.7%. This resulted in a system net power of 9.7 kW and a system efficiency of 18.7 %.

Keywords: Fission Power, Space Power, Stirling

Completion of a 12kW$_e$ Stirling Converter for Fission Power Systems

John C. Stanley[1], J. Gary Wood[1], Ezekiel Holliday and Steven M. Geng[2]

[1]Sunpower, 2005 East State Street, Suite 104, Athens, OH 45701
[2]NASA GRC, 21000 Brookpark Rd, MS 301-2, Cleveland OH, 44135
740-594-2221, john.stanley@ametek.com

Abstract. A 12kW$_e$ Stirling Power Conversion Unit was fabricated and tested by Sunpower under contract with NASA GRC. The converter consists of two 6kW$_e$ engines arranged in a head to head configuration with a common expansion space. To input heat, the converter is designed with a NaK heat exchanger around a stainless steel heater head. The NaK heat exchanger transfers heat from a pumped NaK loop through the stainless steel head into an internal copper finned heat exchanger. The converter and controller were completed and delivered to NASA GRC on Aug 4, 2015.

The conversion unit was tested at Sunpower using an electrically heated test head. This allows for testing without a pumped NaK loop. The converter was operated at Sunpower in the full configuration for a total of 170 hours, including more than 70 hours at steady state.A structural test of the internal components was performed by running the converter at a 10% overstroke condition for 40 hours. The test was not continuous and was completed over 7 test runs. This test was successfully completed on July 21st 2014.

Before delivery, the electric test head was replaced with the final NaK heat exchanger head. The final checkout was a motoring run of the converter to test for operation when acting as a cryocooler. Because the NaK head could not be heated without the pumped NaK loop, a cold motor test was all that could be performed on the final configuration before delivery to GRC.

In addition to the converter, a controller was developed and tested. The controller sets the operation of the two engines, maintaining piston amplitude, frequency and phasing. The controller also converts the AC output of the converter into DC power that is delivered to a user load. The converter control portion of the controller was completed and tested. The Stirling output power was converted to 700 VDC that was dumped into a shunt load for testing. An output DC/DC converter which would step this down to 120 VDC for a user load was not completed due to budget restrictions.

A series of tests were performed on the controller but the final checkout test was a continuous 8 hour run at nominal operating conditions. This test occurred on Dec 2, 2014. The test showed stable operation of the converter and proved out the controller design.

Keywords: Stirling, Power Conversion, Fission Power

Radioisotope Thermoacoustic Power Conversion for Spacecraft

David E. Lee, Michael Petach, and Emanuel Tward

Northrop Grumman Aerospace Systems, One Space Park, Redondo Beach, Ca
90278 310-812-0389; manny.tward@ngc.com

Abstract. Thermoacoustic Power Converters (TAPC) that operate on the Stirling thermodynamic cycle are particularly suited for use on very long lived spacecraft because of their potential for very high reliability and efficiency. This reliability results from their mechanical simplicity that includes a no moving part thermoacoustic heat engine and a balanced linear alternator derived from the non-wearing and proven TRL 9 NGAS thermoacoustic pulse tube cryocooler compressors, and the low complexity electronic control. Ease of integration of TAPC onto spacecraft results from the mechanical and thermal interfaces incorporated into the device as well as the low exported vibration to the spacecraft and sensitive science payloads. This has been flight proven with the NGAS pulse tube cryocoolers in use with very sensitive space telescopes.

In this paper we will describe TAPC, its performance as a space power converter when powered by the radioisotope General Purpose Heat Source (GPHS) and its integration onto a spacecraft.

Keywords: thermoacoustic, power conversion, space, TAPC

An Examination of the engine cycle TRENDS for a HEU and LEU NTP

Claude. R. Joyner II[1], D. J. H. Levack[2], and Ty Jennings[3]

[1]Aerojet Rocketdyne, P.O. Box 109680, West Palm Beach, Florida 33410, USA, [2]Aerojet Rocketdyne, P.O. Box 7922, Canoga Park, California 91309, USA, , [3]Aerojet Rocketdyne, West Palm Beach, Florida 33410, USA,
561-882-5349; claude.joyner-ii@rocket.com

Abstract. Future human exploration missions across the Solar System need transportation technologies that reduce the time of flight, provide efficient payload capability, and reduce the size and effectively use available launch systems in order to reduce mission risk and cost. Nuclear Thermal Propulsion (NTP) is the proven technology that provides the performance to enable rapid transit due to the higher specific impulse. The future of human Mars exploration will see substantial benefit in terms of lower mission mass and shorter in-space mission time when NTP 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 human NTP transfer vehicle. Making the human crewed vehicle as small as technically feasible will permit optimization of the NTP system to lower thrust levels with little or no mass penalty to the spacecraft. This permits the NTP design to have a smaller reactor and present a smaller, more affordable development and operational footprint. Aerojet Rocketdyne's (AR) multidisciplinary design analysis capability has shown in past studies that a cluster of smaller thrust (e.g., <20,000 pounds) can successfully meet mission requirements and provide engine-out capability for reduced a Mars human mission risk.

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 robust NTP system for space travel. It is AR's belief that this could be achieved using smaller reactors for the NTP system (e.g., ≤ 500 MWt) based on the knowledge gained from past research and applying new technologies to improve the life and provide eventual reusability. A smaller NTP can use smaller facilities and lower exhaust flow rates to create less effluent to clean and manage, which, in turn, reduces the development cost due to environmental safety and nuclear material security concerns.

Several researchers have been recently investigating the use of Low Enriched Uranium (LEU) approaches for NTP. AR has collaborated with the Center for Space Nuclear Research (CSNR) to get LEU reactor design data to examine NTP cycle thermo-hydraulic using models created with the Numerical Propulsion Simulation System (NPSS). AR worked with NASA Glenn Research Center under a Space Act Agreement (SAA) to update NPSS NTP models to include AR turbomachinery characteristics. AR used the updated NPSS models to examine LEU reactor characteristics obtained from CSNR to determine the impact on the typical Nuclear Engine for Rocket Vehicle Applications (NERVA) fuel element/tie-tube arrangement design. AR examined many NTP designs over a range of thrust (core) sizes for human exploration systems. This paper will discuss studies performed in 2015 covering how the LEU reactor and cycle operate and the differences between the HEU and LEU approach to a NERVA design configuration relative to "closing" the cycle within liquid rocket materials and turbomachinery limits.

Keywords: Aerojet Rocketdyne, NTP, NPSS, Low Enriched Uranium, Highly Enriched Uranium, Thermo-hydraulic.

Proceedings of Nuclear and Emerging Technologies for Space
(NETS) 2016 - Huntsville, AL, February 22 - 25, 2016

Abstract 6078

The Separation of ^{241}Am From Aged Plutonium Dioxide For Use in Radioisotope Power Systems

Mark J. Sarsfield[1], Michael J. Carrott[1], Chris C. Maher[1], Chris Mason[1], Catherine Cambell[1], Josh Holt[1], Tamara Griffiths[1], Cheryl Carrigan[1], Hannah Fenwick[1], Bliss McLuckie[1], C. Gregson[1], Tim Tinsley[1], Keith Stephenson[2]

[1]National Nuclear Laboratory, Sellafield, Seascale, Cumbria, UK
[2]European Space Agency, ESTEC TEC-EPS, PO Box 299 - 2200 AG Noordwijk, The Netherlands.
+44(0)1946 779259; mark.sarsfield@nnl.co.uk

Abstract. Within Europe ^{241}Am is a feasible alternative to ^{238}Pu that can provide a radiogenic 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 low concentrations of ^{241}Am in the feed. This paper presents the results of increasing the americium levels to beyond full scale process concentrations demonstrating resilience towards radiation effects whilst maintaining 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.

A two-step chemical separation process, Pu/Am followed by Ag/Am separation, was used to process batches of aged PuO_2 to generate multi-gram quantities of pure ^{241}Am as an americium nitrate solution in nitric acid. An oxalate precipitation process was used to generate americium oxalate solid, which was subsequently decomposed into americium dioxide at elevated temperatures. A sample of this oxide was dissolved and analysis of trace metals performed, by resin column separations followed by Inductively Coupled Mass Spectrometry, to establish purity levels.

We have explored the optimum oxalate precipitation conditions, on cerium as a surrogate, to establish whether the process can be controlled to produce oxide powders that are optimal for ceramic pellet fabrication without the need for milling of powders and reducing the potential spread of contamination within glovebox containment systems. This controlled precipitation and decomposition process was applied to the americium system creating ~ 3.6g of americium dioxide ready for eventual fabrication into ceramic pellets.

Keywords: Americium, heat source, solvent extraction, impurity analysis, oxalate, oxide, ceramic pellets.

Proceedings of Nuclear and Emerging Technologies for Space
(NETS) 2016 - Huntsville, AL, February 22 - 25, 2016

Abstract 6079

Sintering and Characterisation of Cerium Dioxide as a Surrogate for Americium-241

Mark J. Sarsfield[1a], Hannah Fenwick[1a], Paul Glenville[1b], Daniel P. Kramer[2], Emily Jane Watkinson[3a], Richard M. Ambrosi[3a], Hugo R. Williams[3b], Chadwick D. Barklay[2], Keith Stephenson[4] and Tim Tinsley[1a]

[1a]National Nuclear Laboratory, Central Laboratory, Sellafield, Seascale, Cumbria, CA20 1PG, UK
[1b]National Nuclear Laboratory, Preston Laboratory, Springfields, Preston, Lancashire, PR4 0XJ, UK
[2]University of Dayton Research Institute, Kettering Laboratories, 300 College Park, Dayton OH 45469-0172, USA
[3a]Departments of Physics and Astronomy & [3b]Engineering, University of Leicester, Leicester, LE1 7RH, UK
[3]Queen Mary University of London, School of Engineering & Materials Science, Mile End Rd, London, E1 4NS, UK
[5]European Space Agency, ESTEC, Noordwijk, The Netherlands
Tel +44(0)1946 779259; email- mark.sarsfield@nnl.co.uk

Abstract. The European Space Agency space nuclear power programme is focused on the use of ^{241}Am as the radiogenic 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. This chemical separation process produces an americium nitrate solution in nitric acid. To obtain the desired americium oxide, an oxalate precipitation process is used to generate americium oxalate solid, which is decomposed into americium dioxide at elevated temperatures. In order to develop the fuel form and also develop the ceramic fuel pellets with mechanical handling strength that can be integrated into RTG and RHU systems, surrogates can be used to develop the fabrication process, understand how the fuel behaves under sintering conditions and test the mechanical properties by using appropriate test standards.

Recent studies have focused on producing cerium oxalate [$Ce_2(C_2O_4)_3.10H_2O$] powders through a continuous precipitation system as a surrogate to the radiotoxic americium equivalent [$Am_2(C_2O_4)_3.10H_2O$]. By varying the precipitation conditions and temperature of the subsequent decomposition to the oxide, a range of powders with varying properties were fabricated into ceramic pellets and characterised with reference to pellet processing, pellet pressing, micro-hardness, density and porosity. Trials carried out by National Nuclear Laboratory and University of Leicester in collaboration with the University of Dayton Research Institute are presented.

Keywords: Americium, heat source, cerium oxalate, cerium oxide, ceramic pellets.

Development and Utilization of Nuclear Thermal Propulsion

Michael G. Houts[1] and Sonny Mitchell[1]

[1]NASA Marshall Space Flight Center, MSFC, AL 35812
(256)544-8136; michael.houts@nasa.gov

Abstract. The potential of Nuclear Thermal Propulsion (NTP) for enabling advanced space exploration has been recognized for decades. However, for a variety of reasons NTP has never been developed and utilized. Several observations can be made concerning the development and utilization of NTP.

1. NTP systems are unique, and the capability to develop NTP does not exist within a single company or government agency. To be affordable and viable an NTP development program must be flexible and designed to facilitate involvement from industry, universities, NASA, the Department of Energy, and others.
2. A reference initial role for NTP should be carefully chosen, and the development program focused on enabling that initial role. If the initial role for NTP is supporting human Mars missions, the development program should focus on qualifying engines that could fulfill that role.
3. Current US policy strongly discourages the use of highly enriched uranium (HEU) in civilian applications. Low enriched uranium (LEU) NTP systems should be considered to significantly reduce security-related cost, schedule, and programmatic impacts, and to avoid generating opposition based on non-proliferation concerns.
4. If possible, any required ground nuclear testing should be designed to eliminate radiation exposure to the public and the planned release of radionuclides. Although extremely safe radiation exposure limits have been set (and could be easily complied with), the planned release of any radioactivity from an NTP ground test could generate significant public opposition.
5. If possible, dual-use fuels or other components should be utilized. For example, a fuel form could be chosen with the potential for enabling both NTP and advanced space fission power systems. A fuel form with commonality to ongoing nuclear fuel development programs (e.g. “Accident Tolerant Fuels”) could be chosen, although that could result in reduced performance.
6. Nuclear testing can be extremely expensive, and it is important to have high confidence in the success of a nuclear test before that test is performed. Non-nuclear testing should be performed to the extent that it is beneficial. Ongoing advances in analytical techniques should also be employed in all aspects of an NTP development program.
7. The potential benefits of NTP must be communicated. NTP can reduce earth-Mars transit times, which can benefit astronaut safety and increase the probability of mission success. NTP can also enable numerous Mars mission scenarios, including opposition class missions that could reduce the total Mars astronaut time away from earth by a factor of two (900 days down to 450 days). Initial NTP systems could provide a stepping stone to the development of much more advanced space nuclear power and propulsion systems, capable of opening the entire solar system.

Keywords: Nuclear, Propulsion, Mars, Exploration, Affordable

First Approach to the Design of Annular Linear Induction Pumps using First Principles

Juha E. Nieminen[1] and Carlos O. Maidana[1,2,3]

[1]MAIDANA RESEARCH, 2885 Sanford Ave SW #25601, Grandville, MI 49418 – United States
[2]Idaho State University, Department of Mechanical Engineering, Pocatello, ID 83209
[3]Chiang Mai University, Dept. of Mechanical Engineering, Chiang Mai 50200, Thailand
Contact person: carlos.omar.maidana@maidana-research.ch | +1 208 904-0401

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/or 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. Electromagnetic pumps and 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.

The standard method used to design electromagnetic pumps of the annular linear induction type is the electric circuit approach. The idea behind this method relies on the assumption that the flow is laminar (pressure and velocity independent of time). Hence the electromagnetic and hydrodynamic phenomena can be separated. Then the theory of linear induction machines and electric circuits can be used. This method is not very accurate and it doesn’t provide an understanding of the phenomenology and instabilities involved. The latter is truth because the coupling between the electromagnetics and thermo-fluid mechanical phenomena observed in liquid metal thermos-magnetic systems, and the determination of its geometry and electrical configuration, gives rise to complex engineering magnetohydrodynamics and numerical problems where the different physical phenomena involved cannot always be decoupled and therefore a multi-physics simulation constitutes a priority. The use of first principles to design annular linear induction pumps leads to a more accurate design process while the analysis of the coupled physical phenomena leads to a better understanding of the magnetohydrodynamics, its instabilities and it also constitutes the base for the development of techniques for optimization and active flow control.

A first approach to the design of annular linear induction pumps using first principles is discussed.

Keywords: EM pumps; liquid metal; MHD; multiphysics; ALIP.

Axisymmetric Analysis of a Hydrogen Containment Process for Nuclear Thermal Engine Ground Testing

Ten-See Wang, Eric T, Stewart, and Francisco Canabal

NASA Marshall Flight Center, Huntsville, Alabama 35812

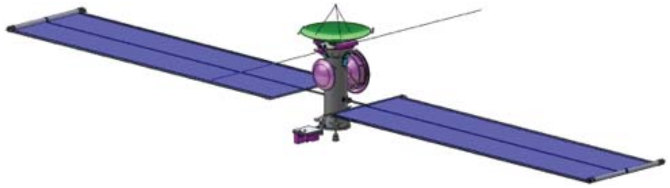
Abstract: This effort proposed a total hydrogen (H_2) containment process to enable the testing required for nuclear thermal propulsion (NTP) engine development. This H_2 removal process comprises of two unit operations: an oxygen-rich burner and a shell-and-tube type of heat exchanger. The goals were assumed for the burner to remove majority of the H_2 through oxygen-rich combustion reactions, and the remaining H_2 is cooled and removed in the heat exchanger with the recombination reactions. A multi-dimensional, pressure-based, multiphase computational fluid dynamics (CFD) methodology was used to analyze the entire hydrogen containment process, by integrating the solutions from a coupled pressure vessel/diffuser/burner and a single cooled-tube representing the heat exchanger assuming uniform mass distribution. A one-dimensional, thermal system model was used to size the heat exchanger. A parametric study on burner size, oxygen inlet temperature, and oxygen-to-hydrogen ratio was performed on the burner to ensure the majority of the hydrogen was removed at the end of the burner. The best solution from the parametric study was used as the inlet for the single cooled-tube heat exchanger analysis. The computed results show that the hydrogen is significantly reduced at the end of the heat exchanger. The flammability computed at the exit of the heat exchanger is less than the lower flammability limit, demonstrating the exhaust hydrogen from the test is totally contained with the proposed process.

Saturn Spacecraft Power: Trading Radioisotope, Solar, and Fission Power Systems

Steven R. Oleson[1], Lisa Kohout[1], Paul Schmitz[2], and Ralph Lorenz[3]
[1]*NASA John H. Glenn Research Center, Cleveland Ohio 44135*
[2] Vantage Partners LLC, 3000 Aerospace Pkwy, Brook Park, OH 4414

[3]Johns Hopkins University Applied Physics Lab, Laurel, Maryland

216-977-7426, Steven.R.Oleson@NASA.gov



Abstract. The Titan Saturn System Mission studied in 2006 assumed a radioisotope power system for the orbiter. Advances in space reactor concepts (e.g. 'kilopower') and large solar arrays for Solar Electric Propulsion Vehicles to retrieve asteroids and send cargo to Mars could both be used as alternative power systems for the Titan orbiter. Two concurrent engineering runs were made by the COMPASS team to evaluate the use of Fission and Solar power for the orbiter. Impacts unique to each system on integration, safety, attitude control, and science were evaluated for each point design. This presentation will focus on the ~ 100 kW solar powered point design but will also allude to the previously published fission options as well as discuss the advantages and disadvantages of each system.

Parameter	2008 Radioisotope	Solar PV
Science	108 kg, 182 W, ~5Tb	108 kg, 182 W, ~5 Tb, Instruments on Pointable platform, no lower atmospheric science, (no enceladus plume flythru)
Mission	13yr, two months	16 yr, 9 months
Launch Vehicle	Atlas 551, short fairing, C3 0.6 km^2/s^2 (6250 kg)	Atlas 551, medium fairing C3 -18.9 km^2/s^2 (9042 kg)
SEP Stage	~15 kW, 500 kg Xe, 2+1 NEXT	~80 kW, 1700 kg Xe, 2+1 NEXT
Orbiter Power System	171 kg, >13 yr operation time	~700 kg, >15 yr operation time
Aerobraking	4 m antenna for drag area, Ballistic Coefficient 77 kg/m^2 (2 month aerobraking campaign)	NO aerobraking – crosswinds and contamination are risks, chemical capture instead
Communications	X/Ka, 4 m pointable antenna, 25W/35WRF, 140 kbps	Fixed X/Ka, 4m fixed antenna, 25W/35WRF, 140 kbps
AD&CS	Four, 25 Nms, LVLH around Titan	Four, 150 Nms reaction wheels, solar inertial around Titan
Dry Mass (w growth)	3224 kg	4126 kg
Cost Δs		~similar cost to radioisotope but three years longer

Keywords: Radioisotope Power, Solar Power, Saturn, Titan

Effect of Sub-Sized Specimen Geometry and Orientation on High Strain-Rate Tensile Impact Ductilities of DOP-26 Iridium

Brian R. Friske and Cecil A. Carmichael, Jr.

Materials Science and Technology Division, Bldg. 2525-Rm. 108, Oak Ridge National Laboratory, 1 Bethel Valley Rd, Oak Ridge, TN 37831
(865) 576-1417; friskeb@ornl.gov

Abstract. There is a need to determine the tensile impact properties of the closure-weld zone of DOP-26 iridium alloy Clad Vent Sets (CVSs) used in General Purpose Heat Sources (GPHS). GPHS are used in Multi-Mission Radioisotope Thermoelectric Generators (MMRTG) to power missions such as Cassini and the Curiosity Mars Rover. A CVS is approximately 30 mm (1 3/16″) tall and consists of two DOP-26 cups, approximately 15 mm (0.59″) tall, with a 6 mm (0.24″) radius. These cups are gas tungsten arc welded to each other while oriented so that the cup blank (sheet) rolling direction of one cup is offset 90° from the rolling direction of the second cup. The dimensions of a full-sized tensile-impact specimen are too large to be removed from a CVS. The purpose of this work was to assess the relationship between the results obtained from tensile impact testing of sub-sized specimens with that obtained from tensile impact testing of full-sized specimens.

Keywords: Iridium, Clad Vent Set, High Strain-Rate Tensile Ductility.

Low Enriched Uranium Nuclear Thermal Rocket Design Considerations

Vishal Patel[1,2]

[1] Department of Nuclear Engineering, Texas A&M University, College Station, TX 77843
[2] Center for Space Nuclear Research, 995 University Blvd., Idaho Falls, ID 83401
832-334-9762; vkp93@tamu.edu

Abstract. Political and economical reasons have sparked interest in low enriched uranium (LEU) fueled nuclear thermal propulsion (NTP) designs. Typical new NTP designs rely on heritage designs with minor adjustments. This approach is only appropriate when the desired reactor has constraints that are similar to the heritage design. Large departures from the original design necessitate a new reactor design that can meet the new design goals. Optimized LEU fueled NTP reactors cannot be created by using a heritage design and exchanging HEU for LEU. As such, reactor design approaches must be used to create the best reactor possible given some constraints. These constraints vary but are generally based on material constrains and mission requirements such as desired thrust, specific impulse, maximum fuel temperatures, and many others. Typical LEU-NTP designs share many similar features as heritage HEU-NTP designs. The designs considered here are NERVA-derived, though other more exotic geometries can be created, initial LEU-NTP design efforts focus on building on previous experiences when possible. The design of a LEU-NTP core also shares some similarities to the design of terrestrial reactors, however there are many differences due to performance metrics and reactor needs. The presentation will overview some of the considerations needed to design a nuclear core for a LEU-NTP by comparing the design process to HEU-NTP and terrestrial reactor design goals.

Keywords: Nuclear Thermal Propulsion & Reactor modeling & Low Enriched Uranium

Ultra-Compact Heat Rejection System

Jeffrey J. Breedlove[1], Thomas M. Conboy[1], and Marc Gibson[2]

[1]Creare LLC, Hanover, NH 03755
[2]NASA Glenn Research Center, Cleveland, OH 44135
(603)640-2442; jfb@creare.com

Abstract: Creare and NASA are working together to develop an ultra-compact, lightweight heat rejection system for Mars and other planets and moons with atmospheric gas. The resulting technology will reduce operating temperatures while decreasing heat rejection system size and mass dramatically. This outcome will enable better performance for a broad range of applications and make them more affordable and practical to launch, deploy, and relocate. Most mission studies to date have assumed that pumped-liquid loops or thermally conductive structures will transfer waste heat to relatively large panels that are cooled primarily by radiation heat transfer. The surface area required for the radiators is large, which makes them difficult to integrate and support. Panel performance may also be degraded by dust and insolation. Our approach replaces the radiator panels with a high-speed axial-flow fan and compact micro-tube heat exchanger modules to use forced convection instead of radiation heat transfer. High rotational speed for the fan is critical for compact size because the atmospheric pressure on Mars is low. Additionally, micro-tube technology enables the heat exchanger modules to be extremely compact and lightweight.

This new heat rejection approach can provide compact cooling for a broad array of needs envisioned on Mars and beyond. Specific applications include nuclear power, cryogenic refrigerators, environmental control, life support, habitation, rovers, and in situ resource utilization. Initial effort has focused on nuclear power systems to provide a detailed assessment of benefits. Here, the heat rejection system reduces mass, and it also increases electric power by enabling a lower heat rejection temperature. For a 3 kW_e Brayton system, we predict mass will decrease by 80 kg and net electric power will increase by 500 W. These changes increase specific power at the system level from 3.79 to 5.14 W/kg, which is 36%. Similarly for a 3 kW_e Stirling system, we predict mass will decrease by 90 kg and net electric power will increase by 480 W, elevating specific power from 4.38 to 5.77 W/kg (32%). The technology is readily scalable, with similarly proportional results expected for other power levels. Additionally, the heat rejection components can be configured to enclose other components and subsystems to create an extremely compact overall system assembly. For example, a conceptual design for 1 kW_e Brayton power system has been created where the heat exchanger modules and fan form a six-sided structure that surrounds the power converter.

Keywords: Heat Rejection, Fission Power, Micro-Tube Heat Exchanger, Fan, Mars

---

Turbo-Brayton Power Converter for Spaceflight Applications

Jeffrey J. Breedlove, Thomas M. Conboy, and Mark V. Zagarola[1]

[1]Creare LLC, Hanover, NH 03755
603-640-2442; jfb@creare.com

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. Component fabrication is nearly complete. Turbomachine assembly and testing will begin soon, and converter testing will follow.

Keywords: Brayton, power converter, turbomachine

Shielding Options for Kilopower Mars Surface Reactors

David I. Poston[1], Scott Eustice[1], Lee S. Mason[2] and Michelle Rucker[3]

[1]Los Alamos National Laboratory, Los Alamos, NM 87545
[2]NASA Glen Research Center, Cleveland, OH 44135
[3]NASA Johnson Space Center, Houston, TX 77058
505-667-4336; poston@lanl.gov

Abstract. This study examines the use of Kilopower fission reactors to provide power to a human outpost on the surface of Mars. The Kilopower reactor is intended for simple, low-power (1 to 10 kWe) space and surface power systems. The Kilopower reactor concept uses heat pipes to transfer fission energy from a solid block of fuel. The heat pipes could be coupled to thermoelectrics, Stirling or Brayton (or other) power systems depending on power, cost, reliability, and mass requirements. The simplicity of Kilopower reactors is not limited to its physical attributes (i.e. number of components, technical maturity of components, ease of assembly); these low-power, compact reactors also allow simplicity in reactor neutronics/dynamics, startup, launch safety, transport, and both non-nuclear and nuclear testing. The reference 10-kWe Kilopower mass is 970 kg (230 kg HEU UMo-fueled, BeO-reflected reactor, 360 kg Stirling power conversion system, 330 kg heat rejection system) or 10.3 We/kg.

Shielding designs and results are obtained for single 10-kWe systems, and clusters of four 10-kWe systems. There are 3 sets of dose requirements: 1) Integral dose to onboard components (Stirling engines, alternators, control motors) – 5e14 n/cm^2 (>100 keV) and 10 MRad (Rad Si) over 12 years. 2) Integral dose to "nearby" electronics (control computers, payload systems, ISRU units, rover charging stations, etc.) – 1e11 n/cm^2 (>100 keV) and 25 kRad (Rad Si) over 12 years. 3) Human dose rate at outpost – 3 mRem/hr from reactor to unshielded human (i.e. not in habitat, behind berm/ridge or on far side of a structure. This is equivalent to 1 rem for every 330 hours of EVA time within the outpost in line-of-site of the reactor region. This dose rate is similar to the dose rate for Galactic Cosmic Rays (GCR) on the Mars surface, but unlike GCR radiation, the reactor radiation can be effectively shielded with a few inches of almost any material, therefore the layout of the outpost and habitat can be designed to take advantage of almost any mass or topography to shield expected high-occupancy regions.

This study evaluates shielding for 3 reactor configurations: left-on-lander, placed-on-ground and buried; on-ground systems can utilize berms, craters, boulders or other topography. Neutron shielding is provided by LiH (95% enriched in 6Li) in stainless-steel (SS) cans. The LiH contains layers of a thin SS chicken-wire mesh to help maintain form and distribute heat. Tungsten is used as the neutron shield. All 3 architecture options utilize 4-pi (fully surrounded) neutron shielding to some extent. The on-lander shield requires lower-axial shielding to reduce ground scatter. The on-ground shield requires lower-axial shielding to reduce the neutrons that use the low-absorbing regolith under the reactor to bypass the high-absorbing radial shielding. The buried shield uses a radial shield to prevent bypass of axial-shield to the surface and a small lower-shield to reduce regolith power deposition. Each shield concept utilizes spherical contours around the reactor, and a platform-shield (separated by a stem-shield that contains the heat pipes) below the power conversion system; due to its appearance, this geometry is referred to as the wine-glass shield. Some of the shield designs include a "snap-on" shield which can be utilized to provide additional shielding in the direction of an outpost and/or sensitive components.

Outpost separation (distance from reactor to humans) is a key variable, but optimizes to different lengths for each configuration, because longer electrical cabling increases mass and electrical losses. The effectiveness of a shielding option must include both mass and delivered electrical power; thus specific power is the best metric. The specific power of various 4-unit configurations are: left-on-lander = 4.2 We/kg at 2-km outpost separation, placed-on-surface = 4.4 We/kg at 2 km, placed-on-surface-bermed/topographic (line-of-site) = 6.0 We/kg at 500 m, buried-in-75-cm-deep-hole = 6.5 We/kg at 200 m, and buried-in-150-cm-deep-hole = 7.1 We/kg at 80 m outpost separation. There are many options to increase specific power, but they would require technology development and/or risk. The quoted powers and masses are for an entry-level, low cost/risk Kilopower system.

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

---

Reactor Design of the Kilowatt Reactor Using Stirling Technology (KRUSTY)

David I. Poston[1], Marc Gibson[2], Tom Godfroy[3] and Patrick McClure[1]

[1]Los Alamos National Laboratory, Los Alamos, NM 87545
[2]NASA Glen Research Center, Cleveland, OH 44135
[3]NASA Marshall Spaceflight Center, Huntsville, AL 35808
505-667-4336; poston@lanl.gov

Abstract. This Kilowatt Reactor Using Stirling TechnologY (KRUSTY) is a prototypic nuclear-powered test of a 5-kWt Kilopower space reactor. Kilopower reactor concepts utilize heat pipes to transfer fission energy from a solid block of fuel, and are intended for simple, low-power (1 to 10 kWe) space and surface power systems. KRUSTY has been designed to be as prototypic as possible within the cost constraints of a 3-year ~$15M program. KRUSTY follows the successful DUFF (Demonstration Using Flattop Fissions) experiment in 2012, which was a low-fidelity demonstration of a Kilopower type system. KRUSTY will be placed within a stainless-steel (SS) vacuum vessel to simulate the space heat-transfer environment and prevent oxidation of components. The vacuum vessel contains the reactor, power conversion and heat rejection systems. The "core-can" is a lower protrusion from the vacuum vessel that contains the core, heat pipes, axial reflector, axial shielding and thermal insulation. The high-neutronic-worth radial reflector is positioned outside of the core-can on a lift-table. The lift-table will be the Comet critical-machine at the Nevada National Security Site, which will provide reactivity control by raising the reflector to increase reactivity and vice-versa. KRUSTY uses eight Haynes-230 heat pipes with a 1.27 cm OD and a K working fluid. Thermal bonding of the heat pipes to the core is achieved through a compressive clamping force (which could be used for a flight reactor depending on the success of the testing).

The KRUSTY fuel is HEU U8Mo. The outer-diameter (OD) of 11 cm was selected to allow the use of existing shipping containers, and the inner-diameter (ID) of 4 cm allows the insertion of a 10-kW electric heater for non-nuclear testing and B4C pellets during nuclear testing to simulate the flight startup-rod. The baseline core length is 25 cm, but the final length may be tweaked to meet any future design changes that alter reactivity. The core will be cast in three parts to allow for "simple" casting – larger parts would require more effort (cost, time, risk) to ensure HEU casting approval. The KRUSTY reflector is BeO. Beryllium-oxide creates the highest worth reflector, which allows robust reactivity margins for safety and operation, as well as low fuel mass (and low-mass for flight). The reflector will be manufactured in 2.5 cm thick rings, with a 14-cm ID and ~30-cm OD. The rings will be added incrementally to measure the approach to critical of the KRUSTY assembly, with a maximum of 14 rings. The upper and lower axial BeO reflectors are 10 cm in height.

The shield design for KRUSTY presented several challenges, because of the need to balance reactivity, thermal and dimensional constraints, mass limits, cost and fabricability. A hydrogenous neutron shield, such as polyethylene, was eliminated due to its low temperature limit (~100 C); it could have been used in some regions, but would have limited the potential operating time of KRUSTY at full power. Lithium hydride also would have been attractive, but it was deemed risky from a cost and schedule perspective. Borated-SS created an ideal balance of neutron and gamma shielding, but was also found to be high-cost with limited availability. High iron-content steel (low Ni, Mo) was great for reactivity and low cost, but did not provide enough neutron shielding (actually, neutron capture gammas were the problem). A layered SS-316/B4C shield was also attractive on paper, and is indeed the baseline for axial shielding, but the cost/complexity of using annular B4C parts (either fabricated pieces or powder-filled cans) was problematic for the radial shield. The final design uses a solid SS-316 radial shield, which provides the required shielding within the mass and volume constraints at a relatively low cost (whereas the axial shield requires SS/B4C layers due to axial dimensional constraints).

Nuclear-powered testing of KRUSTY is slated to occur in FY17. Many of the design parameters provided are subject to change until various final as-fabricated parts can be characterized; e.g. what is the delivered fuel composition (density, isotopics), what is the density/composition of the BeO, what is the final clamp design, lessons learned from non-nuclear testing, possible modifications required for final test approval, etc.

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

A Multi-Dimensional Heat Transfer Model of a Tie-Tube and Hexagonal Fuel Element for Nuclear Thermal Propulsion

Carlos Gomez[1], Eric Stewart[1], Omar R. Mireles[1]

[1]NASA Marshall Space Flight Center, Huntsville, AL 35401
(256) 544-4821; carlos.f.gomez@nasa.gov

Abstract. The Space Capable Cryogenic Thermal Engine (SCCTE) effort considers a nuclear thermal rocket design based around a Low-Enriched Uranium (LEU) design fission reactor. The reactor core is comprised of bundled hexagonal fuel elements that directly heats hydrogen for expansion in a thrust chamber and hexagonal tie-tubes that house zirconium hydride moderator mass for the purpose of thermalizing fast neutrons resulting from fission events. The tie-tubes are cooled by a portion of the engine hydrogen flow. The current state of reactor analysis assumes that all of the heat introduced into the tie-tube hydrogen cooling flow comes from neutron absorption in the moderator mass (neutronic power deposition). Yet, it is readily apparent that some heat will find its way into the tie-tube cooling flow via conductive/radiative and heat transfer across mating hexagonal flats. Also, the amount of heat introduced by the conduction pathway will depend on how intimately the fuel and tie-tube elements contact each other. The SCCTE team created a preliminary 2-D axisymmetric tie tube model using Common Solution (COMSOL) Multiphysics software. The 2D model helped simplify and insure the physics and assumption were correct in order to create a complex 3D model which includes both the tie tube and hexagonal fuel element. The objective of this simulation effort is to quantify the actual total heat flow into the tie tube by all sources/mechanisms (neutronic, conduction, radiation, convection) and understand how the total heat flow may vary due to variances in contact resistance to the conduction pathway across the mating flats.

Keywords: Nuclear, Thermal, Propulsion, Heat Transfer,

Review of a Preliminary Fluid-Thermal Model of Hydrogen Flow in a Fuel Rod Tube of a Nuclear Thermal Propulsion Rocket Engine Reactor Core

Marvin Rocke[1]

Fluid Dynamics Branch (ER42), NASA/Marshall Space Flight Center, Huntsville, Alabama 35812
(256) 544-4140 : marvin.rocker@nasa.gov

Abstract. At the DoE/Idaho National Laboratory, the Center for Space Nuclear Research (CSNR) developed a fluid-thermal model of Hydrogen (H2) flow that served as a module of the Space Propulsion Optimization Code (SPOC) model. The Space code was the preliminary version of the fluid-thermal model. The Space code modeled compressible H2 flow with heating and friction in a tube of constant cross sectional area. The tube was one of many in a fuel rod of a nuclear thermal propulsion (NTP) rocket engine reactor core. The SPOC model is being used for parametric studies in the design of the reactor core.

At the NASA/Marshall Space Flight Center, the Space Capable Cryogenic Thermal Engine (SCCTE) Engine Systems Team Leader in the Engine Systems Branch (ER21) requested that the Fluid Dynamics Branch (ER42) and the Thermal & Combustion Analysis Branch (ER43) investigate the validity of the Space code and validity of a sample fluid-thermal calculation generated by the Space code. ER42 performed the investigation and ER43 provided the NASA/Lewis Research Center fluid properties code used in the investigation.

In the validation of the equations of fluid motion, they were obtained independently by reviewing conservation of mass, momentum, and energy. Kinetic energy was present as part of the total enthalpy on the left-hand side of the energy equation. In the Space code, the assumption was made that kinetic energy could be ignored in the energy equation. This assumption, valid for very low Mach numbers, was made for the sake of faster numerical convergence.

In the review of the tube inlet and exit conditions, from the given sample fluid-thermal calculation, it was determined that the Mach number throughout the tube was very small. This justified ignoring the kinetic energy in the energy equation. However, CSNR reintroduced the kinetic energy into the energy equation in the fluid-thermal portion of the SPOC model for completeness.

In the determination of solution quality, goal was to determine the size of numerical errors in the equations of fluid motion from the results of the sample fluid-thermal calculation. These errors had the maximum absolute values of less than 4% .

In the validation of the wall temperature calculation, two formulas for Nusselt number were considered. The first was the Dittus-Boelter (DB) formula. The second formula was the McCarthy-Wolf-Taylor formula with friction factor correction (MWT-w/FFC). By trial and error, it was determined that the second Nusselt number formula allowed an independent calculation of wall temperature that was consistent with that of the given sample fluid-thermal calculation.

Keywords: CSNR, NTP, SPOC, Space, Nusselt.

Cryogenic Fluid Management Technology and Nuclear Thermal Propulsion

Brian D. Taylor[1a], Jarvis Caffrey[2], Ali Hedayat[1a], Jonathan Stephens[1b], Robert Polsgrove[1a]

[1a]Main Propulsion Systems Branch and [1b]Propulsion Research and Technology Branch, NASA Marshall Space Flight Center, Huntsville, AL 35812
[2]Department of Nuclear Engineering and Radiation Health Physics, Oregon State University, Corvallis, OR, 97331
brian.d.taylor@nasa.gov

Abstract. Cryogenic fluid management (CFM) is critical to the success of future nuclear thermal propulsion powered vehicles. While this is an issue for any propulsion system utilizing cryogenic propellants, this is made more challenging by the radiation flux produced by the reactor in a nuclear thermal rocket (NTR). Managing the cryogenic fuel to prevent propellant loss to boil off and leakage is needed to limit the required quantity of propellant to a reasonable level. Analysis shows deposition of energy into liquid hydrogen fuel tanks in the vicinity of the nuclear thermal engine. This is on top of ambient environment sources of heat. Investments in cryogenic/thermal management systems (some of which are ongoing at various organizations) are needed in parallel to nuclear thermal engine development in order to one day see the successful operation of an entire stage. High durability, low thermal conductivity insulation is one developmental need. Light weight cryocoolers capable of removing heat from large fluid volumes at temperatures as low as ~20 K are needed to remove heat leak from the propellant of an NTR. Valve leakage is an additional CFM issue of great importance. Leakage rates of state of the art, launch vehicle size valves (which is approximately the size valves needed for a Mars transfer vehicle) are quite high and would result in large quantities of lost propellant over a long duration mission. Additionally, the liquid acquisition system inside the propellant tank must deliver properly conditioned propellant to the feed line for successful engine operation and avoid intake of warm or gaseous propellant. Analysis of the thermal environment and the CFM technology development are discussed in the accompanying presentation.

Keywords: Nuclear, Cryogenic, Propellant, Management, Radiation

---

Optimization of NTP System Truss to Reduce Radiation Shield Mass

Luke L. Scharber, Adam Kharofa, Jarvis A. Caffrey

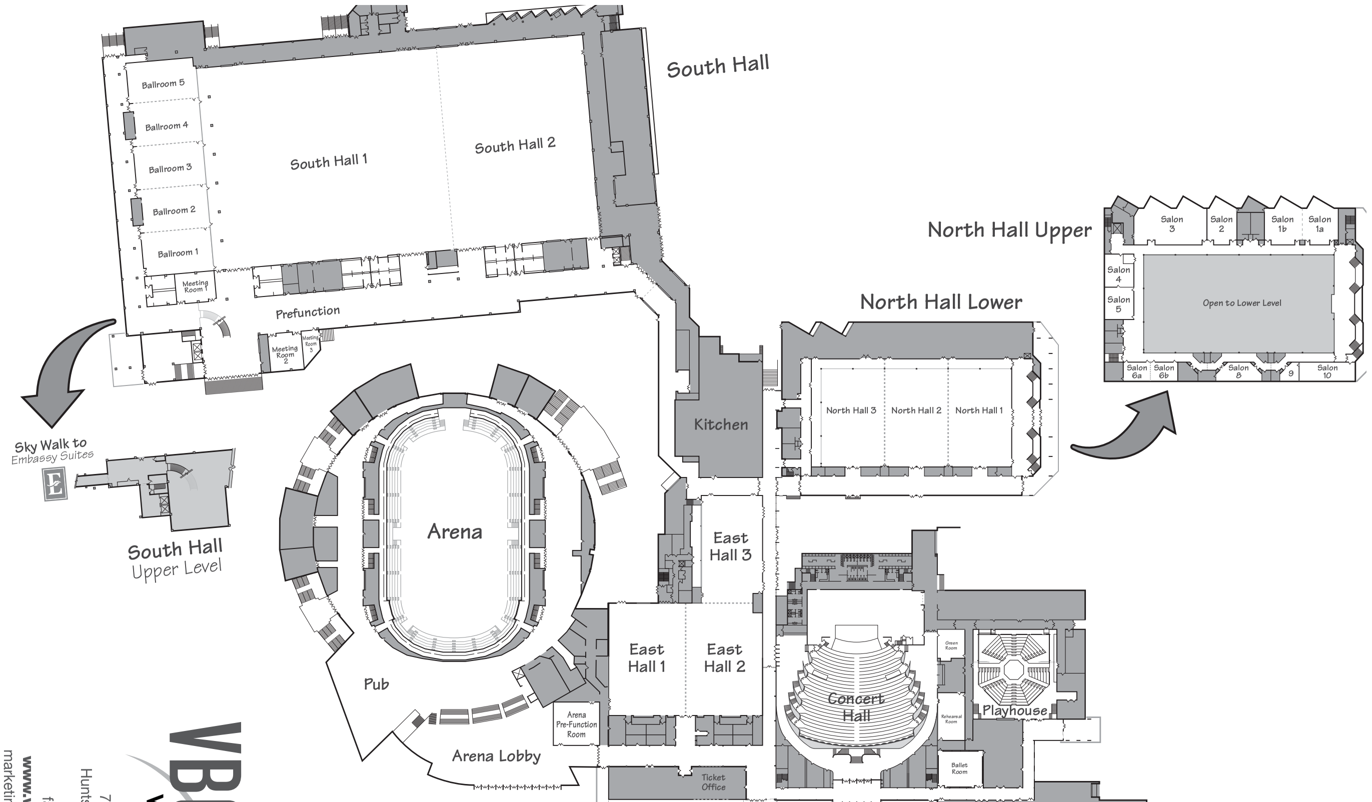
NASA Marshall Space Flight Center, Huntsville, AL 35812
256-544-8310; Luke.L.Scharber@nasa.gov

Abstract. The benefits of nuclear thermal propulsion are numerous and relevant to the current NASA mission goals involving but not limited to the crewed missions to mars and the moon. They do however also present new and unique challenges to the design and logistics of launching/operating spacecraft. One of these challenges, relevant to this discussion, is the significant mass of the shielding which is required to ensure an acceptable radiation environment for the spacecraft and crew. Efforts to reduce shielding mass are difficult to accomplish from material and geometric design points of the shield itself, however by increasing the distance between the nuclear engines and the main body of the spacecraft the required mass of the shielding is lessened considerably. The mass can be reduced significantly per unit length, though any additional mass added by the structure to create this distance serves to offset those savings, thus the design of a lightweight structure is ideal. The challenges of designing the truss are bounded by several limiting factors including; the loading conditions, the capabilities of the launch vehicle, and achieving the ideal truss length when factoring for the overall mass reduced. Determining the overall set of mass values for a truss of varying length is difficult since to maintain an optimally designed truss the geometry of the truss or its members must change. Thus the relation between truss mass and length for these loading scenarios is not linear, and instead has relation determined by the truss design. In order to establish a mass versus length trend for various truss designs to compare with the mass saved from the shield versus length, optimization software was used to find optimal geometric properties that still met the design requirements at established lengths. By solving for optimal designs at various lengths, mass trends could be determined. The initial design findings show a clear benefit to extending the engines as far from the main structure of the spacecraft as the launch vehicle’s payload volume would allow when comparing mass savings verse the additional structure.

Monday, February 22, 2016						
	Ballroom 1		**Ballroom 3**		**Ballroom 4**	
12:30 PM - 1:00 PM	Session Preparation					
1:00 PM - 1:30 PM	RPS (Mission Studies: Part I)	6005	NTP (Project and Mission Architecture)	6080	RPS (Fuel Production: Part I)	6047
1:30 PM - 2:00 PM		6084	NTP (Test Facility and Regulatory Consideraions)	6009		6015
2:00 PM - 2:30 PM		6038		6083		6046
2:30 PM - 3:00 PM	BREAK (Refreshments in Exhibitor Hall)					
3:00 PM - 3:30 PM	RPS (Mission Studies: Part II)	6052	FPS (Reactor Physics and Fuel)	6006	RPS (Fuel Production: Part II)	6026
3:30 PM - 4:00 PM		6023		6014		6078
4:00 PM - 4:30 PM		6033		6017		6001
4:30 PM - 5:00 PM		6045		6090		6039
5:00 PM - 5:30 PM		6059				
7:00 PM - 9 PM	**Opening Reception at the US Space & Rocket Center**					

Tuesday, February 23, 2016						
	Ballroom 1		Ballroom 3		Ballroom 4	
8:00 AM - 8:30 AM	Session Preparation					
8:30 AM - 9:00 AM	RPS (Thermoelectric Conversion: Part I)	6064	FPS (Power Conversion and Associated Technologies: Part I)	6004	NTP (Reactor Design: Part I)	6048
9:00 AM - 9:30 AM		6029		6007		6025
9:30 AM - 10:00 AM		6041		6068		6050
10:00 AM - 10:30 AM		6043		6069		6086
10:30 AM - 11:00 AM		6049		6074		6072
11:00 AM - 1:00 PM	LUNCH					
1:00 PM - 1:30 PM	RPS (Thermoelectric Conversion: Part II)	6040	FPS (Power Conversion and Associated Technologies: Part II)	6075	NTP (Reactor Design: Part II)	6051
1:30 PM - 2:00 PM		6073		6081		6037
2:00 PM - 2:30 PM		6030		6087		6071
2:20 PM - 3:00 PM	BREAK (Refreshments in Exhibitor Hall)					
3:00 PM - 3:30 PM	RPS (Stirling Conversion)	6020	FPS (Power Conversion and Associated Technologies: Part III)	6088	NTP (Rector Design: Part III)	6044
3:30 PM - 4:00 PM		6061		6063		6056
4:00 PM - 4:30 PM		6062	RPS (Fuel Simulant: Part I)	6034		
4:30 PM - 5:00 PM		6076		6036		
5:00 PM - 5:30 PM		6055		6079		

Wednesday, February 24, 2016						
	Ballroom 1		Ballroom 3		Ballroom 4	
8:00 AM - 8:30 AM	Session Preparation					
8:30 AM - 9:00 AM	RPS (Material and Systems Testing: Part I)	6031	FPS Space Nuclear Power Programs	6002	NTP (Engine System and Compant Development: Part I)	6010
9:00 AM - 9:30 AM		6085		6011		6077
9:30 AM - 10:00 AM		6035		6028		6019
10:00 AM - 10:30 AM		6053		6057		6018
10:30 AM - 11:00 AM		6054		6070		6008
11:00 AM - 11:30 AM		6058				6032
11:30 AM - 1:00 PM	LUNCH					
1:00 PM - 1:30 PM	RPS (Fuel Simulant: Part II)	6013	FPS (Reactor Analytical Studies: Part I)	6003	NTP (Engine System and Compant Development: Part II)	6091
1:30 PM - 2:00 PM		6016		6060		6092
2:00 PM - 2:30 PM		6027		6067		6093
2:20 PM - 3:00 PM	BREAK (Refreshments in Exhibitor Hall)					
3:00 PM - 3:30 PM	RPS (Material and Systems Testing: Part II)	6024	FPS (Reactor Analytical Studies: Part II)	6082	NTP (Engine System and Compant Development: Part II)	6012
3:30 PM - 4:00 PM		6021		6089		TBA
4:00 PM - 4:30 PM		6065				
4:30 PM - 5:00 PM		6066				
5:00 PM - 5:30 PM		6042				
7:00 PM - 9:00 PM	**Closing Banquet at Von Braun Center (Ballroom 5)**					



VBC
VON BRAUN
CENTER
700 Monroe Street
Huntsville, Alabama 35801
256-533-1953
fax 256-551-2203
www.vonbrauncenter.com
marketing@vonbrauncenter.com