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Geoscience Laser Altimetry System (GLAS) On-Orbit Flight Report on the Propylene Loop Heat Pipes (LHPs)

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Abstract. The Geoscience Laser Altimetry System (GLAS) instrument which is the sole instrument on ICESat was launched on January 12, 2003. GLAS utilizes two actively controlled propylene Loop Heat Pipes (LHPs) as the core of its thermal system. The LHPs started quickly when the Dale Ohm starter heaters were powered and have as designed. The low control heater power and on-orbit tight temperature control appear independent of gravity effects when comparing ground testing to flight data. The use of coupling blocks was also unique to these LHPs. Their application reduced control heater power by reducing the subcooling from the radiator. The effectiveness in reducing subcooling of the coupler blocks decreased during flight from ground testing, but internal thermal isolation in the compensation chamber between the subcooled returning liquid increased in flight resulting in no net increase in control heater power versus ground measurements. Overall the application of LHPs in the thermal system for GLAS met instrument requirements and provided flexibility for the overall system as last minute requirements became known.

Gamma Densitometry Applications in Microgravity Two Phase Flow Experiments

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Abstract. Measurement of fluid inventory in process streams under reduced gravity conditions presents a unique problem. On earth, a constant acceleration drives the buoyancy process that separates liquid and gas phases of working fluids. Under weightless conditions other methods of separation, such as the vortex phase separator developed at Texas A&M University, are required. The vortex phase separator is a hollow right circular cylinder; two phase fluid enters the separator at a tangential angle, and then follows the inner wall of the separator. The centripetal motion of the fluid creates a radial acceleration field, whereby buoyancy forces separate the gas and liquid phases of the fluid. The resulting annular film distribution of the liquid phase must be maintained within the separator's hydrodynamic limits if it is to continue to function. Therefore, it is necessary to monitor and maintain the liquid phase inventory of a vortex phase separator during extended periods of operation. This paper examines the feasibility of determining the liquid film thickness from measurements of the attenuation of gamma rays through a prototypic vortex phase separator. Counts from the collimated beam of an Am-241 source were collected using a NaI detector for a number of liquid film thicknesses. Initial results indicate that gamma densitometry is a viable method of tacking separator fill levels with 95% confidence.

New Results In Two-Phase Pressure Drop Calculations At Reduced Gravity Conditions

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Abstract. The mass, power, and volume energy savings of two-phase systems for future spacecraft creates many advantages over current single-phase systems. Current models of two-phase phenomena such as pressure drop, void fraction, and flow regime prediction are still not well defined for space applications. Commercially available two-phase modeling software has been developed for a large range of acceleration fields including reduced-gravity conditions. Recently, a two-phase experiment has been flown to expand the two-phase database. A model of the experiment was created in the software to determine how well the software could predict the pressure drop observed in the experiment. Of the simulations conducted, the computer model shows good agreement of the pressure drop in the experiment to within 30%. However, the software does begin to over-predict pressure drop in certain regions of a flow regime map indicating that some models used in the software package for reduced-gravity modeling need improvement.

Loop Heat Pipe: Design and Performance During Operation

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Abstract. Loop heat pipes (LHPs) have been extensively investigated and considered for the thermal control of satellites and other space equipments, but some geometric limitations, as well as the use of hazardous working fluids must be considered. Focusing on such concerns, a LHP was designed and built to accomplish certain requirements towards its future application in space missions. The designing procedure had to consider some limitations, such as a reduced scale capillary evaporator and the use of an alternative working fluid. Thus, an experimental LHP was built and tested for acetone as the working fluid to manage up to 70 W of heat transfer rate. The experimental results showed a good thermal management performance of the proposed LHP for the imposed limitations to its design. The proposed LHP presented to be a reliable thermal management device for applying in future space missions, especially when considering the use of a less hazardous working fluid.

Electrostatic Radiator for Spacecraft Temperature Control

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Abstract. This paper describes development of and test results for an electrostatically switched radiator (ESR). This is a device that can control the radiation emitted from a surface by controlling the position of a thin membrane. The present structure has been fabricated for flight testing on NASA's ST5 New Millennium program. It consists of 4 separately controlled radiator sections with a total active area of 57.6 cm2. As opposed to the original approach, this structure has the outer membrane at ground potential and is constructed onto a printed circuit board. In this paper we discuss the current state of development of the ESR, including device fabrication and test results.

Experimental Study of Heat Transfer Induced by a Single Vapor Bubble Growths. Influence of Liquid Subcooling

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Abstract. Heat exchanges during boiling are of high interest for cooling systems. The objective of this work is to investigate heat transfer around a single vapor bubble, the influence of the liquid subcooling and of the heat flux applied on the nucleation surface. Experiments on subcooled pool boiling at atmospheric pressure for a single vapor bubble were conducted and the obtained results are presented. The bubble was created on a downward facing heating element. Generation of the single bubble was achieved on an artificial cavity; the indentation was made on a fluxmeter (Captec Entreprise®). FC-72 was used as the test liquid, and its subcooling was maintained to 8 and 14K. Two heating powers were applied on the nucleation surface, and maintained constant during each experiment. Evolutions of bubble size and shape, as a function of wall superheat and liquid subcooling, were followed and studied using a 25 fps video camera. The effect of heating power and subcooling on growth periods were found to be significant. Total heat fluxes during bubble growth were measured using the fluxmeter, for different levels of subcooling and heating powers. Image and data processing has enabled us to show up influence of bubble growth on heat transfer and to determine nucleation periodicity. These preliminary results are discussed.

Heat Transfer Induced by Evaporation of a Sessile Drop: Influence of Wetting Surface

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Abstract. In this paper a database of sessile drop evaporation on a heated surface under gravity conditions is presented. For this an experimental setup is presented. It includes the part which allows evaporating the drop under controlled conditions and the data acquisition system. The drop is deposited on a heated surface maintained at constant temperature. Two systems were studied: water PTFE in which the wetting angle is higher than $\pi/2$ and water-aluminum. in which the wetting angle is less than $\pi/2$. Two types of measurements are implemented: the first one is an optical method which enables measurements of drop geometrical parameters and consequently the drop evaporation rate. The second one corresponds to a thermal fluxmeter. This later allows the determination of the heat flux and drop temperature.

The evaporation rate as well as the geometrical parameters (contact angle, wetting diameter) are determined for several operating conditions: wall temperature and drop size for the two systems considered. For the evaporation rate two different behaviors are found according to drop wetting. The experimental results are discussed and analyzed.

Variable Reflectance/Transmittance Coatings for Solar Sail Altitude Control and Three Axis Stabilization

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Abstract. Altitude control and three axis stabilization of the solar sail is critically important and may be accomplished either through a mechanical arrangement or through the use of variable solar reflectance/transmittance coatings (VSRCs/VSTCs). Electrochromic coatings that change reflectance or transmittance in response to the application of an electric potential may be used for this purpose. The primary objective of this work is to evaluate the effect of changes in the emittance of the front and rear surfaces of a solar sail on the thrust modulation efficiency. The results presented in this article demonstrate that the most efficient change in thrust for a solar sail panel with a VSRC is reached when the side shaded from the sun has the higher emittance than the side facing the sun. For a solar sail panel with a VSTC, the condition for the most efficient change in thrust occurs when the side facing the sun has the higher emittance than the side shaded from the sun. Also, it was highlighted that an opaque VSRC is more compatible with an opaque reflective solar sail thruster than a transparent VSTC. This design of a solar sail altitude control system with VSRC panels is recommended for further development.

The Concluding of the ISTC-1360 Project on the Development of Different Types of Loop Heat Pipes

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Abstract The International Science and Technology Center project 1360 was carried out by the Russian Institute of Thermal Physics, supported by several international collaborators. The main ISTC-1360 objective was the creation of improved, highly-efficient two-phase heat transfer devices, with capillary pumping of a working fluid, for the thermal control of modern spacecraft systems: Loop Heat Pipes and their components. Five LHP developments are discussed, i.e. Two miniature (858 mm long, with 2 mm diameter tubing) ammonia Loop Heat Pipes with 720 mm long flat coil condensers and 40 mm long, 8 mm diameter cylindrical wick evaporators: One made of titanium, the other made of Nickel. A miniature (865 mm long, mm diameter-tubing) ammonia Loop Heat Pipe with a 120 Bar proof flat evaporator, with nickel-titanium wick and a bi-porous thermal contact wall layer, and 720mm long flat coil condenser. A 900 W reversible 2 m long Loop Heat Pipe with two identical 24mm diameter, 104 mm long nickel wick evaporators, which have toproof to properly act as condensers (in the reversed mode). A (ramified) multiple-evaporator-condenser Loop Heat Pipe with two cylindrical evaporators (24 mm in diameter with an active zone length of 150 mm) and two condensers (length 200 mm, diameter 24 mm), made as pipe-in-pipe heat exchangers.The experimental results are presented. The conclusions discuss the potential spin-off of the work, being the design and manufacture of: At one side: Miniature (0.2-0.5 m long, 5-8 mm evaporator diameter) Loop Heat Pipes for power electronics and computers. At the other side: Large, 10-40 m long, 1-5 kW, Loop Heat Pipes with one or several evaporators. Everything in between the above extremes.

The MEMS Loop Heat Pipe Based On Coherent Porous Silicon – The Modified System Test Structure

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Abstract. Previous papers presented at STAIF 2002 and STAIF 2003 discussed the design, fabrication and characterization of the evaporator section and the initial test cell of a planar MEMS loop heat pipe based upon coherent porous silicon "CPS" technology. The potentially revolutionary advantage of CPS technology is that it is planar, allows for pores or capillaries of absolutely uniform diameter, and may be mass produced by various MEMS fabrication techniques. The preliminary experiments made with the original test structure exhibited the desired temperature and pressure differences, but these differences were extremely small and oscillatory. This paper describes modifications made to the initial test cell design intended to improve its evacuated, closed loop performance. Included among these changes were the redesign of the compensation chamber and condenser, the shaping of the coherent pores of the primary porous wick to increase porosity, the fabrication of silicon top "hot" plates with an increased depth of the vapor reservoir and the integration of metal resistive heater elements onto the backside of the top plates to simulate the input heat. Changes were made in the test sequence to produce more discernable differences in temperatures and pressures. The most recent results of the tests made with the modified system will be presented.

Electrochromic Variable Emittance Devices on Silicon Wafer for Spacecraft Thermal Control

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Abstract. Small light-weight satellites and space vehicles under development for future NASA missions have reduced thermal mass and are strongly affected by changes in orbital conditions, resulting in large temperature variations. Restrictions on payload weight and volume limit the usefulness of many thermal control technologies.

One thermal control approach, being considered by NASA in both nano- and micro- spacecraft applications, involves the use of electrochromic (EC) variable emittance devices (VEDs). VEDs operating in the harsh space environment (UV radiation, atomic oxygen) must be properly protected if they are to reach their design operational life.

In this paper, we discuss the design of an all-solid-state EC VED built on a silicon wafer. The silicon wafer serves as a window for IR radiation and protects the EC layers from the space environment. The EC VEDs were found to modulate mid infrared emittance from 0.32 to 0.62. Based on FTIR measurements of the IR reflectance of silicon coated with either white paint or aluminum, the resulting variable total emittance of an EC VED on a silicon wafer is expected to fall in the range from 0.16 to 0.61. An expression for the maximum expected emittance modulation is derived using a phenomenological model to define the limits of emittance in terms of reflectance. This expression indicates that lowering the reflectance of the window-substrate and of the EC stack while increasing the transmittance of the window-substrate results in higher emittance modulation. As a result, the variable total emittance of an EC VED on a silicon wafer with an AR coating is expected to fall in the range from 0.23 to 0.87.

The results of optical modeling are in good agreement with the experimental results acquired by FTIR measurements. Also, optical modeling confirms that an AR coating on the silicon wafer increases the emittance modulation of VEDs on a silicon wafer by almost 50%.

Tapered Screened Channel PMD for Cryogenic Liquids

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Abstract. If a conventional propellant management device (PMD) of the screened channel type were employed with a cryogenic liquid, vapor bubbles generated within the channel by heat transfer could "dry out" the channel screens and thereby cause the channels to admit large amounts of vapor from the tank into the liquid outflow. However, a tapered channel in which the cross sectional area increases with distance from the tank exit should, as a result of capillary effects, pump any vapor bubbles in the channel toward the wider end of the channel where they can be vented back to the tank. To demonstrate this effect, laboratory experiments were conducted with two horizontal channels of rectangular cross section having taper angles of 5° and 2.5°. The dimensions of the channel cross-sections were small enough to make buoyancy effects on the bubble negligible. The liquid used in the tests was isopropyl alcohol, a choice mandated by the need to eliminate laboratory complications accompanying the use of cryogenic liquids, and gas bubbles of known volume were injected into the channel. Bubble velocities measured in the tests were in the range of 0.1 to 0.4 cm/sec, depending on bubble size and the channel width at the bubble location. An analytical model of the bubble motion was developed from first principles. The model showed that the bubble velocity (after a brief transient acceleration) is given by:

$$U_B \approx 1.188\sigma L_B H_o^2 F\left(W_{ave}/W_B\right)\tan\alpha/12\mu L$$

Here 2α is the channel taper angle, σ is the liquid surface tension, μ is the liquid viscosity, H_o is the depth of the channel, F is a geometrical shape function, L is the total length of the channel, L_B is a bubble length scale parameter, W_{ave} is the average width of the channel, and W_B is the channel width at the bubble location. This relation not only explained the trends of the measured bubble velocities as a function of bubble position in the channel but it was also in good quantitative agreement with the measured bubble velocities. The analytical model was used to size a tapered screened channel design for a spacecraft tank having a length of 2 meters. It was found that the taper angle would have to be relatively small (0.5° or so) to prevent the width of the channel from becoming too large. However, the pumping rate was satisfactory even for this small taper angle, and it was concluded that vapor bubbles would be cleared from the channel after a relatively short time.

Effect of Pressure and Temperature on the Wetting Behaviour of Volatile Drops

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Abstract. In this paper we present the experimental results of an investigation aiming to demonstrate the role of constraints like substrate temperature and environmental pressure on the evaporation process of wetting droplets. It is clearly shown that increasing the temperature or reducing the pressure enhances the evaporation rate. The effect of changing these two parameters on the wetting behaviour is however not similar. The wetting behaviour is dictated by the surface tensions between the three phases (liquid, vapour and solid). Whilst pressure has little effect on these interfacial tensions, the temperature can greatly change these latter. A force balance at the triple line dictates the anchoring of the three-phase line; changing any of the interfacial tensions can alter this force balance. Increasing temperature tends to reduce the liquid-vapour surface tension, which reduces the Young unbalanced force acting on the triple line. This results in promoting the anchoring of this latter. Reducing pressure will enhance evaporation, which will lead to a greater evaporative cooling effect, this will increase the force acting to depin the triple line. The relationship between the evaporation rate and the anchoring of the three-phase line is discussed. The evaporation rate is found to be constant and proportional to the droplet base as far as the three-phase line is anchored. After depining of the triple line the evaporation rate is reduced. This can have important implications in various applications where both the evaporation and wetting are to be controlled.

Alkali Metal Heat Pipe Life Issues

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Abstract. Alkali metal heat pipes occupy an important niche in space fission power system design. Most space fission systems are predicated on use of alkali metal heat pipes either as radiator elements or as part of the primary heat-transfer system.

Research and development projects during the 1970s and 1980s sponsored by the NASA, DOE, and the US Air Force gave insight into alkali metal heat pipe operating principles. These projects established that if heat pipe container and working fluid impurities are kept low, and care is taken in fabrication, then long operating life is expected. These conditions for long life can be met with standard industry practices. Material purity can be confirmed with standard analytical techniques.

Heat pipes have operated trouble free at 50 times the neutron fluence of most baseline reactor designs. Such data gives confidence that alkali metal heat pipes can operate reliably within most reactor performance envelopes. Using existing and novel processing procedures consistent operation well exceeding 100,000 hours should be also possible. Tests at elevated temperature and evaporator power density can accelerate potential life limiting mechanisms. Properly designed heat pipe qualification and life tests can conclusively predict mission performance during the development cycle. Issues associated with heat pipe life testing will be discussed here. Criteria for evaluating life test data will also be presented.

An Overview of Long Duration Sodium Heat Pipe Tests at Thermacore, Inc.

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Abstract. High temperature heat pipes are being evaluated for use in energy conversion applications such as fuel cells, gas turbine re-combustors, and Stirling cycle heat sources. Long operating life and reliable performance are critical requirement for these applications. Long-term materials compatibility in high temperature heat pipes is being evaluated through the use of life test heat pipes. Thermacore, Inc. has carried out several sodium heat pipe life tests to establish long term operating reliability for these devices. Four sodium heat pipes have recently demonstrated favorable materials compatibility and heat transport characteristics at high operating temperatures in air over long time periods. A 316Lstainless steel heat pipe with a sintered porous nickel wick structure and an integral brazed cartridge heater has successfully operated at 650ºC to 700ºC for over 115,000 hours without signs of failure. A second 316L stainless steel heat pipe with a specially-designed Inconel 601 rupture disk and a sintered nickel powder wick has demonstrated over 83,000 hours at 600ºC to 650ºC with similar success. A representative one-tenth segment Stirling Space Power Converter heat pipe with an Inconel 718 envelope and a stainless steel screen wick has operated for over 41,000 hours at nearly 700ºC. A hybrid (i.e. gas-fired and solar) heat pipe with a Haynes 230 envelope and a sintered porous nickel wick structure was operated for about 20,000 hours at nearly 700ºC without signs of degradation. Detailed design specifications, operating history, and test results are described for each of these sodium heat pipes. Lessons learned and future life test plans are also discussed. These life test results collectively have demonstrated the potential for high temperature heat pipes to serve as reliable energy conversion system components for power applications that require long operating lifetime with high reliability.

Flow Pattern Phenomena in Two-Phase Flow in Microchannels

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Abstract. Space transportation systems require higher-performance thermal protection and fluid management techniques for systems ranging from cryogenic fluid management devices to primary structures and propulsion systems exposed to extremely high temperatures, as well as for other space systems such as cooling or environment control for advanced space suits and integrated circuits. Although considerable developmental effort is being expended to bring potentially applicable technologies to a readiness level for practical use, new and innovative methods are still needed. One such method is the concept of *Advanced Micro Cooling Modules* (AMCMs), which are essentially compact two-phase heat exchangers constructed of microchannels and designed to remove large amounts of heat rapidly from critical systems by incorporating phase transition. The development of AMCMs requires fundamental technological advancement in many areas, including: (1) development of measurement methods/systems for flow-pattern measurement/identification for two-phase mixtures in microchannels; (2) development of a phenomenological model for two-phase flow which includes quantitative measure of flow patterns; and (3) database development for multiphase heat transfer/fluid dynamics flows in microchannels. This paper focuses on the results of experimental research on the phenomena of two-phase flow in microchannels. The work encompasses both experimental and analytical approach to incorporate flow patterns for an air-water mixture flow in a microchannel, which is necessary for the optimal design of AMCMs. Specifically, the following topics will be addressed: (1) design and construction of a sensitive test system for two-phase flow in microchannels, which measured ac and dc components of in-situ physical mixture parameters including spatial concentration using concomitant methods; (2) data acquisition and analysis in the amplitude, time, and frequency domains; and (3) analysis of results and evaluation of data acquisition techniques and their validity for flow pattern detection. .

The Evaluation of Heat Pipe Working Fluids In The Temperature Range 450 to 700 K

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Abstract. In the temperature range of 450-700 K, there are currently no working fluids that have been validated for heat pipes and loop heat pipes, with the exception of water in the lower portion of the range. This paper reviews a number of potential working fluid including several organic fluids, mercury, sulfur/iodine, and halides. Physical property data are used where available, and estimated where unavailable using standard methods. The halide salts appear to possess attractive properties, with good liquid transport factors, and suitable vapor pressures. Where nuclear radiation is not a consideration, other potential working fluids are aniline, naphthalene, toluene, and phenol. The limited available life test data available suggests that toluene, naphthalene, and some of the halides are compatible with stainless steel, while the other fluids have not been tested.

Multi-Megawatt MPD Plasma Source Operation and Modeling for Fusion Propulsion Simulations

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Abstract. The expansion of a high temperature fusion plasma through an expanding magnetic field is a process common to most fusion propulsion concepts. The efficiency of this process has a strong bearing on the overall performance of fusion propulsion. In order to simulate the expansion of a fusion plasma, a concept has been developed in which a high velocity plasma is first stagnated in a converging magnetic field to high (100's of eV) temperatures, then expanded though a converging/diverging magnetic nozzle. A Magnetoplasmadynamic (MPD) plasma accelerator has been constructed to generate the initial high velocity plasma and is currently undergoing characterization at the Ohio State University. The device has been operated with currents up to 300 kA and power levels up to 200 MWe. The source is powered by a 1.6 MJ, 1.6 ms pulse-forming-network. In addition to experimental tests of the accelerator, computational and theoretical modeling of both the accelerator and the plasma stagnation have been performed using the MACH2 MHD code. Insights into plasma compression and attachment to magnetic field lines have led to recommended design improvements in the facility.

A Review of Textured Surfaces, Paints, and Coatings for Space Radiator Applications

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Abstract. Future space nuclear power systems will require large radiators to dissipate excess thermal energy. Such radiators may be composed of carbon-carbon composite fins made from high thermal conductivity graphite fibers or may be a more traditional honeycomb structure with face sheets composed of a suitable high temperature metal. In either case, the surface of the radiator must have a high emittance at the desired operating temperature, envisioned to be in the range of 400 to 900 K, and must be durable for the length of the mission, envisioned to be ten years. Existing thermal control paints and coatings may be applicable at the low end of the envisioned temperature range, but may not be applicable at elevated temperatures. Hence, other avenues of emittance enhancement need to be explored. Previous work has identified a number of promising technologies that may be useful for enhancing the emittance of candidate surfaces, including texturing the radiator surface via sand blasting, oxidation at elevated temperature, and exposure to atomic oxygen. This paper will review existing candidate thermal control paints and coatings to identify their strengths and weaknesses and will review other promising technologies that have been proposed in the past few years to enhance the emittance of radiator surfaces.

Tutorial on Mechanically Pumped Two-Phase Thermal Control Loops

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Abstract. The tutorial starts with a description of the background of the research on two-phase thermal management systems for aerospace applications, followed by a discussion on the advantages and drawbacks of parallel, series and hybrid (a mixture of parallel and series) system configurations. A review of critical issues related to the development of the systems and systems components will be given, covering also the different aspects of thermal-gravitational scaling, thermal modelling equations, pressure drop, flow patterns, condensation, evaporation and flashing. Two-phase technology, sometimes called the major innovation in aerospace thermal control of the last decade, is becoming mature: Capillary pumped two-phase thermal control loops are already frequently applied in (telecommunication) spacecraft. But the number of spacecraft applications of (complex) mechanically pumped two-phase thermal management systems is currently still limited to two European developments, being the two-phase ammonia loop for the Russian segment of the International Space Station ISS and the hybrid two-phase carbon dioxide loop for the Tracker Thermal Control System of AMS-02, the 3-5 years lasting experiment (attached payload on ISS) looking for antimatter, dark matter and lost matter. The tutorial will discuss in detail the various issues related to these two mechanically pumped two-phase thermal control systems.

A Practical Equipment for Tumor-Suppressor Protein Crystal Growth in the International Space Station

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Abstract. Some human diseases as tumors are being studied continuously for the development of vaccines against them. And a way of doing that is by means of proteins research. There are some kinds of proteins, like the p53 and p73α proteins, which are tumor suppressors. There are other diseases such as A.I.D.S., hansenosis, the Parkinson's and Chagas' diseases which are protein-related. The determination of how proteins geometrically order themselves, during its biological functions is very necessary to understand how a protein's structure affects its function, to design vaccines that intercede in tumor-protein activities and in other proteins related to those other diseases. The protein crystal growth in microgravity environment produces purer crystallization than on the ground, and it is a powerful tool to produce better vaccines. Several data have already been acquired using ground-based research and in spaceflight experiments aboard the Spacelab and Space Shuttle missions, and in the MIR and in the International Space Station (ISS). In this paper I suggest to be performed in the ISS Biological Research Facility (which is being developed), multiple crystal growth of proteins related to cancer (as tumors suppressors and oncoproteins), A.I.D.S., hansenosis, the Parkinson's and Chagas' diseases, for the future obtaining of possible vaccines against them. I also suggest a simple and practical equipment, a modification of the crystallization plates (which use a vapor diffusion technique) inside each cylinder of the Protein Crystallization Apparatus in Microgravity (PCAM), with multiple chambers with different sizes. This suggested modification, along with the use of gels inside the chambers, will increase the necessary quantity and quality of several kinds of proteins' crystals, for the later, on ground, continued study and possible manufacture of vaccines against such diseases, and to begin a possible first-stage small factory operated by astronauts aboard the ISS, for producing multiple crystals for future vaccines, for Human use.

Analysis of Fluid Flow and Heat Transfer in a Liquid Hydrogen Storage Vessel for Space Applications

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Abstract. This paper presents a systematic analysis of fluid flow and heat transfer in a liquid hydrogen storage vessel for both earth and space applications. The study considered a cylindrical tank with elliptical top and bottom. The tank wall is made of aluminum and a multi-layered blanket of cryogenic insulation (MLI) has been attached on the top of the aluminum. The tank is connected to a cryocooler to dissipate the heat leak through the insulation and tank wall into the fluid within the tank. The cryocooler has not been modeled; only the flow in and out of the tank to the cryocooler system has been included. The primary emphasis of this research has been the fluid circulation within the tank for different fluid distribution scenario and for different level of gravity to simulate potential earth and space based applications. The equations solved in the liquid region included the conservation of mass, conservation of energy, and conservation of momentum. For the solid region only the heat conduction equation was solved. The steady-state velocity, temperature, and pressure distributions were calculated for different inlet positions, inlet velocities, and for different gravity values. The above simulations were carried out for constant heat flux and constant wall temperature cases. It was observed that a good flow circulation could be obtained when the cold entering fluid was made to flow in radial direction and the inlet opening was placed close to the tank wall.

Paraffin Actuated Heat Switch: Flight Implementation and Performance on the Mars Exploration Rovers

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Abstract. The Mars Exploration Rover (MER) flight system utilizes paraffin actuated heat switches as part of its secondary battery thermal control system. Previous flight qualification and testing efforts[1] have shown the switches to be mechanically robust and to exceed all thermal/structural requirements. Described here is the flight implementation of the heat switches: differences between the flight and qualification units; flight acceptance testing; mechanical configuration and integration into the flight Rovers; flight system thermal vacuum testing performance; and preliminary thermal performance from the surface of Mars.

A total of six flight units were built and delivered to the Jet Propulsion Laboratory by Starsys Research Corporation. The flight units benefited from experience gained in building the engineering and qualification units. Specifically, certain part tolerances were held tighter and the paraffin charge process was improved in the flight build. This led to an increase in the interface pressure v. temperature curve which, in turn, translated to improved thermal performance. Flight units achieved thermal conductance values as high as 1.7 W/K, a 42% increase over qualification unit performance. All units passed the flight acceptance test program which included random vibration, landing loads, and thermal cycle tests. Integration into the flight Rovers posed unique problems due to the requirements that the switches be unrestricted in actuation movement and must be installed last on the overall Rover integration process. System thermal vacuum testing on the flight Rovers revealed significant margin on the overall vehicle thermal control performance. Switch performance was shown to be more than adequate to maintain secondary battery temperatures during worst-case cold diurnal thermal cycles during testing.

Reference:
[1]Sunada, E., Pauken, M., Novak, K., Phillips, C., Birur, G., "Design and Flight Qualification of a Paraffin-Actuated Heat Switch for Mars Surface Applications," 32nd International Conference on Environmental Systems, San Antonio, Texas, July 15-18, 2002.

Carbon Composites for Spacecraft Thermal Management

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Abstract. Under a contract (No. F33615-00-C-5009) with the U.S. Air Force Materials Lab, Cytec Carbon Fibers, LLC is conducting a program to identify high risk, high payoff thermal management applications for the insertion of high thermal conductivity composite materials in future space and military aircraft. The program involves the identification of relevant design requirements, the design of components for thermal management applications utilizing the most appropriate high conductivity composite material solution, the fabrication of prototype test articles, performance and characterization tests on the prototype articles, and test data correlation of measured results. The final step in the program requires end-user acceptance / qualification testing of the designed components. Within this program, several different satellite and military aircraft thermal management applications have been selected and are currently in various stages of development. This paper will provide a summary of the selected applications, a description of the thermal management materials employed, and the progress to date on some example applications.

Cool Chips: An Overview of Thermal Management Solutions Using Electron Tunneling Through a Vacuum Gap

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Abstract. Electron tunneling is an inherently high-efficiency mechanism for solid-state thermal management. Previous attempts to take advantage of this effect have suffered from the large thermal backpath present in designs incorporating thin-film insulators. Cool Chips are designed to eliminate this backpath by incorporating a vacuum gap of ~10nm between the two electrodes. Development efforts to date have resolved most technical hurdles, with work on thin film integration and module packaging currently in progress. Cool Chips offer a compact, lightweight, low maintenance and highly efficient (in excess of 50% of Carnot Efficiency) thermal management solution ideally suited for the needs of aerospace applications.

The Hardware Challenges for the Mars Exploration Rover Heat Rejection System

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Abstract. The primary objective of the Mars Exploration Rover (MER) 2003 Project focused on the search for evidence of water on Mars. The launch of two identical flight systems occurred in June and July of 2003. The roving science vehicles are expected to land on the Martian surface in early and late January of 2004, respectively. The flight system design inherited many successfully approaches from the Mars Pathfinder Mission. This included the use of a mechanically-pumped fluid loop, known as the Heat Rejection System (HRS), to transport heat from the Rover to radiators on the Cruise Stage during the quiescent trek to Mars. While the heritage of the HRS was evident, application of this system for MER presented unique and difficult challenges with respect to hardware implementation. We will discuss these hardware challenges in each HRS hardware element: the integrated pump assembly, cruise stage HRS, lander HRS, and Rover HRS. These challenges span the entire development cycle including fabrication, assembly, and test. We will conclude by citing the usefulness of this system during launch operations, where in particular, the flight Rover battery was thermally conditioned by the HRS since there was no other effective means of maintaining its temperature.

Corrections For Heat Flux Measurements Taken On Lauch Vehicles

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Abstract. Knowledge of aerothermally induced convective heat transfer and plume induced radiative heat transfer loads is essential to the design of thermal protection systems (TPS) for launch vehicles. Aerothermal and radiative models are typically calibrated via the data from cylindrical, in-flight, flush-mounted surface heat flux gauges that are exposed to the external thermal and velocity boundary layers as well as thermal radiation. Typically, Schmidt-Boelter gauges, taking advantage of the 1-Dimensional Fourier's law, measure the incident heat flux. This instrumentation, when surrounded by low-conductivity insulation, has an exposed surface temperature significantly lower than the insulation. As a result of this substantial disturbance to the thermal boundary layer, the heat flux incident on the gauge tends to be considerably higher (potentially by factors of 2 or more) than it would have been on the insulation had the calorimeter not been there. In addition, the gauge can receive energy radially from the hotter insulation, contributing to the increase of the indicated heat flux. This paper will present an overview of an effort to model the heat flux gauge under typical flight conditions that includes an installation surrounded by high temperature insulation. The goal is to correct the measurements to reflect the local heat flux on the insulation had the instrument not been present. The three major components of this effort include: 1) a three-dimensional computational thermal math model including the internal conduction heat transfer details of a Schmidt-Boelter gauge, 2) a two-dimensional Navier-Stokes computational fluid dynamics (CFD) analysis to determine the effects on measurement of the rapidly changing thermal boundary layer over the near step changes in wall temperature, and 3) testing performed on flat plates exposed to an aerothermal environment in the Marshall Space Flight Center (MSFC) Improved Hot Gas Facility (IHGF). A brief summary of calibration issues will be presented, followed by the analytical efforts, as well as an update on testing results and preliminary model calibration results. Finally, recommendations will be made for installation and flight data corrections.

Thermal Integration For NASA Sponsored Payloads On Expendable Launch Vehicles

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Abstract. NASA sponsors a number of scientific payloads that are launched on expendable vehicles. Recent examples of launch vehicles used by NASA include Delta II, Delta IIH, Atlas II, Pegasus, and Athena. Payload examples include Spirit, Opportunity, SORCE, SIRTF, and GALEX. In addition, NASA will also launch satellites for other, non-military, US government entities. Examples of such payloads include the NOAA and GOES satellites. The NASA Launch Services Program performs a number of payload to expendable launch vehicle integration services. The functions of the Thermal-Fluids group in the Mission Analysis Branch are described here. The thermal-fluids group has four main functions, including environment integration, vehicle insight and oversight, new vehicle certification, and internal studies. The environment integration function assures that the spacecraft thermal-fluids models correctly integrate the launch vehicle loads and environments. The vehicle insight and oversight role ensures that any launch vehicle modifications are acceptable for NASA sponsored flights. Vehicle certification, sometimes called risk mitigation, is performed for the first NASA flight on new vehicles. There are currently such efforts underway for the Delta IV, Atlas V, and Taurus vehicles. Finally, the group performs a number of internal studies aimed at improving the processes in the previous three categories and in overall vehicle cost and performance.

Microfabricated Thermal Switches for Emittance Control

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Abstract. The trend to smaller satellites with limited resources in weight and power requires a new approach to thermal control. This paper describes an actively controlled radiator based on a micro electromechanical (MEMS) thermal switch. Design, fabrication, electromechanical and thermal performance of the MEMS device is discussed. A proof-of-concept design has been fabricated that uses a gold membrane suspended on polymer posts. Initial testing results confirm the expected electromechanical behavior of the device.

Sodium Heat Pipe Module Processing For the SAFE-00 KW Thermal Reactor Concept

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Abstract. To support development and hardware-based testing of various space reactor concepts, the Early Flight Fission-Test Facility (EFF-TF) team established a specialized glove box unit with ancillary systems to handle/process alkali metals. Recently, these systems have been commissioned with sodium supporting the fill of stainless steel heat pipe modules for use with a 100 kW thermal heat pipe reactor design. As part of this effort, procedures were developed and refined to govern each segment of the process covering: fill, leak check, vacuum processing, weld closeout, and final "wet in". A series of 316 stainless steel modules, used as precursors to the actual 321 stainless steel modules, were filled with 35 +/-1 grams of sodium using a known volume canister to control the dispensed mass. Each module was leak checked to <10-10 std cc/sec helium and vacuum conditioned at 250 oC to assist in the removal of trapped gases. A welding procedure was developed to close out the fill stem preventing external gases from entering the evacuated module. Finally the completed modules were vacuum fired at 750 oC allowing the sodium to fully wet the internal surface and wick structure of the heat pipe module.

Controlled Acceleration Track Equipment Description

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Abstract. Spacecraft whose rocket motors consume liquid fuel must ensure liquid at the exit of the propellant tanks for correct operation. Thus, a major concern of mission designers is the location of liquid in a propellant tank under weightlessness conditions. Spacecraft perform special maneuvers and specific tank design features are utilized to ensure that fuel is always covering the liquid outlet. To better understand fluid behavior under these conditions, computational codes have been developed to predict fuel behavior. Observation of fluid behavior in a tank under mission conditions is required to validate the codes and increase confidence for mission planning and spacecraft design. In order to validate the computational models, an engineered system is needed to produce specific accelerations under environmental weightless conditions. Since most spacecraft utilize large propellant tanks and terrestrial reduced gravity testing is carried out using aircraft flying a parabolic trajectory, a scaled model system must be utilized. Dimensional analysis was used to determine the dimensions of the scaled tank to be tested under scaled accelerations. In order to produce necessary scaled accelerations, a system described in the following paper has been designed and built to generate axial, roll, and pitch/yaw maneuvers. When maneuvering, a spacecraft can accelerate along a linear path (axial acceleration), roll, or it can turn (Pitch/Yaw). Further, it may produce a combination of the following maneuvers. Texas A&M's Interphase Transport Phenomena Laboratory(ITP) has designed and built the Controlled Acceleration Track (CAT) to simulate these maneuvers. A servomotor powered rack and pinion drive accelerates a cart with the scaled tank along a rail. A small, variable speed, DC motor provides roll motion. Video and acceleration data will be recorded while the scaled tank is subjected to the described accelerations.

STAIF-2004 Abstract Book

Public-Private Models for Lunar Settlement

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Abstract. Since the beginnings of the space age, mission concepts and plans directed at lunar base development have been proposed. With the exception of Apollo, which was driven by cold war geopolitics, these concepts and plans have remained either on the political agenda or as proposed ideas for the commercial sector. This paper examines why this has been the case; why has there not been political formulation and implementation of lunar base missions or implementation of commercial development of the Moon? This paper assesses the issues facing those in both the public and private sectors who view lunar development as a desirable goal and offers suggestions, based on public-private partnerships, as to how to make that goal a reality.

There are several issues that have entrapped lunar development ideas on both the political and business agendas. First, lunar development advocates focus on scientific and technological benefits of lunar development, while providing weak links to economic competitiveness and national security issues that are of interest to political decision-makers in order to support new, revolutionary large-scale programs. Arguments based on unspecified technological spin-offs are ineffective. Further political rationales for lunar base development are constrained due to the weak public support for space in general and to reduced budgets and downsizing in government support for research and development. Second, public policy evolves on an incremental basis. Thus, past policies and practices change slowly and usually in response to a particular crisis or focusing event that warrants public attention. Third, albeit lunar commerce enjoys a prestige status in the private sector, as numerous companies in various stages of development have plans to carry out commercially viable robotic ventures on the Moon, plausible business plans for lunar settlement, catering to scientific, mining, and tourism projects, remain elusive and in the more distant future. The business plans that have been proposed for lunar settlement lack realistic return on investment calculations to make the venture attractive to investors and the private capital markets. These plans fail to properly identify and quantify sustainable long-term markets for the proposed ventures. Fourth, an environment of uncertainty concerning policy and legal regimes further compounds the prospects for commercial sector interest in lunar development.

Public-private partnerships are essential to deal with these issues and to enable prospects for lunar development. This implies the existence of political support and government funding as well as aspects in the lunar development that would attract investor interest and private capital. At issue, is how to fashion a synergistic relationship. To this end, three models, which address ways in which to fashion public-private partnerships for lunar development, are put forward and discussed in this paper. First, is a government model involving the establishment of stable government-sponsored markets. Second, is a technology model entailing lunar development on the basis of dual-use technologies. Third, is a business model dealing with business plans for private sector ventures directed at lunar development activities

Closed End Launch Tube (CELT)

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Abstract. A small-scale test apparatus has been built and tested for the CELT pneumatic launch assist concept presented at STAIF 2001. The 7.5 cm (3-inch) diameter x 305 M (1000 feet) long system accelerates and pneumatically brakes a 6.35 cm diameter projectile with variable weight (1.5 – 5 Kg). The acceleration and braking tube has been instrumented with optical sensors and pressure transducers at 14 stations to take data throughout the runs. Velocity and pressure profiles for runs with various accelerator pressures and projectile weights are given. Velocities approaching 180 m/s (400 MPH) were obtained with both projectile weights. Maximum velocities occurred very early in the pneumatic acceleration, followed by a deceleration due to the rapidly building head pressure within the initially atmospheric pressure acceleration tube. All projectile runs were successfully stopped by the pneumatic braking section. A section of the tube was damaged due to an oscillation of the projectile coupled with compressive forces and positive feedback to the oscillation.

The pressure profiles suggest that a series of vents along the acceleration tube would lower the head pressure enough to allow the projectile to reach the desired 240 m/s, if coupled with an onboard gas generator within the projectile. These vents would remain open until just before the projectile arrives. Additional support posts and relief of the thermal expansion would be required to prevent damage to the tube from small oscillations of the projectile. Funding to support these changes and the development of a CFD model are required to complete the feasibility study. This test apparatus can serve as an important experimental tool for verifying this concept.

ACES: An Enabling Technology for Next Generation Space Transportation

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Abstract. Andrews Space has developed the "Alchemist" Air Collection and Enrichment System (ACES), a dual-mode propulsion system that enables safe, economical launch systems that take off and land horizontally. Alchemist generates liquid oxygen through separation of atmospheric air using the refrigeration capacity of liquid hydrogen. The key benefit of Alchemist is that it minimizes vehicle takeoff weight. All internal and NASA-funded activities have shown that ACES, previously proposed for hypersonic combined cycle RLVs, is a higher payoff, lower-risk technology if LOX generation is performed while the vehicle cruises subsonically.

Andrews Space has developed the Alchemist concept from a small system study to viable Next Generation launch system technology, conducting not only feasibility studies but also related hardware tests, and it has planned a detailed risk reduction program which employs an experienced, proven contractor team. Andrews also has participated in preliminary studies of an evolvable Next Generation vehicle architecture—enabled by Alchemist ACES—which could meet civil, military, and commercial space requirements within two decades.

A Road Map for Future Space Transportation Systems of Japan

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Abstract. NASDA has been successfully conducted five H-IIA launches, our main launch vehicle, in last two years, and ISAS also launched M-V No.5 successfully recently. By those successful launches, NASDA and ISAS overcame the past launch failures of H-II and M-V launch vehicles in 1998 to 2000, and regained our confidence in space development programs. Three space and aeronautical research and development agencies (NASDA, ISAS, and NAL) in Japan were merged in 2003 to establish a new organization called the Japan Aerospace Exploration Agency (JAXA).

Japanese launch vehicle technology has now almost reached the world highest level by successful launches of the H-IIA standard type; therefore, JAXA is progressing from the catching-up stage to the new phase.

Launch operations of the H-IIA standard type will be privatized in a few years to reduce the costs, improve the reliability, and enhance the international competitiveness by private management. JAXA will be in charge of maintenance and enhancement of launch vehicle fundamental technologies including reliability improvement after the privatization.

As we are moving up to the new phase from the catching-up stage,, we shall carry out our technology improvement with a long-term strategy for the future transportation system research and development, and challenge more advanced technologies.

A Review of Recent RLV Research Activities in Japan

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Abstract. Researches on reusable launch vehicle (RLV) in Japan have been conducted mainly by the three space agencies: the National Space Development Agency of Japan (NASDA), the National Aerospace Laboratory of Japan (NAL) and the Institute of Space and Astronautical Science (ISAS). HOPE-X program by NASDA/NAL, spaceplane/ scramjet related researches by NAL, and development studies of ATREX engine and small reusable vehicle testing (RVT) by ISAS are such major activities. After the consecutive launch failures of NASDA's H-II and ISAS's M-V rockets in 1999-2000, it was concluded that more intensive efforts should be concentrated on the reliability improvement of those major expendable vehicles and that RLV related researches should be promoted to establish fundamental technologies essential to future RLV. In past two years, NASDA succeeded in five consecutive launches of new H-IIA, and ISAS successfully resumed the launch of M-V. As for RLV researches, the high speed flight demonstration (HSFD) phase 1 and phase 2 tests have been conducted in HOPE-X program. Considerable progress has been achieved in scramjet tests of Mach 4 to 8 by NAL, and ATREX engine and small RVT tests by ISAS. The current three space agencies will be merged into one in October 2003 to establish a new organization named Japan Aerospace Exploration Agency (JAXA). It is expected that the above research activities will be also merged to promote a higher-level research program on RLV.

Insurance – A Key Business Variable

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Abstract. Availability and the cost of insurance are key elements in the development of space businesses. Insurance is often required to obtain finance and to underpin the commercial success of a space venture. It may also serve as a financial tool to mitigate certain types of business risk, in addition to its more traditional role in managing technical risk. This paper examines different ways in which insurance is used to mitigate risk. It also canvasses potential trade-offs between insurance and new technology; insurance market dynamics and their effect on space projects; and the challenges that new directions in commercial space development may impose on space related insurance. The impact of several different prospective commercial space activities and the associated technologies will be examined in the context of their insurance implications.

Finding the Financing – A Special Case for Space

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Abstract: Since space commercialization and associated creation of new business ventures became an issue app 13 years ago, "external" – respectively non-governmental - financing has become crucial. Numerous commercial endeavors have been proposed over the years, however, besides operators of telecommunication satellites, only few received appropriate financing and even fewer were commercially successful. Over the same period the financial markets boomed, why lack of dedicated finance seems to be a shortfall with respect to commercial space ventures, but presumably is not major one. It is important to understand what it takes to "find the financing", particularly in terms of non-financial factors and the specifics of the space sector.

The paper provides an overview of financing basics and generic types of space business and their characteristics. Sources of finance for space-related business, related objectives and development are being discussed. Examples are given to elaborate on major difficulties, and recommendations for future commercial space ventures are made.

Background is observations made by the author in commercial space and finance, and experiences of own activities in space-related new business creation and venture capital on a global scale over the past 16 years.

X-40A Flight Test Approach

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Abstract. The X-40A flight testing is part of NASA's X-37 Project, which is managing the development and operation of an automated (no crew on board), integrated flight demonstration system. The X-37 will validate and mature critical technologies under combined environments that are beyond the capability of, or pose undue risks to, existing flight or ground platforms.

The X-37 three-phase development approach provides risk mitigation and helps ensure the overall success of the Project: (1) X-40A, (2) X-37 Approach and Landing Test Vehicle (ALTV), and (3) X-37 Orbital Vehicle (OV). The X-40A is an 80-percent scale of the X-37.

The U.S. Air Force-owned X-40A first underwent a series of towed-taxi tests to demonstrate its ability to navigate and control rollout and to verify instrumentation and data collection. The final X-40A tests, completed in 2001, was a series of seven successful captive-carry free-flight Approach and Landing Tests (ALT) from a helicopter at 15,000 feet to demonstrate unpowered flight and landing characteristics. These tests verified flight qualities and vehicle data links (command, control, telemetry, tracking, and flight termination). The X-40A:

- Developed Computed Air Data System (CADS) flight data to support X-37 system design
- Evaluated the Honeywell Space Integrated Global Positioning/Inertial Navigation System (SIGI) under flight conditions
- Provided Flight Operation Control Center (FOCC) site integration and flight test operations
- Flight tested and improved guidance, navigation, and control (GN&C) algorithms

The information gained from these tests is being applied to the design and operation of the X-37 vehicles (ALTV and OV) to reduce the risk of follow-on flight-testing.

ALTV Flight Test Approach

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Abstract. The X-37 Approach and Landing Test Vehicle (ALTV) builds on the lessons learned from the X-40A 15,000-foot flight testing and is a stepping stone to orbital flight and reentry environment demonstrations. The X-37 approach and landing high-altitude flight tests will evaluate the performance of ground and flight system elements in an atmospheric, operational environment.

The X-37 ALTV will undergo a series of towed-taxi tests to demonstrate its ability to navigate and control rollout and to verify instrumentation and data collection. These tests will be followed by a series of captive-carry flights from a B-52H aircraft to verify the flight qualities and vehicle data links (command, control, telemetry, tracking, and flight termination).

The final series of X-37 tests from the B-52 will consist of up to five free-flight approach and landing tests from 40,000 feet to demonstrate automated flight and landing characteristics of the vehicle. The X-37 testing is monitored by the Flight Operation Control Center (FOCC) used for the X-40A. The ALTV will demonstrate:

- Fault-tolerant automated guidance, navigation, and control (GN&C)
- High-temperature composite structures, joints, and seals
- Calculated Air Data System
- Lightweight landing gear
- Rapid turnaround (ground and flight)

The ALTV reduces the risk to the X-37 Orbital Vehicle (OV) by testing a subset of OV technologies and flying the same trajectory from 40,000 feet down. The OV builds on the design, manufacturability, programmatic, and operational lessons learned from the ALTV.

X-37 Orbital Vehicle Flight Test Approach

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Abstract. The X-37 Flight Demonstrator Project's Orbital Vehicle (OV) flight tests will help revitalize America's capability to build and operate an integrated space transportation system. The X-37 Project employs a three-phased approach to flight testing: (1) X40A, (2) ALTV high altitude, and (3) OV. The X-37 OV will provide a versatile technology platform to validate important technologies and obtain flight environment data during critical ascent, on-orbit, reentry, and landing stages of the mission. It will be launched on an Evolved Expendable Launch Vehicle, operate on-orbit without a crew, and return to Earth. OV flight tests will mature and validate advanced high-risk technologies for hot structures, thermal protection systems, and lithium-ion batteries. The OV is being designed and built to support a 270-day mission and will operate with similar functionality as the Space Shuttle, but will be automated and fly without a pilot. The OV is slated to make its first flight in the 2006 - 2007 timeframe.

X-37 Overall Technology Development Benefits Future RLVs

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Abstract. The X-37 Flight Demonstrator Project will pave the way for the development of future integrated space transportation systems and reusable launch vehicles (RLV) by validating and maturing high-payoff technologies. Advanced thermal protection systems (TPS) are being developed to demonstrate reentry environments for the Orbital Space Plane. The X-37 Orbital Vehicle will be launched on an Evolved Expendable Launch Vehicle and will be able to deliver and return 500 pounds of payload. The X-37 will potentially help define the requirements for a robust space transportation system capable of serving NASA and Department of Defense needs for long-term automated on-orbit missions. It will be capable of carrying experimental payloads for Earth sensing, microgravity, and space sciences study. The X-37 will be a key building block to enable safer, more reliable, and less expensive access to space.

On Orbit Servicing and the Future of Commercial Space Flight

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Abstract. Until recently, practical considerations of cost and market applicability have hindered the development of commercial space activities outside of the GEO communications satellite industry. An On Orbit Servicing (OOS) commercial solution has become viable due to the convergence of moderate cost secondary payload access to GEO Transfer Orbit (GTO) via Ariane V, the increase in size and cost of GEO communications satellites, as well as advances in propulsion and other technologies necessary to build a low cost OOS solution. These factors, when coupled together, provide the necessary technical and business case for the life extension of existing and future GEO communications satellites.

The technical requirements of a commercial OOS system for GEO are considerably restricted in comparison with a more generic OOS space tug. The fundamental question that a commercial OOS system must answer is:

"What is the minimum technical implementation that will allow a significant market to be addressed and how low can the cost be driven"?

Cost and feasibility are dramatically intertwined when designing a commercial OOS system. With a rigorous attention to minimal requirements, cost, and with a focus on the one commercial market that routinely spends large sums of money to maximize long term value, OOS can begin a bootstrap approach that can lower costs and increase long term value to customers. Success in this approach will open the door to further advances in OOS based upon proven value to the customer. This paper will examine how commercial implementation of OOS can increase the productivity of orbital assets and lower the system costs for space businesses.

High Temperature Fusion Reactor Cooling Using Brayton Cycle Based Fractional Energy Conversion

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Abstract. With some future high temperature nuclear heat sources for propulsion and power systems most of the output energy will be used in other than electrical form, and only a small fraction of the total thermal energy generated will need to be converted to continuous electric power. In nuclear-fusion propulsion applications for example a large amount of thermal energy will be generated at high temperature. In order to maintain the structural integrity of the propulsion system this thermal energy will need to be rejected to space. By utilizing partial energy conversion to electric power to provide the work required for transport of this thermal energy to space radiators, cooling of the reactor heat source can be accomplished. In order to reduce radiator area requirements for such multi-megawatt heat sources, a high temperature gaseous helium cooling loop is proposed which operates in parallel with a CCGT (Closed Cycle Gas Turbine) power system. A computer code has been written to serve as a tool in performing the thermodynamic analysis and conceptual design for a hypothetical fusion reactor generating a total of 1200 MW thermal power.

In addition to the thermodynamic aspects of the system design a brief treatment of the gas turbine and fan rotor dynamics and proposed bearing support technology along with performance characteristics of the three phase AC electric power generator and fan drive motor is also included.

The analysis is equally applicable to planetary surface reactor applications, where the high temperature thermal energy is not rejected to space, but is used for chemical and metallurgical processing purposes

A New Thermodynamic Power Cycle and Heat Engine for Space Power Applications

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Abstract. A new heat engine concept has been invented that operates on a new two-phase thermodynamic power conversion cycle. This device exploits the space flight proven technique of using a porous capillary structure to separate liquid from vapor through heat addition. This new thermodynamic cycle, the Baker cycle, is different from the existing Rankine because liquid and vapor are at different pressures and are separated during the phase change heat addition process as opposed to the Rankine cycle where liquid and vapor are at the same pressure and mixed during phase change heat addition. This new cycle also differs from Rankine because the heat addition process occurs at varying pressures and temperatures, where as in a Rankine cycle heat addition occurs at constant pressure. It is advantageous to apply this new cycle to space applications because management of the two-phase working fluid in micro gravity can be accomplished as never before using space flight proven Loop Heat Pipe and Capillary Pumped Loop technology. This new power system contains many components with significant flight heritage. Thermodynamic performance calculations are presented for several design cases. The new power cycle and system is inherently more efficient than single-phase systems because minimal compression power is required. One case shows 31.1% overall efficiency with a maximum working fluid temperature of 637.4 K. Since the heat addition process occurs at varying temperatures, waste heat from the spacecraft could be tapped and recovered to supply a large portion of the input energy. For the example cases discussed, between 63.1 to 84.4% of the total input energy could be waste heat. This new system could be used in conjunction with phase change thermal energy storage to supplement power production replacing batteries for solar low-earth-orbit applications. It could also be used as a power converter with a radioisotope heat source yielding efficiencies over 30% while requiring a maximum temperature well below that of single-phase dynamic converters. Because this new power system is capable of operating at high efficiency at relatively low temperatures it could also be used as the bottoming cycle of a space based cogeneration power system with a single-phase or static power converter being the top cycle.

Material Requirements and Selection for the Proposed JIMO Space Power System

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Abstract. NASA is proposing a major new nuclear Space initiative – The Jupiter Icy Moons Orbiter (JIMO). A mission such as this inevitably requires a significant power source both for propulsion and for on-board power. Three reactor concepts, liquid metal cooled, heat pipe cooled and gas cooled are being considered together with three power conversion systems Brayton cycle, Thermoelectric and Stirling cycle Regardless of the reactor system selected it is almost certain that high temperature materials, refractory alloys, will be required. This paper revisits the material selection options, reviewing the rationale behind the SP-100 section of Nb-1Zr as the major cladding and structural material and reconsiders alternatives. A side glance is also taken at the basis behind the selection of Uranium nitride fuel over UO2 or UC and a brief discussion of the reason for the selection of Lithium as the liquid metal coolant for SP-100 over other liquid metals

Nuclear Space Power Systems Materials Requirements

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Abstract. High specific energy is required for space nuclear power systems. This generally means high operating temperatures and the only alloy class of materials available for construction of such systems are the refractory metals niobium, tantalum, molybdenum and tungsten. The refractory metals in the past have been the construction materials selected for nuclear space power systems. The objective of this paper will be to review the past history and requirements for space nuclear power systems from the early 1960's through the SP-100 program. Also presented will be the past and present status of refractory metal alloy technology and what will be needed to support the next advanced nuclear space power system. The next generation of advanced nuclear space power systems can benefit from the review of this past experience. Because of a decline in the refractory metal industry in the United States, ready availability of specific refractory metal alloys is limited.

Net-Shaped Fabrication of Rhenium Components by EB-PVD

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Abstract. Cost-effective net-shaped forming components have brought considerable interest into DoD, NASA and DoE. Electron beam physical vapor deposition (EB-PVD) offers flexibility in forming net-shaped components with tailored microstructure and chemistry. High purity rhenium (Re) components including rhenium-coated graphite balls, Re- plates and tubes have been successfully manufactured by EB-PVD. EB-PVD Re components exhibited sub-micron and nano-sized grains with high hardness and strength as compared to CVD. It is estimated that the cost of Re components manufactured by EB-PVD would be less than the current CVD and powder-HIP Technologies.

NASA's Program in Radioisotope Power System Research and Development

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Abstract. Radioisotope Power System (RPS) Research and Development is one of the main program elements comprising Project Prometheus, the Nuclear Systems Program, which is developing nuclear electric power and propulsion technologies to enable more ambitious space science missions. The objective of the RPS program element is threefold: (1) develop new radioisotope power sources for missions that would launch by the end of the decade; (2) advance promising power conversion technologies to increase the specific power and performance of future RPS; and (3) assess and facilitate the use of advanced RPS technologies for new mission applications. The program consists of two flight unit development projects, a set of 10 competitively-selected research and development efforts in power conversion technology, focused research tasks on thermoelectric and Stirling energy conversion, and system analyses to support selection of technologies and evaluation of RPS for promising future mission applications. This presentation describes the content of the program, and discusses its future direction.

Thermophotovoltaic Converter Design for Radioisotope Power Systems

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Abstract. The development of light weight, efficient power for emerging NASA missions and recent advances in thermophotovoltaic (TPV) conversion technology have renewed interest in combining radioisotope heat sources with photovoltaic energy conversion. Thermophotovoltaic power conversion uses advanced materials able to utilize a broader, spectrally-tuned range of wavelengths for more efficient power conversion than solar cells. Spectral control, including selective emitters, TPV module, and filters are key to high-efficiency operation. The paper outlines the mechanical, thermal, and optical designs for the converter, including the heat source, the selective emitter, filters, photovoltaic cells, and optical cavity components. Focus is on the emitter type and the band-gap of InGaAs PV cells in developing the design. Any component and converter data available at the time of publication will also be presented.

Radiation Effects in Refractory Alloys

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Abstract. In order to achieve the required low reactor mass per unit electrical power for space reactors, refractory alloys are essential due to their high operating temperature capability that in turn enables high thermal conversion efficiencies. One of the key issues associated with refractory alloys is their performance in a neutron irradiation environment. This paper will review the available radiation effects information on alloys based on Mo, W, Nb and Ta. The largest data base is associated with Mo alloys, whereas W and Ta alloys have the least available information. Particular attention will be focused on Nb-1Zr, which is a proposed cladding and structural material for the Jupiter Icy Moons Orbiter (JIMO) space reactor project.

All of the refractory alloys exhibit qualitatively similar temperature-dependent behavior. At low temperatures up to ~$0.3T_M$, where T_M is the melting temperature, the dominant effect of radiation is to produce pronounced radiation hardening and concomitant loss of ductility. The radiation hardening also causes a dramatic decrease in the fracture toughness of the refractory alloy. These low temperature radiation effects occur at relatively low damage levels of ~0.1 displacement per atom, dpa (~$2x10^{20}$ n/m^2, E>0.1 MeV). As a consequence, operation at low temperatures in the presence of neutron irradiation must be avoided for all refractory alloys. At intermediate temperatures (0.3 to 0.6 T_M), void swelling and irradiation creep are the dominant effects of irradiation. The amount of volumetric swelling associated with void formation is generally within engineering design limits (<5%) except at very high doses (>>10 dpa). Very little experimental data exist on irradiation creep of refractory alloys, but data for other body centered cubic alloys suggest that the creep rate per unit stress is ~$0.5x10^{-12}$/Pa-dpa. Therefore, irradiation creep is anticipated to produce negligible deformation for near-term space reactor applications.

ENABLER Nuclear Propulsion System Conceptual Design

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Abstract. The Titan Corporation conducted a systems engineering study to develop an overall architecture that meets both the articulated and unarticulated requirements on the Prometheus Program with the least development effort. Key elements of the Titan-designed ENABLER system include a thermal fission reactor, thermionic power converters, sodium heat pipes, ion thruster engines, and a radiation shield and deployable truss to protect the payload. The overall design is scaleable over a wide range of power requirements from 10s of kilowatts to 10s of megawatts.

Test Facilities and Experience on Space Nuclear System Developments at the Kurchatov Institute

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Abstract. The complexity of space fission systems and rigidity of requirement on minimization of weight and dimension characteristics along with the wish to decrease expenditures on space nuclear system development demand implementation of experimental works which results shall be used in designing, safety substantiation, and licensing procedures. Experimental facilities are intended to solve the following tasks: obtainment of benchmark data for computer code validations, substantiation of design solutions when computational efforts are too expensive, quality control in a production process, and "iron" substantiation of criticality safety design solutions in licensing and public relations. The NARCISS and ISKRA critical facilities along with the unique ORM facility on shielding investigations on the basis of the operating nuclear reactor were created in the Kurchatov Institute to solve the mentioned task. The range of activities at these facilities is described in the paper.

Effects of Asymmetry on IEC Ion Confinement and the Observation of Synchronization Behavior

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Abstract. Inertial Electrostatic Confinement (IEC) Fusion holds promise as a lightweight alternative to magnetically confined fusion machines for future intrasolar system transportation. Current IEC devices are not efficient, with a fusion gain of less than $Q=10^{-4}$. The purpose of MIT's effort is to improve the efficiency and power consumption of the devices by an order of magnitude in order to render the devices economically viable as neutron sources for medical, industrial and security applications. The effect of asymmetries on traditional single grid geometries is examined using a 2-D Particle-in-a Cell Monte Carlo model. Single grids are found to exhibit very poor ion confinement due to the high voltage stalk. The introduction of multiple accelerating grids is shown to effectively shield the stalk and create well-confined ion channels, significantly increasing the ion lifetimes in the device and the fusion gain.

A synchronization effect is observed in the trap and holds promise as a means to counteract long term ion thermalization effects. Under constant ion injection, the recirculating ions 'clump' together and oscillate within the device. A similar synchronization phenomenon has been observed in electrostatic ion traps by H. B. Andersen, et al. at the Weizmann Institute of Science, and they show that the synchronization is a result of the repulsive coulomb interaction in the anode regions of the trap. The IEC model showing this behavior will be presented and the implications of self-organizing oscillating plasma will be discussed. Such a configuration could provide a means to maintain long-lived non-maxwellian fusion plasma in an IEC device.

Advanced Technology Development for Stirling Convertors

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Abstract. A high-efficiency Stirling Radioisotope Generator (SRG) for use on potential NASA Space Science missions is being developed by the Department of Energy, Lockheed Martin, Stirling Technology Company, and NASA Glenn Research Center (GRC). These missions may include providing spacecraft onboard electric power for deep space missions or power for unmanned Mars rovers. GRC is also developing advanced technology for Stirling convertors, aimed at substantially improving the specific power and efficiency of the convertor and the overall power system. Performance and mass improvement goals have been established for second- and third-generation Stirling radioisotope power systems. Multiple efforts are underway to achieve these goals, and the status and results to date for these efforts are discussed in this paper.

Cleveland State University (CSU) is developing a multi-dimensional Stirling computational fluid dynamics code, capable of modeling complete convertors. A 2-D version of the code is now operational. Validation efforts at both CSU and the University of Minnesota are complementing the code development. A screening of advanced superalloy, refractory alloy, and ceramic materials has been completed, and materials have been selected for creep and joining characterization as part of developing a high-temperature heater head. A design has been completed for an advanced controller using power electronics for active power factor control with a goal of eliminating the heavy tuning capacitors that are traditionally needed to achieve near unity power factors. A breadboard characterization of this controller is now underway. An end-to-end system dynamics model is also being developed, and one use will be to help guide the advanced controller work. Key Stirling developments being done under recent NRA (NASA Research Announcement) awards for radioisotope power system technology will also be discussed. These include a lightweight convertor being developed by Sunpower Inc. and an advanced regenerator being done by CSU.

Refractory Metal Compatibility Issues in JIMO Space Reactor Concepts

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Abstract. Refractory metal alloys are often specified for several reactor – thermal conversion systems used for electrical power generation in space applications. because they have many of the essential properties needed for the elevated temperatures required for good thermal efficiency. However, the reactions of refractory metals with the constituents of he various system environments (including alkali metals and inert gases) at high temperatures can lead to materials degradation that would limit system power output or lifetime. The principal corrosion processes that may be operative for these refractory metal systems include dissolution by a liquid alkali metal, mass transfer (driven by temperature gradients and dissimilar materials), and impurity reactions (particularly with oxygen). In the reactor – thermal conversion systems being considered for the JIMO project, all of the above mechanisms are possible. While Nb-1%Zr is the reference fuel cladding material in all concepts, each combination of reactor type and power conversion system includes different sets of materials and environmental conditions. These material-environment combinations require evaluation for possible compatibility issues and operational limitations. For example, in a lithium-cooled reactor or a sodium heat pipe system, dissolution and mass transfer for the fuel cladding and coolant containment materials must be considered but can be managed under most circumstances. In a He-Xe cooled reactor system, impurity reactions and contamination/embrittlement of Nb-1Zr are potential serious compatibility issues, particularly if a superalloy is used in the samecircuit.

A High Efficiency DC Bus Regulator / RPC for Spacecraft Applications

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Abstract. DC bus voltage regulation may be required in spacecraft for deep space due to the length of the busses or because they are not generated at precise voltage levels. In these cases the regulation range is often only a few percent increase or decrease, but conventional DC voltage regulators switch all the power passing through them, and this level of power switched determines the size and losses in the regulator. A recently developed concept uses a low power bi-directional DC-DC converter in series with the bus to raise or lower the bus voltage over a small range. This partial power processing technique combines the small size and power losses of the low power converter with the ability to regulate, (over a small range) a high power bus. The Series Connected Buck Boost Regulator (SCBBR) described herein provides bus regulation with an efficiency of 98%. The circuit also provides bus switching and overcurrent limiting functions of a Remote Power Controller (RPC). This paper describes the circit design and performance of a breadboard SCBBR configured as a bus voltage regulator providing +/- 40% voltage regulation range, bus switching, and overload limiting.

Modeling of an AC Power System for High Power Spacecraft

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Abstract. This paper presents an analysis and simulation of an AC power system for a high power spacecraft that primarily supplies rectified loads. Two different configurations consisting of a three-phase PM synchronous generator and an associated power electronics converter are compared and analyzed. The first configuration consists of a three-phase PM synchronous generator and a three-phase diode bridge supplying a DC load. The second configuration consists of a three-phase PM synchronous generator and a three-phase PWM rectifier supplying the DC load. The modeling equations for both systems are derived. The comparisons between the two different configurations are summarized in a table in terms of efficiency, harmonic content and DC voltage ripple. The simulation results obtained by using SIMULINK are presented.

Advanced Small Free-Piston Stirling Convertors for Space Power Applications

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Abstract. This paper reports on the current status of an advanced 35 We free-piston Stirling convertor currently being developed under NASA SBIR Phase II funding. Also described is a further advanced and higher performance ~80 watt free-piston convertor being developed by Sunpower and Boeing/Rocketdyne for NASA under NRA funding. Exceptional overall convertor (engine plus linear alternator) thermodynamic performance (greater than 50% of Carnot) with specific powers around 100 We /kg appear reasonable at these low power levels.

Internal Gelation as Applied to the Production of Uranium Nitride Space Nuclear Fuel

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Abstract. The production of uranium nitride fuel depends upon a qualified and controlled method for obtaining a final fuel form. The final fuel form must have the desired properties, fuel density, fuel chemistry (X/U ratio), and impurity levels. These properties must be maintained throughout the entire fuel fabrication process and throughout the fuel operational lifetime. A variety of methods have been used during the past 40 years to obtain uranium nitride with applicable work performed on the (U, Pu)Nx system. These methods each have strengths and weaknesses with respect to the above criteria. Of the methods reviewed, the internal gelation process appears to be a viable method for well-controlled production of uranium nitride fuel for space nuclear reactors. It can be used to produce a uniform size microsphere that can in turn be used to produce high quality, low impurity UN fuel. This paper provides a summary review of many of the processes available for obtaining uranium nitride. The internal gelation process is described and limitations and advantages are discussed with respect to the fabrication of uranium nitride. Finally, recent results of uranium nitride fuel fabrication efforts using an internal gelation process are presented and discussed.

Status of Fuel Development and Manufacturing for Space Nuclear Reactors at BWX Technologies

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Abstract. New advanced nuclear space propulsion systems will soon seek a high temperature, stable fuel form. BWX Technologies Inc (BWXT) has a long history of fuel manufacturing. UO2, UCO, and UCx have been fabricated at BWXT for various US and international programs. Recent efforts at BWXT have focused on establishing the manufacturing techniques and analysis capabilities needed to provide a high quality, high power, compact nuclear reactor for use in space nuclear powered missions. To support the production of a space nuclear reactor, uranium nitride has recently been manufactured by BWXT. In addition, analytical chemistry and analysis techniques have been developed to provide verification and qualification of the uranium nitride production process. The fabrication of a space nuclear reactor will require the ability to place an unclad fuel form into a clad structure for assembly into a reactor core configuration. To this end, BWX Technologies has reestablished its capability for machining, GTA welding, and EB welding of refractory metals. Specifically, BWX Technologies has demonstrated GTA welding of niobium flat plate and EB welding of niobium and Nb-1Zr tubing. In performing these demonstration activities, BWX Technologies has established the necessary infrastructure to manufacture UO2, UCx, or UNx fuel, components, and complete reactor assemblies in support of space nuclear programs.

Coupled MEMS Nuclear Battery and FEEP Thruster System

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Abstract. This paper describes research on combining a microelectromechanical system (MEMS) nuclear battery with a field-emission electric propulsion (FEEP) thruster, thereby providing potentially attractive solutions to precise satellite stationkeeping and propulsion requirements. The MEMS nuclear battery, under development at the University of Wisconsin, consists of multiple layers of a radioisotope source alternating with pn junction energy converters. Many radioisotopes have been assessed for this purpose, typically with average beta-particle energies of 10-250 eV, and the beta-emitter Cs-137 tentatively has been identified as most suitable. A slit-style, cesium-propellant FEEP thruster was chosen for the present study because it is a relatively mature technology. For use with a FEEP thruster, many modular MEMS nuclear batteries must be arrayed in series in order to achieve a sufficiently high voltage (~10 kV). Critical issues include achieving an attractively high efficiency for the MEMS nuclear battery, maximizing the battery.s lifetime against radiation damage, producing the relatively high voltage (~10 kV) required for a FEEP thruster, and providing an effective interface between the MEMS nuclear battery modules and the FEEP thruster.

Power Management and Distribution Trades Studies for a Deep-Space Mission Scientific Spacecraft

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Abstract. As part of NASA's Project Prometheus, the Nuclear Systems Program, NASA GRC performed trade studies on the various *Power Management and Distribution* (PMAD) options for a deep-space scientific spacecraft, which would have a nominal electrical power requirement of 100 kWe. These options included AC (1000Hz and 1500Hz) and DC primary distribution at various voltages. The distribution system efficiency, reliability, mass, thermal, corona, space radiation levels, and technology readiness of devices and components were considered. The final proposed system consisted of two independent power distribution channels, sourced by two 3-phase, 110 kVA alternators nominally operating at half-rated power. Each alternator nominally supplies 50 kWe to one-half of the ion thrusters and science modules, but is capable of supplying the total power requirements in the event of loss of one alternator. This paper is an introduction to the methodology for the trades done to arrive at the proposed PMAD architecture. Any opinions expressed are those of the author(s) and do not necessarily reflect the views of Project Prometheus.

Reactor Startup and Control Methodologies: Consideration of the Space Radiation Environment

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Abstract. The use of fission energy in space power and propulsion systems offers considerable advantages over chemical propulsion. Fission provides over six orders of magnitude higher energy density, which translates to higher vehicle specific impulse and lower specific mass. These characteristics enable the accomplishment of ambitious space exploration missions. The natural radiation environment in space provides an external source of protons and high energy, high Z particles that can result in the production of secondary neutrons through interactions in reactor structures. Initial investigation using MCNPX 2.5.b for proton transport through the SAFE-400 reactor indicates a secondary neutron net current of 1.4×10^7 n/s at the core-reflector interface, with an incoming current of 3.4×10^6 n/s due to neutrons produced in the Be reflector alone. This neutron population could provide a reliable startup source for a space reactor. Additionally, this source must be considered in developing a reliable control strategy during reactor startup, steady-state operation, and power transients. An autonomous control system is developed and analyzed for application during reactor startup, accounting for fluctuations in the radiation environment that result from changes in vehicle location (altitude, latitude, position in solar system) or due to temporal variations in the radiation field, as may occur in the case of solar flares. One proposed application of a nuclear electric propulsion vehicle is in a tour of the Jovian system, where the time required for communication to Earth is significant. Hence, it is important that a reactor control system be designed with feedback mechanisms to automatically adjust to changes in reactor temperatures, power levels, etc., maintaining nominal operation without user intervention. This paper will evaluate the potential use of secondary neutrons produced by proton interactions in the reactor vessel as a startup source for a space reactor and will present a potential control methodology for reactor startup procedures in the event of source fluctuations.

NEMO: A Mission to Explore and Return Samples from Europa's Oceans

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Abstract. The NEMO (Nuclear Europa Mobile Ocean) mission would explore and return samples and possible life forms from Europa's sub-surface oceans to Earth. The NEMO spacecraft would land on Europa two years after leaving Earth, using a compact bi-modal NTP engine. NEMO's small nuclear reactor melt probe would then melt a channel through the multi-km ice sheet to the ocean, which a small robotic submarine would explore, transmitting data by sonic link and optical fiber to the spacecraft for relay to Earth. After its exploration, the submarine would rejoin the melt probe, for return to the NEMO spacecraft. Using electricity from the bi-modal MITEE engine, fresh H_2 propellant would be manufactured by electrolysis of melt water from surface ice. NEMO would then hop to a new site, exploring ten sites in a year before returning with samples and life forms to Earth, six years after it left. The design and performance of the NEMO spacecraft, MITEE engine, melt probe, and submarine are described. The probe and submarine use existing reactor technology. A NEMO mission could launch shortly after 2013 AD.

Cylindrical Inverted Multi-Cell (CIM) Thermionic Converter for Solar Power and Propulsion Systems

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Abstract. Design and fabrication of a novel cylindrically inverted multi-cell (CIM) thermionic device is in progress. This device is an experimental prototype consisting of four cells that are externally heated and electrically connected to produce 736 W of electrical power. The prototype is the basis for a 1.5 kW eight cell solar space power thermionic device that, when bussed together with multiple thermionic devices (~ 30 to 40), can produce approximately 50 kW of electric power. The objective of this paper is to describe the design of an experimental prototype four cell CIM thermionic converter that is currently being designed and fabricated by General Atomics (GA).

Planetary Missions Enabled by Nuclear Power and Propulsion

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Abstract. The introduction by NASA of the Prometheus Program has a major impact on the types of planetary missions that are feasible. Spacecraft power levels near or above 100kW suddenly open the door to enabling a new class of robotic missions that could formerly only be dreamed about. This paper will discuss some ways that nuclear power can enable mission design and science return by examining three example missions: a Neptune System Orbiter, a Martian Surface Deep Drilling Platform, and a Small Bodies Explorer. Each of these missions offers significant challenges that are mitigated by the availability of nuclear power and/or propulsion. The Neptune system displays a wealth of physical phenomenon that merits a dedicated, long-duration mission. The large distance of the Neptune system from the sun precludes the sun as a source of spacecraft energy, and an extended tour of this system with sequential mission stages that address Triton, Neptune, and the ring system are optimally done with a NEP mission design.The subsurface of Mars is of extreme interest to both the planetary and astrobiological communities, particularly in light of the recent observation of a large subsurface water-ice reservoir on a global scale. The possibility remains open that this reservoir could coexist with subsurface liquid aquifers that could provide an environment that is conducive to life. Access to such proposed deep aquifers requires deep drilling, enabled by a large power source.There are multiple classes of small bodies in the solar system that could be studied by the propulsive capability offered by NEP, including main belt asteroids, Near-Earth Objects (NEO's), and Kuiper-Belt Objects (KBO's). To optimally understand this large and diverse population requires a set of grand tours that can assess both the composition and structure of such bodies. This information is also critical to assess the optimal methods for NEO hazard mitigation, which is in turn enabled by the prospect of large space-borne power sources.

Overview 2003 of NASA Multi-D Stirling Convertor Code Development and DOE & NASA Stirling Regenerator R&D Efforts

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Abstract. This paper will report on (1) continuation through the 3rd year of a NASA grant for multi-dimensional Stirling CFD code development and validation, (2) continuation through the 3rd and final year of a Department of Energy, Golden Field Office (DOE), regenerator research effort and plans for NASA funding of a grant for continuation of the effort through two additional years, and (3) a new NASA Research Award for design, microfabrication and testing of a "Next Generation Stirling Engine Regenerator." Cleveland State University (CSU) is the lead organization for all three efforts, with the University of Minnesota (UMN) and Gedeon Associates as subcontractors. The Stirling Technology Co. and Sunpower, Inc. acted as unfunded consultants or participants through the 3rd years of both the NASA multi-D code development and DOE regenerator research efforts; they will both be subcontractors on the new regenerator microfabrication contract. Results of the NASA multi-D code development effort and the DOE regenerator research effort will be summarized. Plans for the NASA continuation of the DOE regenerator research effort include extension of the large-scale regenerator testing at UMN from a regenerator matrix of 90% porosity to one of 95%, measurement of thermal dispersion in the regenerator, investigation of the effect of various heat exchanger tube exit geometries on jetting into the matrix, continued regenerator CFD modeling at CSU, and heat transfer and pressure drop testing of random fiber regenerators with porosities as high as ~95% in the NASA oscillating-flow test rig on loan to Sunpower. Early results and planning for the new regenerator microfabrication contract will also be discussed.

Colliding Beam Fusion Reactor Space Propulsion System

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Abstract. The Colliding Beam Fusion Reactor Space Propulsion System, CBFR SPS, is an energetic-ion, magnetic-field-reversed configuration, fueled by a mixture of Hydrogen and Boron^{11} (H-B^{11}). Fusion-product ions (Helium alpha particles) are expelled out of the fusion core along the axis of symmetry. Ions flowing in one direction are decelerated and their energy recovered to "power" the system; ions expelled in the opposite direction provide thrust. Particle confinement and transport in the CBFR SPS are classical, hence the system should be scaleable. Moreover, the system is aneutronic and does not require the use of a massive radiation shield. We are developing a "systems model" for the CBFR SPS that includes component-level designs and performance parameters and which will facilitate rapid evaluation of design tradeoffs and mass-scaling relationships. This paper presents our design for a 100 MW CBFR SPS, including estimates for the propulsion parameters and subsystem masses. Specific emphasis is given to the design of the Thermal Control Subsystem, TCS, which comprises the single, largest, system-mass component.

NASA GRC High Power Electromagnetic Thruster Program

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Abstract. Interest in high power electromagnetic propulsion has been revived to support a variety of future space missions, such as platform maneuvering in low earth orbit, cost-effective cargo transport to lunar and Mars bases, asteroid and outer planet sample return, deep space robotic exploration, and piloted missions to Mars and the outer planets. Magnetoplasmadynamic (MPD) thrusters have demonstrated, at the laboratory level, the capacity to process megawatts of electrical power while providing higher thrust densities than current electric propulsion systems. The ability to generate higher thrust densities permits a reduction in the number of thrusters required to perform a given mission and alleviates the system complexity associated with multiple thruster arrays. The specific impulse of an MPD thruster can be optimized to meet given mission requirements, from a few thousand seconds with heavier gas propellants up to 10,000 seconds with hydrogen propellant. In support of NASA space science and human exploration strategic initiatives, Glenn Research Center is developing and testing pulsed, MW-class MPD thrusters as a prelude to long-duration high power thruster tests. The research effort includes numerical modeling of self-field and applied-field MPD thrusters and experimental testing of quasi-steady MW-class MPD thrusters in a high power pulsed thruster facility. This paper provides an overview of the GRC high power electromagnetic thruster program and the pulsed thruster test facility.

Progress on Low-Power Turbo-Brayton Converters

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Abstract. Previous work has shown that closed-loop Brayton cycle power converters are an extremely attractive option for long-duration (> 10 years) space missions. To date, this technology has been only demonstrated at power levels above 1 kWe. Creare's progress towards the demonstration of the first-generation, low-power converter for use with radioisotope power sources is the subject of this paper. At the 100 We power level, Brayton systems should attain conversion efficiencies of 20% to 40% depending upon the operating conditions. The converter mass for a flight unit is expected to be about 3 kg. The detailed design, performance predictions, and test plans for the first-generation converter are reviewed.

Shock-Tolerant Low-Power Generator Design for Landed Missions

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Abstract. A shock-tolerant thermal enclosure has been designed for use in distributed landed missions. Missions such as Pascal and the Mars Long-Lived Landed Network require low power sources capable of surviving an omnidirectional load at impact and delivering reliable power for several Martian years. With the use of a radioisotope heat source and a thermoelectric converter, power can be generated reliably, but the challenge of developing an insulating canister that delivers sufficient power at end of life and is shock tolerant has been elusive. We describe a manufacturable design using conventional materials that meets mission requirements and show preliminary analysis of impact load response.

Our Milliwatt Radioisotope Power Source (mWRPS) has been designed using two Radioisotope Heater Units (RHUs). Each RHU generates approximately 1 W of thermal power from the decay of ^{238}Pu. The mWRPS is designed to channel the majority of the heat flow through the thermoelectric converter, generating approximately 35 mW at beginning of life. The design meets thermal, mechanical, and power requirements while being explicitly designed within the integration constraints imposed by the use of RHUs. The mWRPS uses a Stewart platform to support the RHU canister through a quasi-static omnidirectional load of up to 500 g's. Aerogel bead insulation was chosen to simplify manufacture, integration, and test while maintaining thermal performance. Detailed, high fidelity thermal and structural models validate the performance. Drawings have been completed to support the fabrication and test of a prototype generator. Further, the modeling and design experience may be applied to alternate designs, such as a generator using a General Purpose Heat Source (GPHS), generating 250 W thermal power, instead of a 1 W RHU.

An Overview of Prismatic Cermet Fuel Development and Test Data

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Abstract. The General Electric space reactor development program in 1960's (GE 710) produced a wealth of nuclear and non-nuclear test data on cermet fuels that are of direct relevance to the current NASA's nuclear powered mission initiative. In mid 1965 the objectives of GE 710 program were changed to accommodate the design of a 200KWe space power reactor for 10,000 of operation. For this design the fuel power density was much lower than previous designs and core temperatures in the range of 2000-2250 K to provide exit gas temperature compatible with a Brayton cycle power conversion system. The cermet fuel design program for both the GE 710 and a parallel nuclear rocket program at Argonne National Laboratory was concentrated primarily on refractory alloys-uranium dioxide with small (~ 100 micron) fuel particles dispersed in continuous refractory alloys with outer cladding of the entire fuel form using refractory alloys. Each of these components of cermet fuel was the subject of material development and testing effort and a considerable boy of data was generated. Burnup data was accumulated for 10,000 hours of test intervals without fuel failure at 1870-2070 K temperature range. Other data obtained during the GE 710 program achieved burnup values ranging from .1 to 16 atom% for all variant cermet compositions in temperatures ranging from 1600 K to 2220 K. In other non-nuclear testing cermet fuel candidates survived temperature environments of up to 3270 K for one hour and 3000 K for 50 hours. An additional major portion of test data are results of thermal cycling (up to 100 cycles) of nuclear fuel to 2070 K. Excellent results were obtained from these experiments, indicating the remarkable strength, durability, and reliability of cermet fuels for space power applications. The most significant outcome of the joint INSPI-LUTCH program was the establishment of the high temperature characteristics of the tungsten-uranium-zirconium cabonitride, W-(U,Zr)CN cermet and that included the demonstration of long term stability and chemical compatibility of (U,Zr)CN with the metallic matrix. The coating of micron size (U,Zr)CN fuel particles fuels refractory alloys provides a strong barrier for fission products retention.

Preliminary Comparison Between Nuclear-Electric and Solar-Electric Propulsion Systems for Future Mars Missions

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Abstract. Recent US and European initiatives in Nuclear Propulsion lend themselves naturally to raising the question of comparing various options and particularly Nuclear Electric Propulsion (NEP) with Solar Electric Propulsion (SEP). SEP is in fact mentioned in one of the latest versions of the NASA Mars Manned Mission as a possible candidate. The purpose of this paper is to compare NEP, for instance, using high power MPD, Ion or Plasma thrusters, with SEP systems. The same payload is assumed in both cases. The task remains to find the final mass ratios and cost estimates and to determine the particular features of each technology. Each technology has its own virtues and vices: NEP implies orbiting a sizeable nuclear reactor and a power generation system capable of converting thermal into electric power, with minimum mass and volumes compatible with Ariane 5 or the Space Shuttle bay. Issues of safety and launch risks are especially important to public opinion, which is a factor to be reckoned with. Power conversion in space, including thermal cycle efficiency and radiators, is a technical issue in need of attention if power is large, i.e., of order 0.1 MW and above, and so is power conditioning and other ancillary systems. These, and other factors will be considered in this comparison. The goal is to provide preliminary guidelines in evaluating SEP and NEP that may be useful to suggest closer scrutiny of promising concepts, or even potential solutions.

Heat Source Neutron Emission Rate Reduction Studies– Water Induced HF Liberation

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Abstract. The neutron emission rate (NER) of general purpose heat source (GPHS) or light-weight radioisotope heater unit (LWRHU) pellets must be decreased to less than 6,000 neutrons/sec/gram 238Pu in order to minimize worker exposures during the assembly of the radioisotope thermal electric generator and to minimize radiation exposure of sensitive equipment. The NER of 238PuO2 fuel is dependent on, among other factors, light elements in the fuel powder. The alpha decay from 238Pu results in a,n reactions with elements such as 17O, 18O, and 19F. The first steps in the fuel processing typically involve aqueous purification (dissolution-reprecipitation-calcination). Removal of fluoride during aqueous plutonium processing within the Department of Energy complex has historically involved an aluminum nitrate treatment followed by ion exchange. At Los Alamos National Laboratory, a new method involving addition of de-ionized water to the purified 238PuO2, followed by heating to remove the water and liberating fluoride as HF, has been shown to further reduce the neutron emission rate in the 238PuO2. Data will be presented to show that the NER-reduction effect of the water rinse treatment is comparable to that of the aluminum nitrate treatment and ion exchange, without the generation of large volumes of liquid waste. During subsequent powder processing, heat treatment of the fuel under an H216O-argon atmosphere allows 16O to be exchanged for 17O and 18O in the fuel, reducing the NER by one-half. Data will be presented on the work performed to optimize the 16O-exchange process so that even lower 238PuO2 fuel NERs are attained.

A Figure of Merit for Geometrical Design of Space Reactor Fuels

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Abstract. Compactness and very high power density and short life for nuclear thermal propulsion, and low power density and very long life are characterizing features of space nuclear power systems. The most important constraint in design of fuel element and reactor core for any level of power operation is the minimization of fuel surface and centerline temperatures. Fuel temperature distribution depends on the volumetric heat generation rate, material properties, geometrical configuration, and dimensions of fuel element. The size of the fuel and core are decided by nuclear design and burnup considerations for any particular fuel and clad material. For any reactor core design, the only variable that impacts fuel temperature distribution is the geometrical design of the fuel. As a result, a variety of fuel designs have been proposed and used in space power reactors. These fuel element designs include tubular (prismatic), pin (rod), plate, square lattice honeycomb, and twisted ribbon. A new dimensionless parameter, delta number, is defined as a figure of merit for fuel element design. Fourier conduction equation is used to derive the delta number, which represents the ratio of heat generation rate in the fuel to the total heat transfer rate to the coolant. The higher value of the delta number means lower value of the fuel centerline temperature for the same level of reactor thermal power. The Fourier conduction equation is solved for all fuel geometries described in this paper to evaluate the delta number as a function of the core flow area ratio. Analytical solutions are obtained for pin and plate fuel geometries. Finite element method is used to solve the Fourier equation for more complicated geometries of tubular, square lattice honeycomb, and twisted ribbon fuels. Results obtained in this work indicate that at core flow area ratios less than 50%, the delta number for the square lattice honeycomb and tubular fuel designs are higher than all others. At flow area ratio of about 50% or more, the delta number for the plate fuel design exceeds the value of delta number for all other fuel designs.

Estimation of Specific Mass for Multimegawatt NEP Systems Based on Vapor Core Reactors with MHD Power Conversion

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Abstract. Very low specific-mass power generation in space is possible using Vapor Core Reactors with Magnetohydrodynamic (VCR/MHD) generator. These advanced reactors at the conceptual design level have potential for the generation of tens to hundreds of megawatts of power in space with specific mass of about 1 kg/kWe. Power for nuclear electric propulsion (NEP) is possible with almost direct power conditioning and coupling of the VCR/MHD power output to the VASIMR engine, MPD, and a whole host of electric thrusters. The VCR/MHD based NEP system is designed to power space transportation systems that dramatically reduce the mission time for human exploration of the entire solar system or for aggressive long-term robotic missions. There are more than 40 years of experience in the evaluation of the scientific and technical feasibility of gas and vapor core reactor concepts. The proposed VCR is based on the concept of a cavity reactor made critical through the use of a reflector such as beryllium or beryllium oxide. Vapor fueled cavity reactors that are considered for NEP applications operate at maximum core center and wall temperatures of 4000 K and 1500K, respectively.

A recent investigation has resulted in the conceptual design of a uranium tetrafluoride fueled vapor core reactor coupled to a MHD generator. Detailed neutronic design and cycle analyses have been performed to establish the operating design parameters for 10 to 200 MWe NEP systems. An integral system engineering-simulation code is developed to perform parametric analysis and design optimization studies for the VCR/MHD power system. Total system weight and size calculated based on existing technology has proven the feasibility of achieving exceptionally low specific mass (α ~1 kg/kWe) with a VCR/MHD powered system.

Attitude & Momentum Control/Operation Strategy and Architecture For Nuclear-Electrical Propulsion Deep Space Vehicles

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Abstract Nuclear-Electrical Propulsion vehicles present many unique challenges to the design of guidance, navigation and control systems. This paper will focus on the attitude and momentum control & operation strategies and the associated system architecture design for the various phases of the spacecraft mission. Of special interests are the strategies and architecture design for the initial nuclear power startup, initial electrical-thrusting startup, earth-spiral out, deep space cruise and coasting, planet and moon spiral-in, planet and moon orbiting. For all the mission phases, pointing and momentum control strategies are designed to maintain spacecraft safety, support science requirements with minimized equipment and propellant mass.

Evaluation of Active Working Fluids for Brayton Cycles in Space Applications

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Abstract. The main parameter of interest for space thermal power conversion to electricity is specific power, defined as the total electric power output per unit of system mass, rather than the cycle thermal efficiency. For a closed Brayton cycle, performance with two active working fluids, nitrogen tetroxide and aluminum chloride, is compared to that with an inert mixture of helium and xenon having a molecular mass of 40. A chemically active working fluid is defined here as a chemical compound that has a relatively high molecular weight at temperatures appropriate for the compressor inlet and dissociates to a lighter molecular weight fluid at typical turbine inlet temperatures. The active working fluids may have the advantage of a higher net turbomachinery work output and an advantageous enhancement of the heat transfer coefficient in the heat exchangers. The fundamental theory of the active working fluid concept is presented to demonstrate these potential advantages. Scoping calculations of the heat exchanger mass for a selected spacecraft application of 36.4 kW of electrical power output show that the nitrogen tetroxide active working fluid has an advantageous 7% to 30% lower mass-to-power ratio than that for the inert noble gas mixture, depending on the allowable turbine inlet temperature. The calculations for the aluminum chloride system suggest only a slight improvement in performance relative to the inert noble gas mixture.

Single Channel Testing for Characterization of the Direct Gas Cooled Reactor and the SAFE-100 Heat Exchanger

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Abstract. Experiments have been designed to characterize the coolant gas flow in two space reactor concepts that are currently under investigation by NASA Marshall Space Flight Center and Los Alamos National Laboratory: the direct-drive gas-cooled reactor (DDG) and the SAFE-100 heatpipe-cooled reactor (HPR). For the DDG concept, initial tests have been completed to measure pressure drop versus flow rate for a prototypic core flow channel, with gas exiting to atmospheric pressure conditions. The experimental results of the completed DDG tests presented in this paper validate the predicted results to within a reasonable margin of error. These tests have resulted in a re-design of the flow annulus to reduce the pressure drop. Subsequent tests will be conducted with the re-designed flow channel and with the outlet pressure held at 150 psi (1 MPa). Design of a similar test for a nominal flow channel in the HPR heat exchanger (HPR-HX) has been completed and hardware is currently being assembled for testing this channel at 150 psi. When completed, these test programs will provide the data necessary to validate calculated flow performance for these reactor concepts (pressure drop and film temperature rise).

Thermally Simulated 32kWatt Direct-Drive Gas-Cooled Reactor: Design, Assembly, and Test

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Abstract. One of the power systems under consideration for nuclear electric propulsion is a direct-drive gas-cooled reactor coupled to a Brayton cycle. In this system, power is transferred from the reactor to the Brayton system via a circulated closed loop gas. To allow early utilization, system designs must be relatively simple, easy to fabricate, and easy to test using non-nuclear heaters to closely mimic heat from fission. This combination of attributes will allow pre-prototypic systems to be designed, fabricated, and tested quickly and affordably. The ability to build and test units is key to the success of a nuclear program, especially if an early flight is desired. The ability to perform very realistic non-nuclear testing increases the success probability of the system. In addition, the technologies required by a concept will substantially impact the cost, time, and resources required to develop a successful space reactor power system. This paper describes design features, assembly, and test matrix for the testing of a thermally simulated 32kWatt direct-drive gas-cooled reactor in the Early Flight Fission – Test Facility (EFF-TF) at Marshall Space Flight Center. The reactor design and test matrix are provided by Los Alamos National Laboratories. The opinions expressed in this paper do not necessarily reflect the views of the JIMO Project.

Early Flight Fission Test Facilities (EFF-TF) To Support Near-Term Space Fission Systems

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Abstract. Through hardware based design and testing, the EFF-TF investigates fission power and propulsion component, subsystems, and integrated system design and performance. Through demonstration of systems concepts (designed by Sandia and Los Alamos National Laboratories) in relevant environments, previous non-nuclear tests in the EFF-TF have proven to be a highly effective method (from both cost and performance standpoint) to identify and resolve integration issues. Ongoing research at the EFF-TF is geared towards facilitating research, development, system integration, and system utilization via cooperative efforts with DOE labs, industry, universities, and other NASA centers. This paper describes the current efforts for 2003..

Deflection Measurements Of a Thermally Simulated Nuclear Core Using A High-Resolution CCD-Camera

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Abstract. Space fission systems under consideration for near-term missions all use compact, fast- spectrum reactor cores. Reactor dimensional change, which affects neutron leakage, is the dominant source of reactivity feedback for these systems. Accurately measuring core dimensional changes during realistic non-nuclear testing is thus useful for helping predict system "nuclear" behavior. This paper discusses one of several techniques being evaluated for measuring such changes. The proposed technique is to use machine vision to obtain deflection measurements of a thermally simulated nuclear reactor core. This paper introduces a technique by which a single high spatial resolution CCD camera is used to measure in real-time the deflection of a core during all phases of testing. Initial results are presented along with a discussion on how several cameras could be placed in different axial positions to achieve a three-dimensional deflection profile of the test article.

PMAD Architecture Options for NEP Vehicles

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Abstract. Proposed Nuclear Electric Propulsion (NEP) vehicles, under development by NASA, utilizing closed Brayton cycle power conversion will require a power management and distribution (PMAD) system capable of conducting high power (100 to 300 kWe) from the alternators to the thruster power processing units (PPUs) and vehicle loads. The PMAD system must also be capable of shunting and radiating excess reactor generated power, handling the effects of thruster power transients, and isolating and bypassing faults. It distributes power to the spacecraft, power system, and mission module loads, and supplies the power required for power system startup. A variety of PMAD architectures and power distribution methods are available that must be analyzed to ensure the best architecture is selected to meet the vehicle and mission requirements. Some of the items that must be addressed are the number of channels or modules required to meet reliability requirements, the alternator type, and the voltage level that should be employed to minimize cable and PPU mass while staying within the constraints of the alternator and transmission line insulation, semiconductor switches and other voltage sensitive devices. DC or AC distribution must be evaluated on the basis of the alternator frequency, PPU input power and fault interruption requirements, and the possible need for paralleling of the PMAD channels to provide power to the thrusters and vehicle loads under various failure scenarios. The pros and cons of these different approaches are explored in this paper to provide guidance in selecting the proper PMAD approach for meeting vehicle and mission requirements.

The Thousand Astronomical Unit (TAU) Mission Revisited

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Abstract. Nuclear electric propulsion (NEP) robotic interstellar precursor missions were studied in the 1980s to assess the feasibility of science missions to distances from 100 to 1,000 astronomical units (AU). These studies demonstrated that, based on the technology assumptions of the time, such missions could be performed with trip times of decades (e.g., 50 years for 1,000 AU, or 20 AU/year solar system escape velocity). This paper will revisit these missions to re-evaluate their feasibility based on contemporary technology capability estimates. Particular emphasis will be placed on technologies being pursued for the Project Prometheus Jupiter Icy Moon Orbiter (JIMO) mission. Of particular interest will be the technology issues associated with scaling up performance from the relatively near-term requirements of the JIMO mission (e.g., ca. 100 kW_e power system, ion thrusters with specific impulse (I_{sp}) around 6,000 lb_f-s/lb_m) to the demands of aggressive interstellar precursor missions (e.g., MW_e-class power systems, >10,000 lb_f-s/lb_m I_{sp} ion engines).

Carbon Nanotubes as Thermionic Emitters

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Abstract. Thermionic converters are an interesting option for lightweight and long-life power generators due to a number of compelling advantages, including all solid construction, no moving parts, and waste heat rejection at high temperature. An experimental set up has been built that allows the screening of thermionic coatings and new nano-materials from room temperature to 2000 K in high vacuum and at gap sizes as small as 1 mm. A new class of very high temperature compatible materials, carbon nanotubes, has been investigated for their performance as cathodes. Seven different types of carbon nanotubes have been screened as thermionic emitter cathodes and compared to tungsten and nitrogen doped diamond. It has been found that some carbon nanotubes combine excellent temperature stability with good thermal emission performance. Yet, other carbon nanotubes exhibited exceptional combined thermal and field enhanced emission performance.

Progress on a New Non-Volatile Memory for Space Based on Chalcogenide Glass

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Abstract. We report on the progress of a recent addition to non-volatile solid state memory technologies suited for space and other ionizing radiation environments. We summarize the material and processing science behind the current generation of chalcogenide phase-change memories fabricated on CMOS structures. The chalcogenide material used for phase-change applications in rewritable optical storage (Ge2Sb2Te5) has been integrated with a radiation hardened CMOS process to produce 64kbit memory arrays. On selected arrays electrical testing demonstrated up to 100% memory cell yield, 100ns programming and read speeds, and write currents as low as 1mA/bit. Devices functioned normally from -55°C to 125°C. Write/read endurance has been demonstrated to 1×108 before first bit failure. Radiation results show no degradation to the hardened CMOS or effects that can be attributed to the phase-change material. Future applications of the technology are discussed.

PowerPC™ RAD750™ - A Microprocessor for Now and the Future

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Abstract. The RAD750™ space hardened microprocessor is a fully licensed PowerPC™ that is identical in architecture, function and operation to the commercial PowerPC 750™ microprocessor. Ongoing performance improvements in both the processor and surrounding devices provide a complete space computer solution for current and future space programs.

Spacecraft Rad Hard Electronics System Design

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Abstract. Space missions to extremely high radiation environments such as Jupiter place many challenges on the design of spacecraft electronics systems. Various parts suppliers in the aerospace electronics industry develop parts which are radiation hardened and/or tolerant to varying degrees. For some part-types sufficiently radiation hardened parts do not exist. This paper explores the techniques used to develop a spacecraft radiation hardened electronics system given this incomplete rad-hard parts availability problem. These techniques include selecting hardware/software architectures that are inherently less susceptible to the effects of radiation, and tolerant of those effects that do occur. Also included is a discussion of the development processes used to implement the selected electronics architecture given the lack of a complete rad-hard parts solution.

Control Resistance Conformal Coating – A New Technology for the Mitigation of the Internal Charging Threat Posed by Jovian Energetic Electrons

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Abstract. The energetic electrons in the Jovian magnetosphere cause charging of dielectric materials and ungrounded metals within electronic assemblies. When the electric field resulting from charging exceeds the breakdown threshold of insulation materials, an electrostatic discharge (ESD) event could occur. The ESD generated transient current could cause circuit upset and electronic parts damage. Of the anomalies that occurred on previous Jupiter bound spacecraft, Voyager and Galileo, most were traced back to internal ESD events. The Boeing Company has developed a control resistance conformal coating (CRCC) for the control of internal ESD. This state-of-the-art coating has sufficient conductivity to bleed off the charging current from energetic electrons in the space environment. Yet, its conductivity is sufficiently low (resistivity sufficiently high) that the functions of electronic circuits are not affected. CRCC has the virtually the same mechanical properties as the currently used Uralane based conformal coating and can be used as a direct replacement. When applied to an electronic assembly, CRCC will ground floating metal. In addition, CRCC also enables a low voltage boundary condition to be present on the surface of dielectric material, reducing the dielectric discharge induced transient to acceptable levels. The use of CRCC on the JIMO avionics will eliminate IESD threats and enhance the survivability of the JIMO spacecraft in the Jovian radiation environment. This paper will present the details of the qualification test program for CRCC.

Experimental Investigations from the Operation of a 2 kW Brayton Power Conversion Unit and a Xenon Ion Thruster

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Abstract. This paper presents experimental test results from the operation of a 2 kWe Brayton power conversion unit (PCU) and a xenon ion thruster. The testing was conducted as part of a Nuclear Electric Propulsion (NEP) Testbed at Glenn Research Center. The 2 kWe Brayton PCU was previously developed for a solar dynamic power system flight experiment planned for the Mir Space Station in 1997. The solar heat receiver was replaced with an electrical resistance heater, simulating the thermal input of a steady-state nuclear source. The PCU was further modified to provide a nominal 1100 VDC electrical output via a NASA Glenn developed Power Management and Distribution (PMAD) system. The ion thruster used was a development model NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) unit. An NSTAR thruster was successfully flown as the main propulsion system on the NASA Deep Space 1 Mission. This test successfully demonstrates that a Brayton PCU can supply and regulate high voltage electrical power to an ion thruster. This test represents follow on work from previous PCU performance characterizations. Future potential uses include Brayton transient mode testing and advanced radiator testing.

A Logical Approach to Designing Safety Test Plans for Space Nuclear Systems

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Abstract. This paper presents a logical approach to designing a safety test plan for a space nuclear system. It is pointed out that two important facts need to underlie the development of a test plan: first, that sequential insults and the accumulation of damage are the rule; and second that the response of the nuclear system is stochastic (i.e., for any given set of conditions a probabilistic range of outcome will occur regardless of the state of our knowledge). Because of these facts a deterministic approach can only be a stating point. The substance of the approach consists of understanding and documenting three basic efforts: (1) a description of the analysts view of the problem and how it fits into the safety analysis, (2) a formal documentation of the purpose and requirements of the test plan (or test), and (3) an assessment of the use or usefulness of existing test data.

Nuclear Photon Rocket vs. Solar Sail

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Abstract. In papers [1,2] the promising use of nuclear photon rockets was shown for exploration of solar system periphery and distant space up to ~ 10000 a.u. from the Earth. Solar sails and nuclear photon rockets have the similar principle of operation except that the power source of the latter is aboard the space unit in the form of a nuclear reactor. It speeds up the space vehicle (SV) while the nuclear fuel is available aboard and the reactor is in its operable conditions. The SV based on solar sails use solar energy whose intensity quardratically decreases depending on the distance to the Sun. So beyond the Mars orbit the speed of the vehicle with a solar sail does not practically increase. In the present work the efficiency of using SVs with nuclear photon systems aboard is compared with that of SVs with solar sails within the framework of the simplest mechanics model at various values of propulsion unit specific power. It has been shown that nuclear photon rockets allow much higher maximum speed to be achieved as compared to that of SUs with solar sails. However in this case the reliable long – term operation of high – temperature nuclear reactor should be provided (several years) at a significant value of thermal power (several hundreds of MW).

High Neutron Fluence Survivability Testing of Advanced Fiber Bragg Grating Sensors

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Abstract. The motivation for the reported research was to support NASA space nuclear power initiatives through the development of advanced fiber optic sensors for space-based nuclear power applications. The purpose of the high-neutron fluence testing was to demonstrate the survivability of fiber Bragg grating (FBG) sensors in a fission reactor environment. 520 FBGs were installed in the Ford reactor at the University of Michigan. The reactor was operated for 1012 effective full power hours resulting in a maximum neutron fluence of approximately 5x1019 n/cm2, and a maximum gamma dose of 2x105 MRad gamma. This work is significant in that, to the knowledge of the authors, the exposure levels obtained are approximately 1000 times higher than for any previously published experiment. Four different fiber compositions were evaluated. An 87% survival rate was observed for fiber Bragg gratings located at the fuel centerline. Optical Frequency Domain Reflectometry (OFDR), originally developed at the NASA Langley Research Center, can be used to interrogate several thousand low-reflectivity FBG strain and/or temperature sensors along a single optical fiber. A key advantage of the OFDR sensor technology for space nuclear power is the extremely low mass of the sensor, which consists of only a silica fiber 125mm in diameter. The sensors produced using this technology will fill applications in nuclear power for current reactor plants, emerging Generation-IV reactors, and for space nuclear power. The reported research was conducted by Luna Innovations and was funded through a Small Business Innovative Research (SBIR) contract with the NASA Glenn Research Center.

Realistic Testing in the Safe Affordable Fission Engine (SAFE-100) Thermal Simulator Using Fiber Bragg Gratings

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Abstract. The motivation for the reported research was to support NASA space nuclear power initiatives through the development of advanced fiber optic sensors for space-based nuclear power applications. Distributed high temperature measurements were made with 20 FBG temperature sensors installed in the SAFE-100 thermal simulator at the NASA Marshal Space Flight Center. Experiments were performed at temperatures approaching 800°C and 1150°C for characterization studies of the SAFE-100 core. Temperature profiles were successfully generated for the core during temperature increases and decreases. Related tests in the SAFE-100 successfully provided strain measurement data.

Thermoacoustic Power Converter for Radioisotope Power Systems

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Abstract. Thermoacoustic engines convert high-temperature heat into acoustic power in the form of pressure and velocity oscillations without using moving parts. Conversion efficiencies of 30% have been demonstrated in 1-kW class engines. By coupling a scaled down (~100 Watt) thermoacoustic engine to a long-life, low-mass, linear alternator, a new type of dynamic power converter is created that is suitable for on board electric power generation during deep space missions. Electric power output and conversion efficiency data will be presented.

Nuclear Safety Analysis for the Mars Exploration Rover 2003 Project

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Abstract. The National Aeronautics and Space Administration's Mars Exploration Rover (MER) 2003 project is designed to place two mobile laboratories (Rovers) on Mars to remotely characterize a diversity of rocks and soils. Milestones accomplished so far include two successful launches of identical spacecraft (the MER-A and MER-B missions) from Cape Canaveral Air Force Station, Florida on June 10 and July 7, 2003. Each Rover uses eight Light Weight Radioisotope Heater Units (LWRHUs) fueled with plutonium-238 dioxide to provide local heating of Rover components. The LWRHUs are provided by the U.S. Department of Energy. In addition, small quantities of radioactive materials in sealed sources are used in scientific instrumentation on the Rover. Due to the radioactive nature of these materials and the potential for accidents, a formal Launch Approval Process requires the preparation of a Final Safety Analysis Report (FSAR) for submittal to and independent review by an Interagency Nuclear Safety Review Panel. This paper presents a summary of the FSAR in terms of potential accident scenarios, probabilities, source terms, radiological consequences, mission risks, and uncertainties in the reported results.

Direct Estimation of Power Distribution in Reactors for Nuclear Thermal Space Propulsion

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Abstract. A recently proposed constant temperature power sensor (CTPS) has the capability to measure directly local power deposition rate in nuclear reactor cores proposed for space thermal propulsion. Such a capability reduces the uncertainties in the estimated power peaking factors and hence increases the reliability of the nuclear engine. The CTPS operation is sensitive to the changes in the local conditions. A procedure is described for the automatic on-line calibration of the sensor through the estimation of these changes.

The CTPS consists of a UO_2 pellet surrounded by electrical heating resistance wire. The pellet and the wire form the sensor core (Node 2). The core is surrounded by an alumina based ceramic thermal insulator (Node 1). A feedback control loop is used to provide the exact amount of input electrical energy needed to keep Node 2 temperature constant in time. The sensor operation involves switching between the feedback-controlled constant-temperature mode (Mode 1) and the dynamic temperature decay mode following the opening of the feedback loop (Mode 2).

The estimation software DSD (Dynamic System Doctor) is based on: a) the representation of the system dynamics in terms of transition probabilities during user specified time intervals (e.g. within data sampling times) between user specified cells that partition the system parameter/state space, and, b) a Bayesian approach that recursively updates posteriors with the priors based on the most recently monitored data. The DSD is used to estimate the coolant temperature T_0 around the CTPS and Node 2-to-coolant thermal resistance R_2 through: a) monitored Node 1 and 2 temperatures during Mode 2, and, b) a user provided CTPS model that relates the Node 1 and 2 temperatures to T_0, R_2 and CTPS thermal properties.

Work to date indicates that DSD yields good results even with: a) 1% simulated random noise on the monitored data (which is substantially larger than the anticipated measurement uncertainty during the operation of the sensor), and, b) non-linear CTPS thermal properties.

Recovery of Pu-238 By Molten Salt Oxidation Processing Of Pu-238 Contaminated Combustibles

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Abstract Pu-238 heat sources are used to fuel radioisotope thermoelectric generators (RTG) used in space missions. The demand for this fuel is increasing, yet there are currently no domestic sources of this material. Much of the fuel is material reprocessed from other sources. One rich source of Pu-238 residual material is that from contaminated combustible materials, such as cheesecloth, ion exchange resins and plastics. From both waste minimization and production efficiency standpoints, the best solution would be to recover this material.

One way to accomplish separation of the organic component from these residues is a flameless oxidation process using molten salt as the matrix for the breakdown of the organic to carbon dioxide and water. The plutonium is retained in the salt, and can be recovered by dissolution of the carbonate salt in an aqueous solution, leaving the insoluble oxide behind. Further aqueous scrap recovery processing is used to purify the plutoniumoxide.

Recovery of the plutonium from contaminated combustibles achieves two important goals. First, it increases the inventory of Pu-238 available for heat source fabrication. Second, it is a significant waste minimization process. Because of its thermal activity (0.567 W per gram), combustibles must be packaged for disposition with much lower amounts of Pu-238 per drum than other waste types. Specifically, cheesecloth residues in the form of pyrolyzed ash (for stabilization) are being stored for eventual recovery of the plutonium.

SiC Semiconductor Detector Power Monitors for Space Nuclear Reactors

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Abstract. As a part of a Department of Energy-Nuclear Engineering Research Initiative (NERI) Project, we are investigating SiC semiconductor detectors as power monitors for Generation IV power reactors. SiC detectors are well-suited as power monitors for reactors for space nuclear propulsion, due to their characteristics of small size, mass, and power consumption; mechanical ruggedness; radiation hardness; capability for high temperature operation; and potential for pulse mode operation at high count rates, which may allow for a reduction in the complexity of the reactor instrumentation and control system, as well as allow for verification of detector sensitivity, verification of channel operability, and channel self-repair. In this paper, a mathematical model of a SiC detector is presented. The model includes a description of the formation of electron-hole pairs in a SiC diode detector, using the computer code TRIM. The TRIM results are used as input to a MATLAB simulation of detector current output pulse formation, the results of which are intended for use as the input to a model of the detector channel as a whole.

Autonomous Control Capabilities for Space Reactor Power Systems

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Abstract. The National Aeronautics and Space Administration's Project Prometheus is investigating a possible Jupiter Icy Moons Orbiter (JIMO) mission, which would conduct in-depth studies of three of the moons of Jupiter by using a space reactor power systems (SRPS) to provide energy for propulsion and spacecraft power for more than a decade. Terrestrial nuclear power plants have relied upon varying degrees of direct human control and decision-making for operations and periodic human interaction for maintenance. SRPSs are intended to provide continuous, unattended operation for up to fifteen years. Uncertainties, rare events, degradation, and communications delays are challenges that SRPS control must accommodate. To address these challenges and optimize the reactor control design, autonomous control is needed and should be addressed early in the design phase of the SRPS. In this paper, we describe an autonomous control concept for generic SRPS designs. The formulation of an autonomous control concept, which includes identification of high-level functional requirements and generation of a research and development plan for enabling technologies, is among the technical activities that are being conducted under the U.S. Department of Energy's Space Reactor Technology Program in support of Project Prometheus.

Multi-Megawatt MPD Plasma Source Operation and Modeling for Fusion Propulsion Simulations

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Abstract. The expansion of a high temperature fusion plasma through an expanding magnetic field is a process common to most fusion propulsion concepts. The efficiency of this process has a strong bearing on the overall performance of fusion propulsion. In order to simulate the expansion of a fusion plasma, a concept has been developed in which a high velocity plasma is first stagnated in a converging magnetic field to high (100's of eV) temperatures, then expanded though a converging/diverging magnetic nozzle. A Magnetoplasmadynamic (MPD) plasma accelerator has been constructed to generate the initial high velocity plasma and is currently undergoing characterization at the Ohio State University. The device has been operated with currents up to 300 kA and power levels up to 200 MWe. The source is powered by a 1.6 MJ, 1.6 ms pulse-forming-network. In addition to experimental tests of the accelerator, computational and theoretical modeling of both the accelerator and the plasma stagnation have been performed using the MACH2 MHD code. Insights into plasma compression and attachment to magnetic field lines have led to recommended design improvements in the facility.

TPV Network Sensitivity: A Simulation Study

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Abstract. A viable thermophotovoltaic power conversion system requires an electrically connected network of diodes that is designed to be fault tolerant for a prescribed power rating and generator life. This paper describes simulation studies investigating the sensitivity of various series/parallel network configurations to diode variability, diode failure, and non-uniform illumination. The results show the effect of diode mismatch and reverse breakdown behavior on network performance.

Space Fission System Test Effectiveness

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Abstract. Fission technology can enable rapid, affordable access to any point in the solar system. If fission propulsion systems are to be developed to their full potential; however, near-term customers must be identified and initial fission systems successfully developed, launched, and utilized. One key to successful utilization is to develop reactor designs that are highly testable. Testable reactor designs have a much higher probability of being successfully converted from paper concepts to working space hardware than do designs which are difficult or impossible to realistically test. "Test Effectiveness" is one measure of the ability to realistically test a space reactor system. The objective of this paper is to discuss test effectiveness as applied to the design, development, flight qualification, and acceptance testing of space fission systems. The ability to perform highly effective testing would be particularly important to the success of near-term missions, such as the Jupiter Icy Moons Orbiter.

Mechanically Alloyed-Oxide Dispersion Strengthened Steels for Use in Space Nuclear Power Systems

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Abstract. The mechanical and thermo-physical properties of Mechanically Alloyed (MA)-Oxide Dispersion Strengthened (ODS) steels are reviewed and their potential for use in space nuclear reactor power systems is examined. The three MAODS alloys examined are Inconel MA-ODS754 (77.55Ni, 20Cr, 1Fe, 0.5Ti, 0.3Al, 0.05C, and 0.6Y_2O_3), Incoloy MAODS956 (74.45Fe, 20Cr, 4.5Al, 0.5Ti, 0.05C, 0.5Y_2O_3), and Incoloy MA-ODS957 (84.55Fe, 14Cr, 0.3Mo, 0.9Ti, 0.25Y_2O_3). The major advantages of these alloys are: (a) their strength at high temperatures (>1000 K) is relatively higher and decreases slower with temperature than niobium (Nb) and molybdenum (Mo) refractory alloys; (b) they are relatively lightweight and less expensive; (c) they have been shown to experience low swelling and embrittlement with exposure to high-energy neutrons (> 0.1 MeV) up to a fluence of 10_{23} n/cm_2; and (d) their high resistance to oxidation and nitration at high temperatures, which simplifies handling and assembly. These MS-ODS alloys are also lighter and much stronger than 316-stainless steel and super-alloys such as Inconel 601, Haynes 25, and Hastalloy-X at moderately high temperatures (688-1000 K). The little data available on the compatibility of the MA-ODS alloys with alkali liquid metals up to 1100 K are encouraging, however, additional tests at typical operation temperatures (1000-1400 K) in liquid metal cooled and alkali metal heat pipe-cooled space nuclear reactors are needed. The anisotropy of the MA-ODS alloys when cold worked, and in particularly when rolled into tubes, should not hinder their use in space nuclear power systems, in which the operation pressure is either near atmospheric or as high as 2 MPa.

Parametric Analysis of Nuclear Reactor Lithium Heat Pipes of STCM Power System for JIMO missions1

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Abstract. A team that includes the Jet Propulsion Laboratory, the Boeing Company, and the University of New Mexico's Institute for Space and Nuclear Power Studies (UNM-ISNPS) has developed a conceptual design of a Segmented Thermoelectric Module (STCM), heat pipe cooled, space nuclear reactor power system for JIMO mission. The 126 lithium heat pipe in the nuclear reactor core are radiatively coupled to multitudes of Segmented Thermoelectric Modules (STMSs) having an estimated efficiency of 8%.

The STCM modules are cooled using potassium c-c heat pipes with a titanium liner for rejecting excess heat to space. This paper presents the results of a parametric analysis of the radiator heat pipes in which the effects of a number of variables on the total mass of the heat pipe, the temperature drop along the heat pipe, and the radiator average surface temperature are presented and discussed. The variables investigated are the outer diameter of the heat pipe, the evaporator temperature (650 K to 750 K), the width of the connected C-C fins, the total length of the heat pipe, the lengths of the adiabatic and the condenser section, and the outer diameter of the heat pipe. The presented results are single side radiating surface. Based on this analysis, estimates of the radiator's specific mass (kg/kW) for both armored surface and armored surface and bumpered radiator heat pipes. These estimated are presented for a design point that is 50%, 75%, and 100% of the sonic limit of the heat pipes

Performance Analysis of Potassium Heat Pipes Radiator for HP-STMCs Space Reactor Power System

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Abstract. A detailed design and performance results of C-C finned, and armored potassium heat pipes radiator for a 110 kW_e Heat Pipes-Segmented Thermoelectric Module Converters (HP-STMCs) Space Reactor Power system (SRPS) are presented. The radiator consists of two sections, each serves an equal number of STMCs and has 162 longitudinal potassium heat pipes with 0.508 mm thick C-C fins. The width of the C-C fins at the minor diameter of the radiator is almost zero, but increases with distance along the radiator to reach 3.7 cm at the radiator's major diameter. The radiator's heat pipes (OD = 2.42 cm in front and 3.03 cm in rear) have thin titanium (0.0762 mm thick) liners and wicks (0.20 mm thick with an effective pore radius of 12-16 μm) and a 1.016 mm thick C-C wall. The wick is separated from the titanium liner by a 0.4 mm annulus filled with liquid potassium to increase the capillary limit. The outer surfaces of the heat pipes in the front and rear sections of the radiator are protected with a C-C armor that is 2.17 mm and 1.70 mm thick, respectively. The inside surface of the heat pipes in the front radiator is thermally insulated while the C-C finned condensers of the rear heat pipes are exposed, radiating into space through the rear opening of the radiator cavity. The heat pipes in both the front and the rear radiators have a 1.5 m long evaporator section and each dissipates 4.47 kW while operating at 43.6% of the prevailing sonic limit. The front and rear radiator sections are 5.29 m and 2.61 m long with outer surface area and mass of 47.1 m^2 and 314.3 kg, and 39.9 m^2 and 243.2 kg, respectively. The total radiator is 7.63 m long and has minor and major diameters of 1.48 m and 5.57 m, respectively, and a total surface area of 87 m^2; however, the effective radiator area, after accounting for heat rejection through the rear of the radiator cavity, is 98.8 m^2. The radiator's total mass including the C-C armor is 557.5 kg and the specific area and specific mass are 6.41 kg/m^2 and 5.07 kg/kW_e, respectively.

Cascaded Thermoelectric Conversion-Advanced Radioisotope Power Systems (CTC-ARPSs)

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Abstract. Conceptual designs of Advanced Radioisotope Power System (ARPS) with Cascaded Thermoelectric Converters (CTCs) are developed and optimized for maximum efficiency operation for End-Of Mission (EOM) electrical power of at least 100 We. These power systems each employs four General Purpose Heat Source (GPHS) bricks generating 1000 Wth at Beginning-of-Life (BOL) and 32 Cascaded Thermoelectric Modules (CTMs). Each CTM consists of a top and a bottom array of thermoelectric unicouples, which are thermally, but not electrically, coupled. The top and bottom arrays of the CTMs are connected electrically in series in two parallel strings with the same nominal voltage of > 28 VDC. The SiGe unicouples in the top array of the CTMs are optimized for nominal hot shoe temperature of 1273 K and constant cold shoe temperature of either 780 K or 980 K, depending on the thermoelectric materials of the unicouples in the bottom array. For a SiGe cold junction temperature of 780 K, the unicouples in the bottom array have p-legs of TAGS-85 and n-legs of 2N-PbTe and operate at constant hot junction temperature of 765 K and nominal cold junction temperature of 476.4 K. When the SiGe cold junction temperature is 980 K, the unicouples in the bottom arrays of CTMs have p-legs of CeFe3.5Co0.5Sb12 or CeFe3.5Co0.5Sb12 and Zn4Sb3, segments and n-legs of CoSb3 and operate at constant hot junction temperature of 965 K and nominal cold junction temperatures of 446.5 K or 493.5 K, respectively. The CTCARPSs have a nominal efficiency of 10.82% - 10.85% and generate BOL power of 108 We. This system efficiency is ~80% higher than that of State-of-the-Art (SOA) Radioisotope Thermoelectric Generators (RTGs), requiring 7 GHPS bricks and generating 105 We at BOL. The CTC-ARPSs have specific powers of 8.2 We/kg to 8.8 We/kg, which are 71% to 83% higher, respectively, than that of the SOA-RTGs, and use ~ 43% less 238PuO2 fuel.

Performance Tests of Skutterudites and Segmented Thermoelectric Converters

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Abstract: This paper presents results of three performance tests of Skutterudites and Segmented Thermoelectric (STE) unicouples performed at average hot and cold shoe temperatures of ~ 973 K and 300 K, respectively, to verify theoretical predictions. The first two tests (MAR-03 and JUN-03) involved non-segmented Skutterudites unicouples of slightly different dimension but same materials for the n- ($CoSb_3$) and p- ($CeFe_{3.5}Co_{0.5}Sb_{12}$) legs. The test duration is 450 hours for MAR-03 and 1200 hours for JUN-03. The third test (JUL-03) is for a Skutterudites/Segmented (STE) unicouple, in which the p-leg has two segments of $CeFe_{3.5}Co_{0.5}Sb_{12}$ and $Bi_{0.4}Sb_{1.6}Te_3$ and the n-leg has two segments of $CoSb_3$ and $Bi_2Te_{2.95}Se_{0.05}$. The segments in the n- and p-legs have different lengths and cross-sectional areas. The JUL-03 test duration is 645 hours. All tested unicouples are fabricated at JPL and assembled and tested in the vacuum facility at the University of New Mexico in argon at ~ 0.051 to 0.068 MPa to suppress the sublimation of antimony from the legs near the hot shoe. Detailed measurements of the open circuit voltage, voltage across the n- and p-legs, the voltagecurrent (V-I) characteristics, and the hot and cold shoe temperatures are performed in all tests. In JUL-03, additional measurements of the interfacial temperatures and the voltage across the segments in the n- and p-legs are obtained as functions of test duration. Estimates of beginning-of-life (BOL) conversion efficiencies of 10.7% for Shutterudites and 13.5% for STE unicouples are within 10% of theoretical predictions assuming zero side heat losses and zero contact resistances. Estimates of these losses in the tests are 2.3 W in MAR-03 to 9.3 W in JUL-03, thus actual efficiencies in the tests are ~ 40-50% lower. Because cross sectional areas of the legs of JUL-03 are much larger than of both MAR-03 and JUN-03, the measured BOL peak electrical power per unicouple is 1.295 W_e versus 0.671 W_e for the latter.

Conceptual Design of HP-STMC Space Reactor Power System for 110 kWe

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Abstract. A conceptual design of a Heat Pipe-Segmented Thermoelectric Module Converters (HP-STMCs) space reactor power system (SRPS) for a net power of 110 kWe is developed. The parametric analysis changed the number of radiator's potassium heat pipes from 224 to 336 and calculated the effects on the operation parameters and total mass of the system. The reactor has a hexagonal core comprised of 126 heat pipe modules, each consists of three UN, 1.5 cm OD fuel pins brazed to a central lithium heat pipe of identical diameter. The Re cladding of the fuel pins is brazed along the active core length to the lithium heat pipe using 6 Re tri-cusps. The reactor control is accomplished using 12 B4C/BeO control drums, a large diameter one on each side of the hexagonal core and a small diameter one at each corner. The control drums are placed within the radial BeO reflector (7.1-9.1 cm thick). The fuel pin peak-to-average power ratio in the reactor core is 1.12-1.19. Despite its very high density and fabrication challenge, using rhenium structure in the reactor core is necessary for three main reasons: (a) the high reactor temperature (> 1500 K); (b) excellent compatibility with the UN fuel and lithium; (c) to cause a spectrum shift that ensures having sufficient negative reactivity margin during a water submersion accident. The reference HP-STMC system with 324, 2.42-3.03 cm OD potassium heat pipes in the radiator is 9.60 m long and has a cone angle of 30^{o}. The nominal operation of the reactor's lithium heat pipes and of the radiator's potassium heat pipes is at or below ~ 45% of the prevailing wicking and sonic limit, respectively. The masses of the reactor and radiation shadow shield are 753.7 kg and 999.5 kg, respectively; the average heat pipes temperature in the reactor is 1513 K; the mass of the reactor's lithium heat pipes with a C-C finned condenser that is 1.5 m long is 516.1 kg; the mass of the radiator is 557.5 kg, with an outer surface area of 87 m2 (6.41 kg/m2) and effective temperatures of 752 K and 734 K for the front and rear radiator sections, respectively. These estimates are for a constant collector temperature for the STMCs of 1300 K and STMCs' thermal and electrical losses of 5% and 8%, respectively. The estimates of the total mass and specific power of the reference HP-STMCs SRPS, pending future detailed design and analysis, are 4261 kg and 25.8 We/kg, respectively.

System Mass Variation and Entropy Generation in 100-kWe Closed-Brayton-Cycle Space Power Systems

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Abstract. State-of-the-art closed Brayton-cycle space power systems were modeled to study performance trends in a trade space characteristic of interplanetary orbiters. For working-fluid molar masses of 48.6, 39.9 and 11.9 kg/kmol, peak system pressures of 1.38 and 3.0 MPa and compressor pressure ratios ranging from 1.6 to 2.4, total system masses were estimated. System mass increased as peak operating pressure increased for all compressor pressure ratios and molar mass values examined. Minimum mass point comparison between 72% He at 1.38 MPa peak and 94% He at 3.0 MPa peak showed an increase in system mass of 14%. Converter flow loop entropy generation rates were calculated for 1.38 and 3.0 MPa peak pressure cases. Physical system behavior was approximated using a pedigreed NASA-Glenn modeling code, Closed Cycle Engine Program (CCEP), which included realistic performance prediction for heat exchangers, radiators and turbomachinery.

Restricted Complexity Framework for Nonlinear Adaptive Control in Complex Systems

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Abstract. Control law adaptation that includes implicit or explicit adaptive state estimation, can be a fundamental underpinning for the success of intelligent control in complex systems, particularly during subsystem failures, where vital system states and parameters can be impractical or impossible to measure directly. A practical algorithm is proposed for adaptive state filtering and control in nonlinear dynamic systems when the state equations are unknown or are too complex to model analytically. The state equations and inverse plant model are approximated by using neural networks. A framework for a neural network based nonlinear dynamic inversion control law is proposed, as an extrapolation of prior developed restricted complexity methodology used to formulate the adaptive state filter. Examples of adaptive filter performance are presented for an SSME simulation with high pressure turbine failure to support extrapolations to adaptive control problems.

Overview of Fuel Rod Simulator Usage at ORNL

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Abstract. During the 1970s and early 1980s, the Oak Ridge National Laboratory (ORNL) operated large out-of-reactor experimental facilities to resolve thermal-hydraulic safety issues in nuclear reactors. The fundamental research ranged from material mechanical behavior of fuel cladding during the depressurization phase of a loss-of-coolant accident (LOCA) to basic heat transfer research in gas- or sodium-cooled cores. The largest facility simulated the initial phase (less than 1 min. of transient time) of a LOCA in a commercial pressurized-water reactor. The nonnuclear reactor cores of these facilities were mimicked via advanced, highly instrumented electric fuel rod simulators locally manufactured at ORNL. This paper provides an overview of these experimental facilities with an emphasis on the fuel rod simulators.

Electric Fuel Rod Simulator Fabrication at ORNL

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Abstract. Commercial vendors could not supply the high-quality, highly instrumented electric fuel rod simulators (FRS) required for large thermal-hydraulic safety-oriented experiments at the Oak Ridge National Laboratory (ORNL) in the 1970s and early 1980s. Staff at ORNL designed, developed, and manufactured the simulators utilized in these safety experiments. Important FRS design requirements include (1) materials of construction, (2) test power requirements and availability, (3) experimental test objectives, (4) supporting thermal analyses, and (5) extensive quality control throughout all phases of FRS fabrication. This paper will present an overview of these requirements (design, analytics, and quality control) as practiced at ORNL to produce a durable high-quality FRS.

Status of Stirling Radioisotope Generator Development For Mars Surface and Deep Space Missions

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Abstract. Nuclear power is an enabling technology for extended missions on the Martian surface, which is being proposed for the Mars Science Laboratory for launch in 2009, and for exploration of the outer planets. In the past, Radioisotope Thermoelectric Generators (RTGs) have made possible such missions as Viking, Pioneer, Voyager, Galileo, Ulysses, and Cassini. However, due to the characteristically low conversion efficiency of thermoelectric devices, several kilograms of PuO_2 are required in each RTG. The higher conversion efficiency of the Stirling cycle compared with that of thermoelectrics offers the advantage of a four-fold reduction in PuO_2 fuel requirement, thereby saving cost and reducing radiation exposure of support personnel. This paper discusses the status of the Phase IIA 110-We Stirling Radioisotope Generator (SRG110) program funded by the Department of Energy for future multi-mission applications. Preliminary design of a generator concept that will operate both on the Martian surface and in deep space is described. Development of components and subsystems to ensure long life and high reliability of the Stirling engine/alternator is also described. The generator incorporates opposed pair of Stirling engine/alternators and heat sources, and an integrated controller that regulates and conditions the electrical power from AC to DC. The proposed design is modular, which mitigates the effect of fault propagation, low in mass, compact, and provides user interfaces that are similar to that used in the RTGs. Annealed Pyrolytic Graphite with higher thermal conductance is used to provide efficient heat input to and waste heat removal from the Stirling engine/alternator. For Mars application, the generator operates open to its environment and includes features for integrating active cooling system during launch, cruise and Mars surface operation.

The NEPA Process as it Applies to Nuclear-Powered Space Missions

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Abstract. This presentation describes the National Environmental Policy Act (NEPA), as it applies to U.S. nuclear-powered space missions. Specifically, it discusses the content, steps, and schedule involved in getting an Environmental Impact Statement (EIS) approved, via a Record of Decision (ROD), for a U.S. nuclear-powered space mission.

The Safety Analysis and Launch Approval Processes for Space Radioisotope Power Systems

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Abstract. The Department of Energy (DOE) provides radioisotope heaters and power systems to the National Aeronautics and Space Administration (NASA) for a variety of space missions. The radioisotope power sources used on these missions enable the collection of scientific knowledge about the solar system. Presidential approval is required for these launches. An established launch approval process is followed to evaluate the nuclear safety of the launches, provide information to the participating agencies and to the President through the Director of the Office of Science and Technology Policy (OSTP). This approval process includes the establishment of an ad hoc Interagency Nuclear Safety Review Panel (INSRP) for each mission. An INSRP performs an independent evaluation and reports its findings in a Safety Evaluation Report (SER).

In preparation for each mission DOE and NASA analyze the nuclear risks associated with the launch process. NASA provides a databook which identifies potential accident scenarios that might occur during a launch vehicle accident and characterizes the environments associated with and the probabilities of those accidents. DOE uses the launch vehicle databook information as input to a probabilistic risk assessment to determine how the radioisotope power system hardware would respond to the accident scenarios, and estimates potential consequences if an accident were to occur. The DOE findings are reported in a Safety Analysis Report (SAR)

INSRP conducts an independent evaluation of the DOE safety analysis and issues its SER. If DOE approves the SAR and adopts the SER, it forwards the SAR and SER to NASA. NASA and the other participating agencies review the SAR-SER package. NASA makes a determination whether to submit a request for Presidential nuclear launch safety approval through OSTP.

Design Approaches For Externally Controlled Space Reactors

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Abstract. This paper analyzes design approaches used in the optimization of externally controlled nuclear reactors for the JIMO mission. The ability to control a nuclear reactor without internal control rods provides many benefits to the design as a whole. However, external controls also increase the complexity of keeping a reactor subcritical in accident situations. This paper provides a brief overview of three reactor systems and methods of control for water and wet sand submersion accident scenarios. The challenges associated with the design of accident safe reactors with adequate excess reactivity for the life of the mission will be discussed in detail along with valuable relationships between reactor parameters determined from various sensitivity studies.

Johnson Noise Thermometry For Space Reactor Temperature Measurement

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Abstract. A primary difference between terrestrial and remotely located reactors is the ability to periodically recalibrate and replace the instrumentation. Because of this, space reactors place a premium on self-calibrating, long-term reliable instrumentation. The primary temperature measurements for the SP-100 reactor were to be made using W/W-Re thermocouples. However, the large gamma and neutron dose expected at the coolant outlet (>1 MGy γ; $3x10^{15}$ fast neutron fluence) combined with the high temperature (1375 K nominal; 1650 K maximum) meant that the thermocouples would drift significantly over the lifetime of the reactor. A combined Johnson noise resistance thermometer capable of performing under these extreme conditions was developed by ORNL (Carroll, 1994).

Johnson noise is a fundamental representation of temperature—it is the vibration of the electronic field surrounding atoms as they thermally vibrate. Johnson noise, however, is fundamentally a small signal (~4x10-7 V_{rms} for a 100 Ω resistor at 300 K, using a 100 kHz bandwidth) spread throughout the frequency spectrum. Creating the electronics and signal processing required to effectively measure and interpret the noise signal remains challenging. ORNL has recently developed closely related Johnson Noise Thermometry (JNT) electronics and signal processing capabilities under a DOE International Nuclear Energy Research Initiative Project with the Korean Atomic Energy Research Institute (U.S. DOE, 2002). An overview of the application of JNT to space nuclear power and the current status of the ORNL JNT capabilities is the subject of this paper.

Cascaded Thermoelectric Converters for Advanced Radioisotope Power Systems

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Abstract. Three Cascaded Thermoelectric Converters (CTCs) are optimized for potential use in Multi-Mission Advanced Radioisotope Power Systems (MM-ARPS) for electrical powers up to 1 kW_e, or even higher, in support of 7-10 year missions. The peak efficiencies of these CTCs of 9.43% to 14.32% are 40% to 110% higher than that of SiGe in State-of-the-Art (SOA) Radioisotope Thermoelectric Generators (RTGs). Such high efficiencies would significantly reduce the amount of $^{238}PuO_2$ fuel and the total system mass for a lower mission cost. Each CTC is comprised of a SiGe top unicouple that is thermally, but not electrically, coupled to a bottom unicouple with one of the following three choices of thermoelectric materials: (a) p-leg of TAGS-85 and n-leg of 2N-PbTe; (b) p-leg of $CeFe_{3.5}Co_{0.5}Sb_{12}$ and n-leg of $CoSb_3$; and (c) segmented p-leg of $CeFe_{3.5}Co_{0.5}Sb_{12}$ and Zn_4Sb_3 and n-leg of $CoSb_3$. The length of the top and bottom unicouples is 10 mm, but the cross-sectional areas of the n- and p-legs of the unicouples are optimized for maximum efficiency operation. They vary with the thermal power inputs of 1, 2, and 3 W_{th} per SiGe unicouple, and the heat rejection temperature of 375 K, 475 K, and 575 K, from the bottom unicouple. Such geometrical optimization is at nominal hot shoe temperature of 1273 K for the SiGe unicouple and cold shoe temperature of either 780 K or 980 K, depending on the materials of the bottom unicouples. The hot shoe temperature of the bottom unicouples is 20 K lower than the cold shoe of the top SiGe unicouple, but the rate of heat input is the same as the rate of heat rejection from the top unicouple. The present results are conservative as they assume a contact resistance of 150 μ-cm^2 per leg for the top and the bottom unicouples in the CTCs; however, decreasing this resistance to 50 μ-cm^2 per leg could increase the current efficiency estimates by an additional 1 - 2 percentage points.

Thermal Stability Characterization of Skutterudite Thermoelectric Materials

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Abstract. High-efficiency, segmented thermoelectric unicouples employing advanced thermoelectric materials with superior thermoelectric figures of merit are currently under investigation at the Jet Propulsion Laboratory (JPL). The paper reports investigations concerning the thermal stability of these novel materials. The primary emphasis is on characterizing sublimation behavior of Sb from the skutterudite compounds. Additionally, methods of suppressing sublimation are also presented and discussed. A concept for suppressing sublimation in advanced thermoelectric materials has been developed and tested. Although this concept is similar to other sublimation suppression concepts, this has been specifically tailored for use with skutterudite (SKD) antimonides. The concept involves the application of thin, continuous films or silica-based aerogel on the surface of SKD thermoelectric elements. It is clear that the presence of these protective films significantly decreases the sublimation rate of antimony.

Research and Development Status of JAXA 35-cm Ion Thruster Technology

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Abstract. Japan has started using ion thrusters in space applications. Ion engine systems were launched for north-south station-keeping of ETS-6 and COMETS. Another plan is now in progress to use ion engines on ETS-8, which is scheduled for launch in 2004. Microwave discharge thrusters were developed and are currently in operation on MUSES-C. Many future applications of ion thrusters will require large thrust levels. In Japan, for example, studies are being carried out on scientific space missions for which ion propulsion with large thrust will be essential. Ion propulsion is attractive as a practical way to increase payload in orbit transfers. Studies are to be started on quasi-zenith satellite systems, which require ion propulsion with 200-mN thrust. The ion thrusters developed so far in Japan had thrust levels ranging from 8 to 25 mN, which are far below the requirements of upcoming missions. The objective of this development program is to provide basic ion thruster technology which meets the high thrust requirements of these missions. In this paper, the research and development status of the 150-mN-class xenon ion thruster is described. After a couple of redesigns and trial fabrications, the first breadboard thruster achieved a very low ion production cost of 104 W/A. Endurance tests suggest that the grid system will have a lifetime of about 25,000 h. A hollow cathode wear test suggests that it will be over 30,000 h before its orifice plate is completely worn out. A thrust range of 80 to 200 mN without performance degradation has been demonstrated at a specific impulse of 3,500 s. In the power conditioner development, efficiencies of 87 to 88% have been achieved in the main power supplies.

Technology Directions For Electrically Accelerated Space Vehicles

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Abstract. Propulsion systems for launch and in space transportation involve the acceleration and ejection of mass through either combustion or electric and magnetic fields to provide thrust for the vehicle. The process remains the same whether the vehicle is accelerating outward to its destination or, if necessary, decelerating. Rocket propulsion has been the primary method of space transportation. Due to dependence on mass for acceleration as well as deceleration, the associated costs remain a barrier to full space utilization. Space transportation systems, like their terrestrial counterparts, must evolve toward systems that can cost effectively transport people and materials back and forth to a desired location. In order to provide the necessary energy for such a transportation system, an electric system using linear induction machines, electro-magnetically coupled to an energy storage flywheel, is being conceptualized. The energy needed to accelerate a vehicle is supplied by the flywheel that is charged by electrical sources, and potential energy associated with the orbit of the accelerator. The linear machine and flywheel energy storage system is used as both accelerator and decelerator depending on whether the vehicle is outbound or inbound. Maximum recovery and reuse of electric and orbit energy decreases cost of transportation. This presentation summarizes the concepts for the linear machine, the high speed flywheel used to activate and control acceleration, the orbital mechanics issues associated with an earth/moon transportation system, and electric energy associated with such a system. It is expected that this technology can be developed within the next ten to fifteen years, and a modular system assembled in space to allow transportation between the earth and moon.

Thermal Isolator with Strong Mechanical Support for a Radioisotope Heating Unit

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Abstract. We have developed a suspension system using pre-tensioned titanium alloy wires to support a 1 Watt Radioisotope Heating Unit (RHU) for a mission to Mars. This suspension is very strong in all directions and has quite low thermal conduction between the RHU and its colder surroundings. This will allow the RHU to operate at 250 °C for generating electrical power from an attached thermoelectric converter (TEC) after surviving multiple 300 G impacts on the Martian surface. We have tested the suspension under impact loads that have the same duration as the impacts expected from the air-bag cushions planned for the Mars mission. The suspension survives impacts of 500 G with the RHU canister at room temperature and at 250 °C. We calculate that with the RHU at 250 °C there will be only 86 mW of heat conducted through the support structure. This design in intended for use with multilayer insulation in a good vacuum. We estimate that the conduction through such insulation would be 75 mW. This leaves more than 800 mW of the heat from the RHU to flow through the TEC, yielding more than 40 mW of electrical power.

Qualification of Radioisotope Power Systems for Space Applications

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Abstract. Radioisotope thermoelectric power systems have been the enabling technology for exploration of the outer planets, exemplified by the Voyager I and II, Galileo, Ulysses, and Cassini missions. Radioisotope power systems employing other power conversion technologies, such as Stirling engine/alternators, are being developed for future missions, including requirements for operation within a planetary atmosphere as well as the vacuum of deep space. The experience of qualifying the General Purpose Heat Source – Radioisotope Thermoelectric Generator (GPHS-RTG) provides guidance for the qualification process required for radioisotope power systems (and other space nuclear power systems) now under development. The qualification process ideally begins with a well-defined mission and a conceptual design of the spacecraft configuration from which performance requirements and operating environments for the radioisotope power system (RPS) can be derived. More often, the RPS needs to be designed, developed and qualified years in advance of the spacecraft, and the requirements for qualification must be chosen to envelope all potential missions. The qualification process requires a combination of analyses, tests, and inspections as evidence that each of the provisions of the product specification has been demonstrated. It is not always practical to perform all qualification testing with an isotope-heated unit, with the result that it may be necessary to supplement the results with tests performed on an electrically heated unit. The environment with the greatest impact on mechanical design of the RPS is dynamic testing to simulate responses during launch. Negotiating an appropriate dynamic test environment early in the design and development phase of the RPS may be difficult because of uncertainty in the selection of launch vehicle and the spacecraft configuration. Qualification for a specific set of mission requirements may need to be revisited when the RPS is subsequently used on a different mission.

RF Ion Gun Injector In Support Of Fusion Ship II Research And Development

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Abstract. An inertial electrostatic confinement (IEC) power source used neutral-beam injection for fueling and heating the plasma. It was used in the design of a very attractive Fusion Ship II intended for a fast manned deep space missions [1]. This paper describes a newly designed external ion source, ILLIBS (Illinois Ion Beam Source) designed for ion injection into IEC's. This unit represents an approach to beam injection such as envisioned in the Space Ship II study. ILLIBS uses a RF generated plasma in a unique graded magnetic-field design for efficient ion generation. The ILLIBS experiments provide the first experimental data on this important new regime for ion injected IEC operation. A key advantage of such operation is that it allows initiation of a discharge below the normal (Paschen curve) breakdown region, significantly reducing the background pressure, hence charge-exchange losses. Sub-breakdown deuterium pressures were studied over a wide region ranging from 0.4 to 2 mTorr. The ILLIBS provides high ion current in a small well focused beam and good extraction efficiency over this range. An injected deuterium ion flux of 6 x 1018 ions/(cm2-sec) was measured at 65 mA with a beam diameter of 2.89 mm with the ILLIBS set at 100 W RF power. A D-D fusion neutron rate of 2 x 107 n/sec was achieved with the IEC grid voltage and current at 75 kV and 15 mA respectively, and a 1.2 mTorr deuterium background pressure. This data is very encouraging and is in line with the assumptions made in the design of the conceptual neutral-beam injected D-He3 IEC in Fusion Ship II. This ion injection and the physics involved in the development of a magnetically-channeled IEC array [2] represent two of the key physics issues involved in scaling the IEC up to the large power levels required for future interplanetary missions. This presentation will provide detailed results from the ILLIBS gun experiments. Implications for the design of a future fusion propulsion unit will also be discussed.

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Progress Status of Skutterudite-Based Segmented Thermoelectric Technology Development

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Abstract. Segmented thermoelectric (STE) unicouples based on combination of state-of-the-art and skutterudite materials are currently being developed at the Jet Propulsion Laboratory (JPL) for potential integration into Advanced Radioisotope Power Systems (ARPS) to be used for future NASA deep space missions. Progress made in the fabrication, characterization, performance testing and lifetime demonstration are reported. To date, a maximum conversion efficiency of ~ 14% has been demonstrated for a unicouple operating at a hot-side temperature of 975K and a cold-side temperature of 300K. This result fully validates the predicted performance of the unicouple based on the thermoelectric properties of the materials used in the unicouple. The projected performance and benefits of Advanced Radioisotope Power Systems (ARPS) utilizing these advanced unicouples is presented and compared to state-of-the-art SiGe and PbTe-base systems that been used for a variety of NASA deep space missions. The projected system efficiency of the STE-ARPS is about 10% (~ twice that of state-of-the-art) and the specific power is 7-8 W/kg (~ twice that of state-of-the-art). Future development plans and challenges are also briefly reviewed.

Engineering and Fabrication Considerations for Cost Effective Space Reactor Shield Development

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Abstract. Investment in developing nuclear power for space missions cannot be made on the basis of a single mission. Current efforts in the design and fabrication of the nuclear module, including the reactor shield, must be in light of cost effectiveness including scalability and fabricability for currently planned and future missions. Engineering considerations for the shield need to accommodate passive thermal management, varying radiation levels and effects, and structural/mechanical issues. With these challenges in mind the authors will present engineering and fabrication principles and cost drivers specific to the engineering and fabrication approach of the reactor shield that will contribute to lower recurring mission costs.

SP-100 Materials Testing Data Recovery to Support the Jupiter Icy Moons Orbiter Program

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Abstract. Efforts under the SP-100 program produced a significant amount of information related to the selection and evaluation of materials for use in a space reactor shield. The efforts under SP-100 reactor shielding work produced information on the radiation effects on lithium hydride and material compatibility. Although the materials evaluation work under SP-100 was only partially completed, it serves as a sufficient baseline for conceptual reactor shield designs and for defining future material evaluation requirements. This paper will highlight the material evaluation information recaptured from SP-100 and outline specific areas where additional information is required to reduce technical and programmatic risks related to future space reactor missions.

Mission Design Challenges and Trends using Nuclear Electric Propulsion

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Abstract. The design trade space for Nuclear Electric Propulsion missions is large if no restrictions on the performances of the technologies are set. This trade space intimately ties the design of the system with the design and performances of the achievable trajectories. Several parameters can be traded against: mission architecture, launch vehicle performance, electrical power level, system technologies. This paper's intentions are to go back to the basics of low-thrust trajectory design and to investigate the trends and sensitivities to the mission design due to system performances. An example of the wide range of trade results is provided for a Jupiter Moon Tour mission.

Mars Exploration Rovers Launch Contingency Efforts

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Abstract. On 10 June 2003 at 1:58 p.m. Eastern Daylight Time (EDT) and 7 July 2003 at 11:18 p.m. EDT, two separate spacecraft/rovers were successfully launched to Mars atop a Delta II 7925 and Delta II 7925H, respectively. Each spacecraft/rover carried eight Light Weight Radioisotope Heater Units (LWRHUs) for thermal conditioning of electronics during the cold Martian nights. As a part of the joint National Aeronautics and Space Administration/U. S. Department of Energy safety effort, a contingency plan was prepared to address the unlikely events of an accidental suborbital reentry or out of orbit reentry. The objective of the contingency plan was to develop and implement procedures to predict, within the first hour, the probable Earth Impact Footprints (EIFs) for the LWRHUs or other possible spacecraft debris after an accidental reentry. No ablation burn-through of the heat sources' aeroshells was expected, as a result of earlier testing. Any predictions would be used in subsequent notification and recovery efforts. The Johns Hopkins University Applied Physics Laboratory, as part of a multi agency team, was responsible for prediction of the EIFs, and the time of reentry from a potential orbital decay. The tools used to predict the EIFs included a Three Degree of Freedom (3DOF) trajectory simulation code, a Six Degree of Freedom (6DOF) code, a database of aerodynamic coefficients for the LWRHUs and other spacecraft debris, secure links to obtain tracking data, and a high fidelity special perturbation orbit integrator code to predict time of spacecraft reentry from orbital decay. This paper will discuss the contingency plan and process, as well as highlight the improvements made to the analytical tools. Improvements to the 3DOF, aerodynamic database, and orbit integrator and inclusion of the 6DOF have significantly enhanced the prediction capabilities. In the days before launch, the trajectory simulation codes were exercised and predictions of hypothetical EIFs were produced. The contingency efforts, while not exercised for the two successful launches, still contributed to mission safety and demonstrated cooperation among multiple agencies.

Multi-Mission Radioisotope Thermoelectric Generator Program Review

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Abstract. Future NASA missions require safe, reliable, long-lived power systems for surface exploration of planetary bodies such as Mars, as well as exploration of the solar system in the vacuum of space beyond Earth orbit. To address this need, the Department of Energy and NASA have initiated the development of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). In June 2003, the Department of Energy awarded the MMRTG system design, development, test and integration contract to a team led by the Boeing Company's Rocketdyne Propulsion and Power Division. The program consists of six phases. Phase 1 is for preliminary design, development, fabrication and test of an engineering unit. Boeing will complete testing of this electrically-heated thermoelectric generator (ETG) early in 2005. Final design will be completed under a Phase 2 option to fabricate and test a flight-like qualification unit. Boeing will test the qual unit as an ETG, and then deliver it to Argonne National Laboratory-West where it will be fueled and tested to qualification-level environments. These qual RTG tests are scheduled for completion in mid-2006. Optional follow-on phases allow for development of flight MMRTGs for three potential missions plus a spare unit. Preliminary requirements for the MMRTG design have been established. At beginning of mission, the MMRTG is designed to generate over 110 watts of power at 28 volts DC, and to have a design life of at least 14 years. The heat source consists of eight General Purpose Heat Source (GPHS) modules similar to those used in the GPHS-RTG that powers the Galileo, Ulysses, and Cassini spacecraft. Teledyne Energy Systems has lead responsibility for design and fabrication of the thermoelectric converters. The MMRTG uses PbTe/TAGS (Tellurium-Antimony-Germanium-Silver) thermoelectrics, similar to those in the SNAP-19 generators that powered the Viking and Pioneer missions.

Small Radioisotope Power Source Concepts

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Abstract. NASA's Mars Program has identified potential applications for small, multi-purpose radioisotope power systems for future Scout-class missions and other Mars applications. The chief motive is to enable long-lived monitoring stations distributed broadly across the Mars surface. Such units could also be used for science packages on other planetary bodies and in deep space. At this point, unit power level and operational requirements are not fully defined. As a first order characterization of such systems, Orbital Sciences Corporation has developed concepts for generators utilizing existing heat source options, namely the Light Weight Radioisotope Heater Units (RHU) and the General Purpose Heat Source (GPHS). The RHU systems focused on milliwatt generators, typically 40 mW, and a single GPHS system resulted in 15-20 watts.

Development of Optimization Methodology for Space Reactor Power System Design*

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Abstract. A breakthrough methodology has been developed and applied to the design of a multimegawatt space reactor power system (SRPS). A traditional optimization method for such a system with multicomponents whose design is inter-dependent, often involves a lengthy and extensive interaction and iteration process between engineers and analysts to meet specific design objectives. Although this approach has been used successfully to design a variety of engineering systems, it does not fully integrate the design disciplines, nor does it provide a systematic method of achieving an optimal overall system design. A new SRPS design optimization tool has been developed at Oak Ridge National Laboratory. Preliminary assessments indicate rapid turnaround of optimized design variables for the SRPS. The paper will describe the procedure and methodology, including the results of parametric studies to investigate the behavior of selected design variables over the design space.

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Reactor Shielding Trade Study Analyses for the Jupiter Icy Moons Orbiter (JIMO) Project

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Abstract. The Jupiter Icy Moons Orbiter (JIMO) mission has an objective of propelling a large science package to Jupiter and then orbiting the three moons Ganymede, Callisto, and Europa. Analyses have been performed to provide the JIMO project with performance data for candidate shield materials such that mass-sensitive design choices can be made in the selection of the reactor system and radiation shielding. For these design studies, analyses have focused on the mass required for the reactor radiation shielding. Shielding mass requirements for the natural space radiation environment have been studied separately. The goal is to use the results from the trade study to obtain an optimum overall spacecraft shielding mass for which the mission payload total ionizing dose and 1-MeV equivalent neutron damage fluence requirements are met. An additional goal is to quantify shielding issues and trade-offs for materials and their locations within the neutron and gamma shield. Shielding design calculations for these analyses have incorporated the state-of-the-art cross-section data bases and computer codes and have been performed for all candidate reactor/power conversion system design concepts being considered for JIMO. A strategy utilizing Monte Carlo, multi-dimensional discrete ordinates calculations, and coupled Monte Carlo-Discrete Ordinates calculations has been implemented. For some calculations, the analysis has been automated to enable a broad range of shielding configurations to be assessed in a short time. The principal computational tools and data utilized in the analysis include the Monte Carlo Neutral Particle Transport Code (MCNP), the DOORS3.2 Discrete Ordinates Neutron/Photon Transport Code System package and multi-group ENDF/B-VI cross-section libraries.

A Historical Perspective on Space Nuclear Functional Safety Requirements with Application to the JIMO Mission

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Abstract Reactor nuclear safety requirements have developed in the last fifty years primarily based upon the implicit assumption of terrestrial operation. Although there has been significant national and international effort employed in the development of space based nuclear reactors; the implementation of consistent, codified safety requirements for space based systems has never been completed. Currently, NASA is developing plans for a mission to orbit three planet-sized moons of Jupiter; Callisto, Ganymede and Europa. The Jupiter Icy Moons Orbiter (JIMO) mission will make extensive scientific investigations and examine their potential for sustaining life. The JIMO mission will also raise NASA's capability for space exploration to a revolutionary new level by pioneering the use of electric propulsion powered by a nuclear fission reactor.

The paper presents an historical perspective on space based nuclear reactor safety along with proposed Tier 1 and Tier 2 safety requirements for various phases of the JIMO mission. The Tier 1 requirements represent mandatory mission-independent safety requirements that are seen to be generally applicable to space nuclear reactor safety. Tier 2 safety requirements are those that encompass the JIMO mission specifically. Finally, the Tier 3 requirements will be proposed by the organization(s) contracted to design and fabricate the reactor so as to ensure the Tier 1 and Tier 2 requirements are met or exceeded. The use of a multi-phased approach reflects the recognition that different aspects of safety assurance predominate different phases in the life-cycle of an operational mission. It is hoped that this approach to reactor safety will serve as a template for future space based reactor system safety analysis.

Fabrication and Testing of Thermoelectric Modules and Milliwatt Power Supplies

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Abstract. This paper reports the recent progress at Hi-Z Technology, Inc., following from earlier work in development of a milliwatt radioisotope power suppliy (MRPS) for space applications. A program for the U S Department of Energy (DOE) continues on the MRPS, which uses the thermal power of 1 W from the Light Weight Radioisotope Heater Unit (RHU) that is already developed and has been deployed by the National Aeronautics and Space Administration (NASA). The nominal output of this generator is 40 mW. Several papers have been presented previously regarding the development of this MRPS, and the focus of the development is a Flight System MRPS. Several units of this generator design have been built and tested. From the results of these tests, from ongoing design and analysis and from continued communication with DOE and with potential users of these generators at NASA, there have been suggested revisions and improvements. In this paper we discuss the most recent testing of power conversion modules and of units representing the Flight System MRPS design, and we describe two improved generator designs and their features.

Reliability Based Life Assessment of Stirling Convertor Heater Head

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Abstract. Onboard radio-isotope power systems being developed and planned for NASA's deep-space missions require reliable design lifetimes of up to 14 yr. The structurally-critical heater head of the high-efficiency Stirling power convertor has undergone extensive computational analysis of operating temperatures (up to 650 °C), stresses, and creep resistance of the thin-walled Inconel 718 bill of material. Additionally preliminary assessment of the effect of uncertainties in the material behavior was also performed. Creep failure resistance of the thin-walled heater head could show variation due to small deviations in the manufactured thickness, and in uncertainties in control temperature, and pressure. Durability prediction and reliability of the heater head are affected by these deviations from nominal design conditions. Therefore, it is important to include the effect of these uncertainties in predicting the probability of survival. These uncertainties are accounted for in predicting the reliability of the heater head under mission loads. Furthermore, it may be possible for the heater head to experience rare incidences of small temperature excursions of short duration. These rare incidences would affect the creep strain rate and therefore the life. This paper addresses the effects of such rare incidences on the reliability. The sensitivities of variables affecting the reliability are also quantified and guidelines developed to improve the reliability are outlined. Reliability is being quantified with the test data from the NASA Glenn Research Center's accelerated benchmark testing program.

Identification of Initiating Events for Safety Assessment of a Space Reactor Powered Mission

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Abstract. When launching radioactive material into space in support of space exploration missions, part of ensuring the protection of workers and the public is to generate a Safety Analysis Reports (SARs). These SARs are prepared to systematically examine the safety aspects of all activities and to assess the risks by using process hazards analyses (PHAs) or probabilistic safety assessments (PSAs). All facets of nuclear safety must be examined—including evaluating the safety of the reactor system during fabrication, assembly, packaging, transport, handling, testing, storage, disposal, launch preparation, and launch under both normal and accident conditions. Because an initiating event (IE) is the beginning of an accident sequence, the first step in a safety assessment is to identify those IEs that can potentially cause an upset of normal operations and that result in a radiological or toxic release or exposure to an individual. In order to cover all facets of nuclear safety, the IEs must be identified for all phases of the mission. This paper focuses on identifying those IEs and potential accidents during the ground-based and launch/ascent phases of a space reactor system development effort and use as part of a mission. The ground-based activities were divided into three main categories: transportation, nonreactor nuclear facilities, and nuclear reactor facilities. The analysis techniques for identifying IEs in each of these categories are different. All transportation accident analyses generally follow the methodology outlined in NUREG-0170. Packaging and transportation of radioactive materials are conducted in compliance with DOT (49 CFR 171-180) and NRC (10 CFR 71) regulations. This includes transporting powdered fuel, fuel pins, or even an assembled reactor. The Department of Energy nonreactor nuclear facilities typically evaluate their safety basis through the use of process hazards analyses. The level of detail and effort depends on whether the facility is an existing facility or a new facility. Because of the vastly different safety concerns, the reactor facilities are subdivided into two parts: terrestrial activities and launch/ascent activities. Because all reactor operations—such as criticality tests and full-power tests—must occur in a licensed or certified facility, the identification of IEs for the reactor facilities follows the probabilistic safety analysis methods used in the nuclear power plant industry. For the launch/ascent activities, separate SAR is prepared and undergoes evaluation by an Interagency Nuclear Safety Review Panel (INSRP) prior to launch approval.

Non-Nuclear Materials Compatibility Test of Niobium – 1% Zirconium and 316 Stainless Steel for Space Fission Reactor Applications

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Abstract. Next generation power production and propulsion technologies are critical to achieving NASA's future goals. Fission power technologies are in development to meet this need. Many reactor concepts may utilize a combination of refractory metals and stainless steels. One such material Niobium –1% Zirconium (Nb-1Zr) will be used because of its neutron absorption properties and strength at high temperatures. Niobium has a high solubility for oxygen at elevated temperatures. As oxygen diffuses into the material it will dissolve interstitially. Small amounts of dissolved oxygen can significantly deteriorate the mechanical properties of the alloy. This paper presents an on-going experiment to study the interaction of type 316 stainless steel (316 SST) and Nb-1Zr. The objective of the experiment is to better understand how an inert helium working fluid can transport oxygen from oxide layers on SST 316 and deposit the oxygen onto Nb-1Zr, degrading material the performance properties after several hundred hours of operation. Tests will be performed in a realistic non-nuclear environment at the appropriate operating conditions. These experiments will be conducted at the Early Flight Fission Test Facility at NASA Marshall Space Flight Center.

Neutron and Energy Balance Constraints for Rankine Power Conversion Systems

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Abstract. Nuclear designs parameters, that is: pitch and enrichment of the fuel lattice, dimensions of the core, the reflector and pressure vessel, and neutron and gamma shielding have been conveniently correlated for quick and scoping calculation of liquid-Lithium cooled reactors which are candidates for the nuclear reactor of Rankine Power Conversion systems (also Brayton's). A database has been created after detailed calculations of the neutron balance in UN pins with Rhenium liner and Nb1Zr clad, cooled with liquid-Lithium and reflected with BeO. The correlations were then incorporated into a program that solves for the simultaneous solutions of two balance equations: energy and reactivity under conditions defined by the designer: power level, duration of the mission, burnup, sizes, shapes and reactivity balance at the end of the mission. Free variables such as enrichment, pitch of the lattice, one of the two dimensions are then sorted to match the input requirements. If the two balance equations cannot be satisfied the code then relaxes some of the inputs to satisfy them. In any case the code produces a menu of alternatives and a detailed thermal-hydraulic analysis of the core. Independently of the details and approximations of the correlations these two equations illustrate and define compromises to be made between two competing design parameters: energy required and minimum mass for the nuclear power source.

Preliminary Tests of a 20 kWe, 7500 s NEXIS Ion Thruster

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Abstract. The Nuclear Electric Xenon Ion System (NEXIS) Program is one of three proposals selected by NASA to develop thruster technologies for high power, high Isp nuclear electric propulsion systems for outer planet exploration. These exploration missions will require vehicles with system powers of 100 kWe or more and thrusters capable of operating at over 20 kWe per engine at an Isp of 6000-9000 s and efficiencies greater than 65%. The thrusters must process over 1000 kg of propellant per engine. To meet these needs, a team of university, government and industry participants led by JPL has developed a number of advanced technologies that are currently being tested in a laboratory model thruster.

The NEXIS thruster technologies represent a dramatic improvement in the state-of-the-art for ion propulsion and are designed to essentially eliminate the thruster wear-out failure modes observed in previous engine development programs while increasing the thruster power to ≥20 kW and *Isp* to ≥6000 s. The NEXIS thruster uses erosion resistant carbon-carbon grids to achieve very long optics life. A graphite keeper electrode is used to eliminate keeper erosion observed in other long duration thruster wear tests. High efficiency is achieved with a 65-cm diameter chamber masked to produce a 57-cm diameter ion beam. Preliminary tests of the laboratory model thruster have demonstrated efficiencies over 70% at Isp's greater than 6000 s at power levels over 20 kW. The results of preliminary tests of the laboratory model thruster will be reviewed in this presentation.

Development of the NEXIS Ion Thruster

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Abstract. The Nuclear Electric Xenon Ion System (NEXIS) Program is one of three proposals selected by NASA to develop thruster technologies for high power, high Isp nuclear electric propulsion systems for outer planet exploration. These exploration missions will require vehicles with system powers of 100 kWe or more and thrusters capable of operating at over 20 kWe per engine at an Isp of 6000-9000 s and efficiencies greater than 65%. The thrusters must process over 1000 kg of propellant per engine. To meet these needs, a team of university, government and industry participants led by JPL has developed a number of advanced technologies that are currently being tested in a laboratory model thruster. The proposed NEXIS technologies represent a dramatic improvement in the state-of-the-art for ion propulsion and are designed to essentially eliminate the thruster wear-out failure modes observed in previous engine development programs while increasing the thruster power to ≥20 kW and *Isp* to ≥6000 s. The NEXIS thruster uses erosion resistant carbon-carbon grids to achieve very long optics life. To prevent exhaustion of barium observed in conventional hollow cathodes, a new reservoir hollow cathode incorporating as much as 10 times as much barium is being developed. A graphite keeper electrode biased with respect to the cathode potential is used to eliminate keeper erosion observed in other long duration thruster wear tests. Very high efficiency is achieved with a 65-cm diameter chamber masked to produce a 57-cm diameter ion beam, and a shared neutralizer architecture. Preliminary tests of the laboratory model thruster have demonstrated efficiencies over 71% at Isp's greater than 6000 s, and efficiencies as high as 76% are expected for a multi-engine configuration with a shared neutralizer. The key technologies and plans for further development will be reviewed in this presentation.

Mission Steering Profiles of Outer Planetary Orbiters Using Radioisotope Electric Propulsion

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Abstract. Radioisotope Electric Propulsion (REP) has the potential to enable small spacecraft to orbit outer planetary targets with trip times comparable to flyby missions. The ability to transition from a flyby to an orbiter mission lies in the availability of continuous low power electric propulsion along the entire trajectory. The electric propulsion system's role is to add and remove energy from the spacecraft's trajectory to bring it in and out of a heliocentric hyperbolic escape trajectory for the outermost target bodies. Energy is added and the trajectory is reshaped to rendezvous with the closer-in target bodies. Sample REP trajectories will be presented for missions ranging for distances from Jupiter orbit to the Pluto-Kuiper Belt.

Evaluation of Computer Programs for Small Rankine Power Conversion Systems

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Abstract. In support of NASA's Project Prometheus, the Nuclear System Program, a set of computer programs has been reviewed at Oak Ridge National Laboratory (ORNL) to analyze small space Rankine Power Conversion Systems. The base case to be analyzed and designed with these programs is a 100 kWe Rankine System employing a lithium-cooled, uranium nitride-fueled, fast reactor that produces potassium vapor in a boiler driving the turbine-generator.

The computer programs reviewed are: RSMASS, ALKASYS, MNRANK, HREJECT, and ATHENA. RSMASS is a space reactor code developed by Sandia National Laboratories in 1997. ALKASYS is an integral space reactor program developed at ORNL in 1987 written in BASIC. The MNRANK program models the power conversion system (boiler, turbo-generator, and piping) of a Rankine system. The HREJECT program is a generic heat rejection code that models heat pipe radiators and heat exchangers. These last two programs were developed by Rocketdyne for NASA about 10 years ago. ATHENA was developed by INEL, can analyze transients in liquid metal systems, and is based on the transient thermal/hydraulic code RELAP5/Mod3.2.

ALKASYS was developed to analyze multimegawatt reactor systems. Consequently, it did not run or yielded erroneous results for the low reactor powers (100 kWe) of the present study and the program was modified. The modified ALKASYS program, called ALKASYS-RPS, is now written in FORTRAN 77, and is fully modular, with separate modules for the reactor, the shielding, the power conversion system, and the radiator. The reactor module has been modified extensively and calculates small reactor cores based on criticality considerations. The modular architecture of ALKASYS-RPS allows for substitution of modules – an advanced radiator module can be employed instead of the original radiator model.

The MNRANK and HREJECT programs have also been modified to extend their range of applicability to powers as low as 50 kWe.

Calculations for different powers and conditions have been completed by the different codes, and their results have been compared.

Disclaimer: "This work was performed by the Oak Ridge National Laboratory (ORNL) for the U.S. Department of Energy (DOE) in support of NASA's Project Prometheus, the Nuclear Systems Program. ORNL is managed for DOE by UT-Battelle, LLC, under contract DE-AC-05-00OR22725. Any opinions expressed in this paper are those of the authors and do not necessarily reflect the views of NASA's Project Prometheus or DOE."

Evaluation of Candidate Materials for a High-Temperature Stirling Convertor Heater Head

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Abstract. The Department of Energy (DOE) and NASA have identified Stirling Radioisotope Generators (SRG) as a candidate power system for use on long-duration, deep-space science missions and Mars rovers. One of the developments planned for an upgraded version of the current SRG design is to achieve higher efficiency by increasing the overall operating temperature of the system. Currently, the SRG operates with a heater head temperature of 650°C and is fabricated from the nickel base superalloy 718. This temperature is at the limit of Alloy 718's capability, and any planned increase in temperature will be contingent on identifying a more capable material from which to fabricate the heater head. To this end, an assessment of material candidates was performed assuming a range of heater head temperatures. The chosen alternative material candidates will be discussed, along with the development efforts needed to ensure that these materials can meet the demanding system requirements of long-duration operation in hostile environments.

Determination of Reliability Test for Redundant Multi-Train System

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Abstract. The objective of this paper is to demonstrate a methodology to determine the number of failure-free tests for mission duration and operational conditions for multiple-train system with m/n combination success configuration. Such assessment will primarily depend on single train Reliability and confidence Interval. In some programs, quantitative reliability requirements may not be allocated down to the system level. It is therefore necessary to perform the assessment based on a range of reliability distribution. It is also necessary to determine possible options (success criteria) for the overall system configuration (e.g., m/n trains for system success). Further, using the resultant single train reliability values, different test intervals can be calculated for different confidence levels. Finally, based on forecast budget and schedule, a range of number of life tests required to verify a distribution of reliability goals at different confidence levels are determined. In summary, this trade study uses Binomial and Sample Size Calculation methodologies to determine the number of failure-free life tests for different redundancy configurations.

Radioisotope Powered Missions to Martian Moons Using Electric Propulsion

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Abstract. Many of the planetary missions recommended by the recently completed Decadal Planning Survey require radioisotope or reactor based power sources due to the distance from the Sun and lack of adequate solar energy. This paper discusses the results of a study performed assessing two different spacecraft power and propulsion system architectures that utilize a radioisotope based heat source and Stirling power Convertors to support a science based mission to the Martian moons Phobos and Deimos.

The first approach utilizes already developed components including the General Purpose Heat Source (GPHS) radioisotope heat source, the Stirling Radioisotope Generator (SRG) power conversion system, and the NSTAR ion thruster and power processor unit.

The second approach utilizes a unique power system design that includes second generation Stirling engine technology in conjunction with the concept of a vector controlled multi-Convertor Stirling power conversion system to achieve significant improvement in specific power as well as higher system efficiency and better mechanical stability. This approach also enables the required 1000 – 2000 Vdc bus power for the envisioned ion thruster electric propulsion system to be produced directly off the generator rather than employing a traditional DC/DC conversion approach, resulting in much higher efficiency and both lower Power Processing Unit (PPU) mass and lower heat rejection system mass. The results of the study illustrate the significant performance advantages of the next generation approach compared to using the more traditional approach with existing components toward improving system specific mass (α).

Optimizing Space Rankine Power Conversion System Design

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Abstract. Potassium Rankine power conversion systems offer the promise of the lowest mass per unit power for Space Reactor Power Systems (SRPS) that deliver powers above approximately 100 kWe. A NASA sponsored research program to design and optimize an advanced in-direct potassium Rankine power conversion system for moderate power electrical systems (100 kWe to 250 kWe) is on-going at ORNL, in conjunction with Boeing/Rocketdyne and Swales Aerospace. The latest available technologies and material design data are being considered in optimization studies that include operating temperatures and pressures and system configuration. The trades associated with the major component designs are described and the results of initial optimization efforts are presented.

Technical Bases to Aid in the Decision for Conducting Full Power Ground Nuclear Tests for Space Reactors

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Abstract. The extent to which, if any, full power ground nuclear testing of space reactors should be performed has been a point of discussion within the industry for decades. Do the benefits outweigh the risks? Are there equivalent alternatives? Can a test facility be constructed (or modified) in a reasonable amount of time? Is the test article an accurate representation of the flight system? Are the costs too restrictive? The obvious benefits of full power ground nuclear testing; obtaining systems integrated reliability data on a full-scale, complete end-to-end system; come at some programmatic risk. Safety related information is not obtained from a full-power ground nuclear test. This paper will discuss and assess these and other technical considerations essential in the decision to conduct full power ground nuclear–or alternative–tests.

Nuclear Electric Vehicle Optimization Toolset (NEVOT): Integrated System Design Using Genetic Algorithms

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Abstract. The Nuclear Electric Vehicle Optimization Toolset (NEVOT) optimizes the design of all major nuclear electric propulsion (NEP) vehicle subsystems for a defined mission within constraints and optimization parameters chosen by a user. The tool uses a genetic algorithm (GA) search technique to combine subsystem designs and evaluate the fitness of the integrated design to fulfill a mission. The fitness of an individual is used within the GA to determine its probability of survival through successive generations in which the designs with low fitness are eliminated and replaced with combinations or mutations of designs with higher fitness. The program can find optimal solutions for different sets of fitness metrics without modification and can create and evaluate vehicle designs that might never be conceived of through traditional design techniques. It is anticipated that the flexible optimization methodology will expand present knowledge of the design trade-offs inherent in designing nuclear powered space vehicles and lead to improved NEP designs.

Comparison of Structural Optimization Techniques for a Nuclear Electric Space Vehicle

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Abstract. The purpose of this paper is to investigate optimization methods for structural design of a nuclear electric vehicle. In particular, the methods are applied to analysis of the primary truss structure in efforts to arrive at an optimal vehicle having minimum structural weight. The primary optimization technique of interest in this study is the use of genetic algorithms (GA). Genetic Algorithm-based optimization is a guided, random search that begins with a large population of structural designs, then modifies the population through several types of genetic operations to arrive at the optimal design best satisfying a fitness function and set of constraints.

To verify the GA's capabilities, traditional gradient-based structural optimization was used for comparison to GA results. In all the analyses, the structure weight was minimized subject to constraints on buckling stress in the members. The GA approach was applied to a simple beam and a 10-member benchmark planar truss structure, and results compared well to gradient-based optimization for both cases. Gradient optimization was also applied to (a) large-scale 25-member benchmark three-dimensional truss, and (b) 80m 356-member truss representative of nuclear vehicle structures.

Optimization of Space Reactor Power Systems using Genetic Algorithms

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Abstract. A Space Reactor Power System (SRPS) optimization tool has been developed that uses Evolutionary Computational Algorithms called Genetic Algorithms (GA) to optimize the design of SRPS subsystems for a Nuclear Electric Propulsion (NEP) space vehicle. The second generation SRPS optimization tool has been developed with independent reactor, shield, power conversion and heat rejection design modules to either optimize the integration of those components to a defined space vehicle or to include the truss and the Electric Propulsion (EP) system in the overall optimization problem. The SRPS optimization tool is designed to work in conjunction with the Nuclear Electrical Vehicle Optimization Tool (NEVOT), which is being jointly developed by Oak Ridge National Laboratory, Marshall Space Flight Center and Arnold Engineering Development Center. Although the tool was developed for a space power application, the methodology can be applied to any multi-discipline, multi-objective optimization problem.

Magnetically-Channeled SIEC Array (MCSA) Fusion Device For Interplanetary Missions

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Abstract. A radical new Inertial Electrostatic Confinement (IEC) concept, the Magnetically-Channeled Spherical-IEC Array (MCSA) fusion propulsion system was proposed recently for interplanetary space travel [1]. IEC fusion concepts are widely recognized to be attractive for space power because they are simple and lightweight. However, existing IEC concepts, while very successful for low-level power neutron sources, do not extrapolate well to high power space applications due to poor plasma confinement time scaling and grid heating/ ion- losses. The MCSA concept addresses both issues - eliminating the need for a central grid and providing improved confinement time scaling. While the MCSA geometry uses coupled IEC units, the real innovation lies in the formation of potential and magnetic field surfaces such that they retrap leaking particles while forming a gridless potential well confinement region. This results in a greatly improved fuel economy and significantly increases the overall confinement time. Because of the energetic ion beam and it's non-Maxwellian, non-neutral plasma, aneutronic fuels, such as D-^{3}He, can be easily implemented in the MCSA. This provides a strong source of high-energy (14-MeV) protons, ideally suited for use as an ultra-high ISP thruster. Thus, the MCSA concept has the potential to meet the demanding requirements for future deep space propulsion and power. This promise was amply demonstrated in a recent design study by Burton et al. [1] which used a MCSA to accomplish a fast manned mission to Jupiter.

In the present paper, we discuss the basic MCSA concept and pin point some physics issues that must be resolved to access it's feasibility. The MCSA configuration has yet to be studied in detail experimentally, but some important supporting data carries over from prior IEC experiments. If proven feasible, the MCSA development path would involve experiments at progressively higher powers aimed at the ultimate demonstration of a full-scale multi-MW propulsion unit. This development plan will be briefly discussed.

R. Burton, H. Momota, N. Richardson, Y. Shaban, and G. H. Miley, "Fusion Ship II- A Fast Manned Interplanetary Space Vehicle Using Inertial Electrostatic Fusion," Space Technology and Applications International Forum - STAIF-2003, edited by M.S. El-Genk, American Institute of Physics, Conference Proceedings, 2003, pp. 553 – 562.

Hybrid Coolant System Concept for Space Nuclear Reactors

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Abstract. Current designs of liquid metal (LM) cooled reactors for long duration space mission use implement only a single primary (through reactor core) coolant loop, which is thus a critical single failure point. Leakage of the LM as a result of a micrometeoroid or debris "hit" would result in loss of the mission and a possible "loss of coolant accident" (LOCA). Conceptualized is a scheme in which the reactor core is divided into two sections, each with its own LM coolant loop, and the sections are thermally joined by an array of in-core heat pipes. With properly sized LM coolant loops and heat pipes this would permit continued operation at near rated power after the failure or shutdown of one LM loop, and would drive the core towards more nearly isothermal conditions during normal, two-loop operations. Ramifications regarding additional flexibility afforded to (sub)system operations and simplicity of fabrication will also be addressed.

A Pulse Gas Core Reactor Concept for Space Power & Propulsion Applications

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Abstract. A pulse Gas Core Reactor (P-GCR) concept based on using non-moving fissile gas is designed. The concept utilizes well-established fusion plasma confinement and compression methods to achieve supercritical condition in a highly subcritical fissile gaseous fuel in a reflected cylindrical configuration. In particular, electromagnetic induced shock wave compaction and gas dynamic trap techniques are merged to bring a relatively small volume (~ 1 m^3) of fissile (^{235}U, ^{233}U, ^{239}Pu, or ^{242m}Am) gas compounds to supercritical condition, thereby, releasing an intense pulse of fission power. A magnetic field compaction scheme is designed to directly convert the fission energy to electricity. The estimated specific power of the pulsed magnetic field driven Nuclear Electric Propulsion (NEP) system is above 1 KWe/Kg. An alternative P-GCR design option provides direct thrust in nuclear thermal propulsion configuration. The direct propulsion system is designed based on a merger between Magnetized Target Fusion (MTF) and hydrodynamic confinement techniques to achieve long duration (~ 100 to 1000 ms) criticality and ultrahigh burnup in a fissile gas. The MTF technique induces large pressure ratio (~ 10) adiabatic compaction of fissile gas by rapid collapsing of a cylindrical layer of a low neutron absorbing metal (Al or Zr). Hydrodynamic confinement in a leaky reversed mirror configuration is used to contain and direct the fission plasma through a nozzle, thereby, generating intense thrust (~ 100's of Klb) at specific impulse levels in excess of 2000 seconds.

Close Brayton Cycle Space Power Systems – An Historical Perspective

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Abstract. The first Brayton engines were made in the late 1800s as constant pressure combustion piston engines that competed with Otto and Diesel cycle engines. In the early 1900s, advances in aerodynamics and metallurgy led to the gas turbine, the first successful constant pressure combustion, or Brayton cycle, engine. This was soon followed by the invention of the closed Brayton cycle engine for power plant applications in the mid-30s. In the early 60s, the Garrett Corporation (now part of Honeywell International) built the Brayton Cycle Demonstrator, the first close Brayton cycle system configured for space applications. The success of this demonstrator initiated a 30-plus year collaboration between Garrett (now part of Honeywell International) and the NASA Lewis Research Center (now the NASA Glenn Research Center) in the development of closed Brayton cycle space power systems. This paper presents the highlights of that 30 year history.

Pulsed Inductive Thruster: Progress Toward Flight Readiness

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Abstract. The pulsed inductive thruster (PIT) is a versatile type of space electric propulsion capable of high and independently variable thrust and specific impulse. Currently producing a nominal 0.1 N-s impulse at 5000 s I_{sp}, the thruster can be throttled between 2000 and 8000 seconds I_{sp}, at approximately 50% overall efficiency, by varying injected propellant mass. Benefits of the PIT also include inductive coupling of energy into the plasma, eliminating electrode erosion, and the use of inexpensive and readily available propellants -- ammonia, hydrazine, or water -- rather than xenon.

Northrop Grumman Space Technology is now developing new pulsed inductive thrusters, MkVI and MkVII, to reproduce and verify the performance measured on PIT MkV in the early 1990s, and to demonstrate high power, long-duration firing, essential for any space mission. The PIT MkVI prototype is being developed to reproduce the MkV single-shot tests, which completely characterize thruster performance. The MkVI uses a new coil of copper tube construction and a new propellant valve, but is otherwise electrically identical to MkV, using the same capacitors and switches. The MkVII has the same geometry as MkVI, but is designed for long-duration firing, with a liquid-cooled coil, long-life capacitors, and fast, high-power solid-state switches. The goal for MkVII is to demonstrate 50 pulses per second at the rated efficiency and impulse bit per pulse, at 200 kW input power.

This paper describes the design, fabrication, and testing of the new components of the PIT prototypes. High-speed propellant valve and thyristor development and test results, in particular, are described. Also included are descriptions and results of the tests performed on MkVI. The paper concludes with the ongoing work on MkVII, including the power processing unit and facility preparation for long-duration firing.

PRESTO – A Simple, Compact, Fission Power System For Mars Surface Power Applications

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Abstract. Oak Ridge National Laboratory (ORNL) has recently proposed a simple, compact fission power system for surface power applications on Mars. The baseline concept, termed PRESTO for Power REactor for Surface Terminal Operations, incorporates a boiling liquid metal reactor and a Stirling power conversion system to provide 3 to 30 kWe to support fixed-based surface operations on Mars. PRESTO combines insights and technologies developed during the Medium Power Reactor Experiment (MPRE) project at ORNL during the mid 1960s, with more recent Stirling power conversion technology developments. ORNL is currently conducting a preliminary investigation to examine the feasibility of the PRESTO concept. Design factors under investigation include but are not limited to: fission energy spectrum, thermal power level, fuel and coolant selection, physical sizing, shielding approaches, and the feasibility of employing natural circulation reactor cooling. This presentation will report the early results of the feasibility study, discuss technology and design options, and identify PRESTO technology development activities required to demonstrate concept feasibility.

The Impact of Core Cooling Technology Options on JIMO Reactor Designs

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Abstract. The Jupiter Icy Moons Orbiter (JIMO) Project requires a reliable, low-mass, high-temperature, long-lived reactor that than can be developed/qualified in ~6 years. This has led to the design choice of a compact, fast-spectrum, highly-enriched ^{235}U, externally-controlled reactor. In addition, most JIMO concepts use identical reactor materials: UN fuel, Nb1Zr clad/structure, Re fuel liner, BeO and/or Be reflectors. The major design choice that remains is how the power will be transported from the reactor core to the power conversion system. This choice is important because it can substantially affect development risk, testing, and reliability. The primary options for core cooling are: pumped liquid-metal (Na or Li), liquid metal heat pipes (Na or Li), and inert gas (He or HeXe). Each option has been evaluated under past and current space reactor programs. These options have also been evaluated for decades for terrestrial reactors (some more than others), which can provide substantial information concerning reactor technologies, but not as much information concerning the operation of this class of reactor (which is unique from any reactor ever operated). Fortunately, in comparison to terrestrial systems the JIMO reactor is rather simple in terms of operation because (1) there are a relatively small number of design basis events, (2) powered-operation on Earth is not required (which removes operational transients as a safety concern), (3) reactivity feedback values are non-heterogeneous, simple and small, (4) reactivity feedback is dominated by core geometry and density, which can be tested extensively with non-nuclear testing and linked to zero-power nuclear testing, and (5) reactor power system thermal hydraulics can be tested realistically with non-nuclear testing. Reactor cooling does provide some discrimination in reactor operation, but given the factors above, the JIMO reactor concepts are much more similar to each other than they are to any terrestrial systems (especially considering the materials they use and how power is removed by the various power conversion systems). This presentation will examine the impact of core-cooling technology on the design of JIMO reactors, including the core, reflector, shield, control system, and any other components that may or may not be needed for each concept (e.g. vessel, heat exchangers, pumps, separators, thaw systems, etc.).

The Impact of Power and Lifetime Requirements on JIMO Reactor Designs

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Abstract. One of the most challenging issues faced by the Jupiter Icy Moons Orbiter (JIMO) Project is to balance how well a reactor concept can meet the desired objectives of JIMO and Project Prometheus (performance) versus the difficulty of developing and qualifying the reactor in ~6 years (technical risk). The key differentiating elements of performance are mass, reliability, power, and lifetime. Safety is not a performance parameter because all concepts must meet project safety requirements without exception. This presentation will focus on how power and lifetime requirements affect the design and other performance parameters of JIMO reactors, as well as the impact on development risk.

The power and lifetime potential of space fission reactors is essentially limitless when compared to the requirements of any potential NASA mission in the foreseeable future. However, this does not imply that space fission reactor performance and risk are independent of power and lifetime. To the contrary, the performance and technical risk of a space fission reactor are tightly coupled to power and lifetime requirements. It is important that these technical risks are understood before NASA proceeds down the path of developing its first, and subsequent fission systems. The first-step needs to be small enough to ensure that success is highly probable, so that the experience and infrastructure will be in place to continue and develop more advanced systems.

This presentation will focus on how power and lifetime requirements impact the design and development of potential JIMO reactors. In many cases the impact is quantified with a mass savings/penalty, while in other cases the impact is qualified in terms of technical risk.

Efficient Skutterudites for High Temperature Thermoelectric Power Generation

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Abstract. Filled Skutterudites have emerged as the most prospective novel thermoelectric materials for power generation applications at intermediate temperatures (700 to 1000K). In this temperature range, high ZT values in excess of unity have been established for both p-type and n-type forms of filled cobalt triantimonide. The results far exceed the performance of the existing thermoelectric materials, and are superior to any novel material system that is being considered for high temperature applications. Indeed, filled skutterudites are starting to be employed in the uppermost stages of segmented unicouples where the conversion efficiencies are expected to exceed 15% with hot side junctions operating near 100K. Even higher thermal-to-electric system performance values are predicted if such high ZT values could be extended to higher temperatures. Our current effort focuses on two areas: the development and fabrication of filled solid solutions of skutterudites of both p- and n-type conductivity with the dimensionless figure of merit ZT in excess of 2, and operational efficiencies of 15 to 20% in the 600 to 1000K temperature range; and extending the temperature range of operation of filled and unfilled skutterudites up to the 1200 to 1300K temperature range by developing more refractory compositions of the antimonide compounds characterized so far.

A Space Elevator Based Exploration Strategy

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Abstract. Technological advances and recent studies have laid the groundwork for eventual construction of a space elevator. Within 15 years an operational space elevator could be running from Earth to beyond geosynchronous. The basic mechanical operation allows for low operational cost ($100/lb), high capacity (>13tons, >5tons/day/elevator), range of destinations (LEO, GEO, Moon, Mars, Asteroids, and Venus), and minimal launch forces. The low risk operation of the space elevator would allow large scale robotic and human exploration of the solar system. An operational elevator will immediately move primary interest from LEO to GEO for many activities and open commercial space activities such as solar power satellite arrays for beaming power to Earth. Robotic exploration to all destinations would be able to use larger, fixed structures, more massive platforms and be launched for a fraction of current costs. Human exploration could start at GEO for maintaining commercial assets, and enhanced Earth-observing systems and then step to Mars where a receiving elevator could also be established. In this paper we will cover the basics of a space elevator and a comprehensive strategy for human and exploratory use of space based on the space elevator.

The Hematopoietic Stem Cell Therapy For Exploration Of Deep Space

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Abstract. It is well documented that prolonged exposure to space environments causes severe/invasive disorders in astronauts. These include hematological/cardiac abnormalities, bone and muscle losses, immunodeficiency, neurological disorders and cancer. Exploiting the extraordinary plasticity of hematopoietic stem cells (HSCs), which differentiate not only to all types of blood cells, but also to various tissues, including muscle, skin, liver, neuronal cells and possibly bone, we have advanced a hypothesis that some of the space-caused disorders may be amenable to hematopoietic stem cell therapy (HSCT) so as to maintain astronauts' homeostasis. If this were achievable, the HSCT could promote human exploration of deep space. Using mouse models of human anemia (β-thalassemia) as well as spaceflight (hindlimb suspension unloading system), we have obtained feasibility results of HSCT for space anemia, muscle loss, and immunodeficiency. For example, the β-thalassemic mice were successfully transplanted with isologous HSCs, resulting in chimerism of hemoglobin species and alleviation of the hemoglobinopathy. In the case of HSCT for muscle loss, β-galactosidase-marked HSCs were detected by the X-gal wholemount staining procedure in the hindlimbs of unloaded mouse following transplantation. Histochemical and physical analyses indicate structural contribution of HSCs to the muscle. To investigate HSCT for immunodeficiency, β-gal-transformed *Escherichia coli* was infected to control and the hindlimb suspended mice. Results of the X-gal staining procedure indicate that the HSCT could help eliminate the *E.coli* infection. In an effort to facilitate the HSCT in space, growth of HSCs has been optimized in the NASA Rotating Wall Vessel (RWV) culture systems, including Hydrodynamic Focusing Bioreactor (HFB). (Supported by NASA Grants NIAC/NAS5-98051and USRA/NCC9-142 to SO)

Where Should We Look For Life On Mars: The Case For Large Impact Craters

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Abstract. The foremost question for Martian exploration is the investigation of environments favorable for the evolution or flourishing of pre-biotic organic chemistry or primitive life. Hydrothermal systems are the most sought after targets because terrestrial life probably originated in such systems. Large craters on Mars may contain aqueous and hydrothermal deposits that provide clues to organic and biological processes. The great depth of impact craters, up to several kilometers relative to the surrounding terrain, can allow the breaching of local aquifers, providing a source of water for lakes and hydrothermal systems. Craters can also be filled with surface water from outflow channels and valley networks to form large lakes with accompanying sedimentation. Therefore, large craters may represent giant Petri dishes culturing preexisting life on Mars and promoting biogeochemical processes. These deposits represent an important goal for sampling by robotic or human exploration. Landing sites must be identified in craters where processes, such as erosion from outflow channels, faulting, aeolian erosion, or excavation by later cratering events has provided access to the buried lake sediments and impact melt deposits. Recent excavation of early large craters by small superimposed craters, and by the formation of fresh gullies may expose samples, such as organic material, that would be degraded by long-term exposure to oxidation or UV light present in the surface environment. Exploring such craters on Mars will involve technical challenges of finding, accessing, and sampling the aqueous and hydrothermal deposits. Instrumentation and exploration scenarios to study large impact craters may require a combination of lander-based remote sensing instruments and in situ analysis techniques.

Benefits of a Mars Sample Return

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Abstract. Robotic Mars sample return missions (MSR) can provide a wide spectrum of fundamental data on the geology and the biological potential of Mars that cannot be acquired through remote sensing or in-situ techniques in current or planned one-way orbiter and lander missions. One of the great advantages of MSR is that returned samples can be studied by multiple research groups, using every analytical technique available in the world's best laboratories. MSR-acquired data are crucial for understanding the evolution of Mars, searching for evidence of life, and planning future exploration campaigns that include human missions to Mars. Hence, a robust and visionary Mars exploration program should have as its centerpiece a long-term sample return strategy. The first MSR should come early in the program in order to maximize our knowledge of the Martian surface and subsurface that will guide future exploration pathways. With an early sample return mission there is no need to prejudge what we will find and the dilemma of in-situ missions that must choose a limited set of instruments to fly is avoided. When the samples are available for study in Earth-based laboratories, experiments can be designed in real time as the characteristics of the materials are revealed. Thus research on Mars samples can follow many paths and the studies may evolve as hypotheses are tested and refined. No restrictions on power, instrument size and mass, data rates, consumables, or component life exist for returned-sample studies. Elaborate sample preparation techniques are usually required for isotopic studies and for micro, nano-, and atomic scale characterization. Such preparation techniques are impractical or impossible by remote robotic methods on Mars, but are standard operating procedures in our state-of-the art SEM, TEM, microprobe, and isotope laboratories. Mars science studies best done by sample return include (1) precise isotopic measurements of atmospheric gases, soil, and rock, (2) age dating of rock, (3) trace element chemistry of soil and rock, (4) characterization of very small phases, (5) characterization of complex weathering products, (5) detailed rock mineralogy and petrology, (6) detailed organic/biological analyses, (7) search for biomarkers and microfossils.

Xanadu: A Polar Base for Manufacturing Supplies on Mars

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Abstract. Human exploration of Mars requires much greater supplies of propellants, fuels, breathable air, construction materials, and food then can come from Earth. However, all these materials can be robotically manufactured from CO_2 and N_2 in the Martian atmosphere and water ice on the North Polar Cap. A small, nuclear powered robotic factory landed on the Polar Cap, can manufacture and stockpile hundreds of tons of supplies under the ice for astronauts coming from Earth. Sub-surface insulated ice caves can also provide insulated habitats to shield from cosmic radiation. Design and operation of the robotic factory is described including the nuclear reactor and chemical process units. The water-cooled reactor uses Zr/UO_2 cermet nuclear fuel. Commercial chemical process technology would include water electrolysis, liquefaction of H_2, O_2, and air (N_2/O_2), methane, methanol, and polyethylene synthesis from CO_2 and H_2, and algae and yeast foodstuff from methanol feedstock. Development and mission scenarios for the Xanadu concept are described with implementation possible within the next decade.

Planetary Sampling Strategies. Lessons Learned from the Analysis of Small Extraterrestrial Samples

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Abstract. The next series of planetary sampling missions to the Moon, Mars, Venus, Mercury, and asteroids will result in the return of sample mass (100g to 1 kg) substantially smaller than those returned by the manned Apollo missions (380 kg). Samples to be returned by these new missions are vital for (1) calibrating the late impact history of the inner solar system, (2) deciphering the effects of catastrophic impacts on a planetary body, (3) reconstructing the thermal and magmatic evolution of a cooling planet, (4) exploring the interior of a planet, (5) examining volatile reservoirs and transport in different types of planetary environments, (6) exploring for past environments hospitable for life and (7) searching for remnants of life. In most cases, these questions cannot be answered by in situ analysis of material on a planets surface. Can small samples returned to Earth be used to answer these and other pressing questions concerning important solar system processes? Two potential problems with small, robotically collected samples are placing them in a geologic context and extracting robust planetary information. Although geologic context will always be a potential problem with any planetary sample, newly returned samples may be placed within the context of the burgeoning planet-scale remotely sensed data sets for the Moon, Mars, Venus, Mercury, and various asteroids. Here we illustrate the usefulness of applying both new or refined analytical approaches in deciphering information locked in small extraterrestrial samples. We present three examples in which the analysis of small extraterrestrial materials from planetary bodies have added greatly to our knowledge of the solar system: chemical analysis of lunar volcanic glasses, stable isotopic analysis of martian sulfides, and radiometric age dating of lunar and martian samples. Included in our discussion of sample analysis in terrestrial labs are contrasts with in situ analysis on planetary surfaces, requirements of the analysis, and interpretation of the data.

StarTram: Ultra Low Cost Launch for Large Space Architecture

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Abstract. StarTram is a new launch system concept that can launch massive volumes of passengers and cargo, 1000 times present volume, at ultra low cost, 1/1000th of present $/kg values. StarTram will enable major new applications and exploration capabilities, including solar-beamed power satellites, space tourism and manufacturing, lunar colonies, and human exploration of Mars and the Outer Solar System. StarTram spacecraft are magnetically levitated and accelerated to orbital speeds, 8 km/sec and higher in an evacuated Maglev tunnel at ground level. No propellant is required, and the cost of launch energy is only 60 cents per kg based on 5 cents per KWH. The StarTram spacecraft then transitions into a magnetically levitated evacuated Maglev launch tube that ascends from the ground to an altitude of 70,000 feet or more. The spacecraft then enters the low density atmosphere through a ionized air MHD "window" that prevents atmospheric flow into the evacuated tube. Two StarTram designs are described, a shorter, low cost, 20 g system for launch of bulk cargo and a longer, more expensive 2 g system for launch of passengers and more fragile cargo. The superconducting and materials technology required for StarTram already exists commercially. An engineering development and implementation plan to build StarTram is described.

In-Space Propulsion Options for Mars Sample Return Missions

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Abstract. In-Space transfer stage options for conducting Mars Sample Return (MSR) missions are presented. Comparative analyses were performed with the objective of aiding technology funding decisions relevant to future in-space propulsion technologies suited to Mars specifically, and to other planetary exploration missions generally. MSR system analyses, conducted for NASA Marshall Space Flight Center under the multi-year *In-Space Technologies Assessment contract*, show how vehicle performance varies with key system characteristics. Payload to Mars mass is shown as a function of propulsion type (chemical, solar electric), propellant type (chemical storable, cryogenic and exotic), electric thruster type (Ion, Hall), orbit capture mode (all propulsive, propulsive with aerobrake assist, and aerocapture), aerocapture brake mass, lander entry mode (capture or direct entry), and other key items. Analyses also show performance sensitivities to mission related items, such as launch vehicle type, Earth departure energy (C3), Mars entry and departure hyperbolic velocity (Vhp), Mars orbit altitude and other items. This and other studies will help to lay the foundation for developing a family of low cost, reliable, and versatile concepts leading to exciting MSR robotic missions.

Exploring Planets with Directed Aerial Robot Explorers

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Abstract. Under funding from the NASA Institute for Advanced Concepts (NIAC), Global Aerospace Corporation is developing a revolutionary system architecture for exploration of planetary atmospheres and surfaces from atmospheric altitudes. A key element of this architecture is the Directed Aerial Robot Explorer (DARE) platform, which essentially is a long-duration autonomous balloon with flight path control capability that can deploy swarms of miniature probes over multiple target areas. Trajectory control capabilities offer unprecedented opportunities for high-resolution targeted observations of atmospheric and surface phenomena. The probes are deployed from the DARE platforms over the target areas, and can perform a multitude of scientific functions, such as atmospheric profiling or surface exploration, and then relay their data back to the balloon or to an orbiter. The DARE architecture enables low-cost, low-energy, long-term global exploration of planetary atmospheres and surfaces. A conceptual analysis of DARE capabilities and science applications for Venus, Titan and Jupiter are presented. Preliminary simulations with simplified atmospheric models show that a relatively small trajectory control wing can allow for global coverage of the atmospheres of Venus and Titan by a single balloon over a 100-day mission. This presents unique opportunities for global in situ sampling of the atmospheric composition and dynamics, atmospheric profiling over multiple sites with small dropsondes and targeted deployment of surface packages. At Jupiter, path guidance capabilities of DARE allow to target localized regions of interest, such as “hot spots” or the Great Red Spot. A single DARE platform at Jupiter can sample major types of the atmospheric flows (zones and belts) over a 100-day mission. Observations by deployable probes would reveal if differences exist in radiative, dynamic and compositional environments at these sites.

Systems Analysis of Concepts for Planetary Defense from Near Earth Objects

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Abstract. Several recent near-miss encounters with asteroids and comets have focused attention on the threat of a catastrophic impact with the Earth. This document reviews the historical impact record and current understanding of the number and location of Near Earth Objects (NEO's) to address their impact probability. Various ongoing projects intended to survey and catalog the NEO population are also reviewed. Details are then given of an MSFC-led study, intended to develop and assess various candidate systems for protection of the Earth against NEO's. An existing program, used to model the NEO threat, was extensively modified and is presented here. Details of various analytical tools, developed to evaluate the performance of proposed technologies for protection against the NEO threat, are also presented. Trajectory tools, developed to model the outbound path a vehicle would take to intercept or rendezvous with a target asteroid or comet, are described. Also, details are given of a tool that was created to model both the un-deflected inbound path of an NEO as well as the modified, post-deflection, path. The number of possible options available for protection against the NEO threat was too numerous for them to all be addressed within the study; instead, a representative selection were modeled and evaluated. The major output from this work was a novel process by which the relative effectiveness of different threat mitigation concepts can be evaluated during future, more detailed, studies. In addition, several new or modified mathematical models were developed to analyze various proposed protection systems. A summary of the major lessons learned during this study is presented, as are recommendations for future work. It is hoped that this study will serve to raise the level attention about this very real threat and also demonstrate that successful defense is both possible and practicable, provided appropriate steps are taken.

Technology Validation Experiment for On-Orbit Assembled, Large Aperture Modular Space Telescopes

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Abstract. A revolution in the next generation of Earth and Space science missions would be enabled by large-aperture (greater than 20-meter diameter) space telescopes. Up to an aperture diameter of approximately 3 meters (Hubble Space Telescope size), a telescope can be built as a complete spacecraft and launched to orbit. Somewhat larger apertures can be obtained, and still placed in orbit using a single launch vehicle, by using deployable optics/spacecraft systems that are folded and packaged for launch and deployed on orbit (James Webb Space Telescope approach). Because of limitations with these two approaches, a third approach, where the telescope/spacecraft is assembled on orbit, must be considered if the large apertures desired for future missions are to be realized. A modular telescope system that is transported to (with multiple launches), and assembled on orbit has many potential benefits. One is to relax mass constraints on all of the telescope subsystems, which can lead to less expensive subsystems and more robustness and reliability to be built into the system. The resulting spacecraft can also be easily designed for on-orbit repair and servicing, significantly reducing program risk. The objectives of this paper are to outline an on-orbit technology validation experiment for Large Space Telescopes and to demonstrate that this experiment can take place in the near term. Executing this experiment would demonstrate and validate a near-term path to a revolutionary capability in Earth and Space Science. Potential definitions and options for each telescope modular subsystem as well as its state-of-the-art will be described. Various options for launch vehicles, launch vehicle packaging and on-orbit assembly location, along with their associated pros and cons will be described and a preferred combination defined for the assembly portion of the experiment. Finally, a proposal for the technology validation experiment, consisting of objectives, key milestones, schedule and scope-of-effort will be outlined.

Preliminary Analysis Of ISS Maintenance History And Implications For Supportability Of Future Missions

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Abstract. The International Space Station (ISS) enables the study of supportability issues associated with long-duration human spaceflight. The ISS is a large, complex spacecraft that must be maintained by its crew. In contrast to the Space Shuttle Orbiter vehicle, but similar to spacecraft that will be component elements of future missions beyond low-Earth orbit, ISS does not return to the ground for servicing and provisioning of spares is severely constrained by transportation limits. Although significant technical support is provided by ground personnel, all hands-on maintenance tasks are performed by the crew. It is expected that future missions to distant destinations will be further limited by lack of resupply opportunities and will, eventually, become largely independent of ground support.

ISS provides an opportunity to begin learning lessons that will enable future missions to be successful. Data accumulated over the first several years of ISS operations have been analyzed to gain a better understanding of maintenance-related workload. This analysis addresses both preventive and corrective maintenance and includes all U.S segment core systems. Systems and tasks that are major contributors to workload are identified. As further experience accrues, lessons will be learned that will influence future system designs so that they require less maintenance and, when maintenance is required, it can be performed more efficiently. By heeding the lessons of ISS it will be possible to identify system designs that should be more robust and point towards advances in both technology and design that will offer the greatest return on investment.

Emerging Radiation Health-Risk Mitigation Technologies

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Abstract. Past space missions beyond the confines of the Earth's protective magnetic field have been of short duration and protection from the effects of solar particle events was of primary concern. The extension of operational infrastructure beyond low Earth orbit to enable routine access to more interesting regions of space will require protection from the hazards of the accumulated exposures of Galactic Cosmic Rays (GCR). There are significant challenges in providing protection from the long duration exposure to GCR: the human risks to the exposures are highly uncertain and safety requirements places unreasonable demands in supplying sufficient shielding materials in the design. A vigorous approach to future radiation health-risk mitigation requires a triage of techniques (using biological and technical factors) and reduction of the uncertainty in radiation risk models. The present paper discusses the triage of factors for risk mitigation with associated materials issues and engineering design methods.

Preliminary Status on the Development of a Catalog Addressing Approaches for Forming Large Space Systems

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Abstract. Many future space missions require systems too large to be deployed from a single launch vehicle. These missions range from manned vehicles for astronaut transport to Mars to great observatories that are capable of imaging distance planets. Because these systems are too large for a single launch vehicle, they will require some form of on-orbit integration or assembly to satisfy their mission. To enable efficient system level analyses to be conducted of such missions an in-depth study and cataloging effort has been initiated of the vast literature on large space structures.

This presentation will begin with a discussion of the methodology used for cataloging the findings on techniques applicable to constructing large systems on-orbit. Attention was focused on systems capable of producing entire large space systems or significant components of large space systems. For example the search captured techniques that enable a space telescope to be formed in a modular fashion by deploying a large solar shield and primary aperture that is then integrated with the science instrument on-orbit. To limit the scope of the literature search, spatially large systems formed using tethers or formation-flying spacecraft were not included.

The presentation will describe organizations identified to date that have, or are actively pursuing, techniques to form large systems on-orbit and their area of expertise. During the literature search several past surveys in the area of large space system were identified and these will be summarized. The presentation will also highlight important papers located to date addressing techniques for forming large space systems on-orbit. The effort described in this presentation is the first step toward creating a handbook focusing on large space structures.

It is hoped that this presentation will inspire others to volunteer information for future updates and the authors encourage contact to discuss database expansion or future handbook and cataloging efforts.

Evolutionary Space Communications Architectures for Human/Robotic Exploration and Science Missions

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Abstract. NASA enterprises have growing needs for an advanced, integrated, communications infrastructure that will provide services for multiple human, robotic and scientific missions beyond 2015. Furthermore, the reliable, multipoint infrastructure is required to provide continuous, maximum coverage of areas of concentrated activities, such as in the vicinity of the Moon or Mars, with access made available on demand of the human or robotic user. As a first step, the definitions of NASA's future space communications and networking architectures are underway. Architectures that describe the communications and networking needed between the nodal regions consisting of Earth, Moon, Lagrange points, Mars, and the places of interest within the inner and outer solar system have been laid out. These architectures will need the modular flexibility that must be included in the communication and networking technologies to enable the infrastructure to grow in capability with time and to transform from supporting robotic missions in the solar system to supporting human ventures to Mars, Jupiter, Jupiter's moons, and beyond. The protocol-based networking capability seamlessly connects the backbone, access, inter-spacecraft and proximity network elements of the architectures employed in the infrastructure. In this paper, we will present the summary of NASA's needs and capability requirements, the architecture definitions and tradeoffs, and the technology gap assessments. To reduce cost, the technologies for implementing the capabilities required of the inter-nodal links include modularization, very high degrees of integration, microwave frequencies above 20 GHz, advanced antennas, optical communication links, routing and circuit switching, and protocols that support inter-networking in space and that are compatible with Earth networks.

1,000 W/kg Solar Concentrator Arrays for Far-Term Space Missions

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Abstract. The state of the art for currently flying space solar photovoltaic arrays is represented by the following key metrics:

- Areal Power: < 300 W/sq.m.
- Specific Power: < 60 W/kg
- Operating Voltage: < 200 V

To enable the most ambitious and challenging space missions 10-20 years in the future, each of these performance metrics must be improved dramatically. Only one future solar array technology has the potential to ***simultaneously*** extend ***all*** of these performance metrics: ultra-light refractive concentrator array technology. Under NASA funding, our team has recently developed a near-term ultra-light concentrator array with the following excellent metrics:

- Areal Power: > 300 W/sq.m.
- Specific Power: > 180 W/kg
- Operating Voltage: > 500 V

More recently, under NASA and NSF funding, our team has been investigating longer term versions of the same basic technology, and has identified a path to the following revolutionary metrics:

- Areal Power: > 600 W/sq.m.
- Specific Power: > 1,000 W/kg
- Operating Voltage: > 1,000 V

In addition to these breakthrough performance metrics, the cost ($/W) of the far-term ultra-light concentrator will be much lower than for competing approaches, the stowed power at launch will be unprecedented at more than 100 kW/cu.m., and the array capacity will be extended from the current limit of about 30 kW to 100 kW and, eventually, to multi-MW systems. The paper will describe the ultra-light concentrator technology, including the developmental road map to achieve the mission-enabling far-term performance metrics summarized above.

Mobil Lunar Base Concepts

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Abstract. Abstract. This paper describes an innovative concept for the "Habot" mobile lunar base that uses robotic walking systems for landing and mobility. The concept combines design research for habitat architecture, mobility systems, habitability, radiation protection, human factors, and living and working environments on the lunar surface.

The mobile lunar base presents several key advantages over conventional static base notions. These advantages concern landing zone safety, the requirement to move modules over the lunar surface, and the ability to stage mobile reconnaissance with effective systemic redundancy. All of these concerns lead to the consideration of a mobile walking habitat module and base design. The key issues involve landing zone safety, the ability to transport habitat modules across the surface, and providing reliability and redundancy to exploration traverses in pressurized vehicles.

With self-ambulating lunar base modules, it will be feasible to have each module separate itself from its retro-rocket thruster unit, and walk five to ten km away from the LZ to a pre-selected site. These walking modules can operate in an autonomous or teleoperated mode to navigate the lunar surface. At the site of the base, the walking modules can combine together, make pressure port connections among themselves, to create a multi-module pressurized lunar base..

Future Concepts for Modular, Intelligent Power Systems

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Abstract. As larger, more complex spacecraft continue to appear on NASA's long-term roadmaps, the challenges in providing efficient, robust, and low cost electrical power become more difficult. The NASA Glenn Research Center is committed to developing the technologies that will meet those challenges through two means – develop advanced electrical components for high power, high temperature power electronics; and develop modular, intelligent power systems. This presentation will describe the technology roadmap being pursued to develop intelligent power systems, the progress made to date, and plans for further development in the near future.

NASA's vision for future electrical power systems centers around four key goals – 1) enable higher levels of system autonomy, 2) reduce costs to design and build electrical power systems, 3) enable simple integration with the spacecraft structure and loads, and 4) improve power system "robustness" and its ability to handle multiple failures without loss of mission. These four goals will be presented in detail, including status on the supporting technologies developed to date.

Finally, the inclusion of intelligence and communications into PMAD components allows the possibility of radical new distribution topologies that can provide high levels of fault protection for critical missions. One such topology concept is that of the multi-ring bus topology. This modular system concept allows for de-centralized load protection, high levels of fault tolerance for critical loads, and a highly flexible topology that can be reconfigured to mitigate faults. This topology concept will be presented and the technologies being developed to accommodate this new distribution system will be discussed.

Nuclear Power for a Mars Polar Robotic Base

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Abstract. A second-generation study was conducted by Aerospace for a Mars Robotic Polar base, to define a notional robotic outpost and begin to identify major challenges and issues. The scope of the notional Mars base and the type of sensors, instruments and scope of science activities led to an estimate of about 3 kWe central power requirement, to be provided by a suitable solar array. This follow-on assessment is intended to address the trade of a baseline central solar power station vs optional nuclear power sources. The Polar Base Study findings are recapped, and emphasis is placed on planning ahead looking to future human presence on Mars (HEDS). The issues pertaining to the solar power central station are reexamined. Additional insight helps to more specifically define some of the solar array characteristics, for example, vertical orientation arrays at the polar region, with single axis tracking, preference for high efficiency crystalline solar cells, light weight flexible substrates - requiring deployable stretch frames, a need for specific cell cleaning or mitigating methods, and RHU for thermal control network, to help get a more precise estimate of the solar power system baseline (although the array is still schematic).

This backdrop provides a baseline rationale for the nuclear power options. Available and emerging radio-isotope heating and power systems are reviewed briefly and their application limits rationalized, leading to the necessary consideration of the nuclear reactor power sources for the 3kwe Mars Base central power. The types of space nuclear reactors are reviewed and a convenient selection is made to use HOMER, Heatpipe Operated Mars Exploration Reactor, as the design reference nuclear reactor power source, at this stage of review. It is also apparent that mass trends with power will be affected by the operating power level, but not very much by the type of reactor power conversion scheme. Reactor power levels and masses are assessed for current payload delivery capability to the Mars surface. Finally, these study findings will be surveyed to define appropriate high priority research and development, to plant the milestones on the road to Mars.

Telerobotic Servicing Option for Hubble Space Telescope SM5

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Abstract. With planning for HST End-of-Life activities well under way and SM5 (sixth servicing mission) once again under active consideration this paper proposes the base lining of the SM5 tasks for telerobotic accomplishment in connection with the Shuttle Orbiter, with risk mitigation in the form of 100% on-scene EVA (human) backup. The technological capabilities for such telerobotic servicing have long existed, and are in current use in the radioactive materials handling, deep submergence operations, and microsurgical fields. SM5 presents an unique opportunity to advance the TRL (Technology Readiness Level) of such technology in space, laying the "past experience" foundation required to consider satellite servicing in geostationary orbit and/or contingency servicing of the James Webb Space Telescope in its operational site a million miles from Earth.

Microwave Resonant Transfer Plasma Propulsion

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Abstract. During the past decade, several research groups have begun to report unique spectroscopic results for mixed gas plasma systems in which one of the species present is hydrogen gas. In these experiments, researchers have reported excessive line broadening of H emission lines and peculiar non-Boltzmann population of excited hydrogen states. The hydrogen line broadening in these studies has been attributed to Doppler broadening associated with anomalously high random translational velocity of H atoms (i.e. fast hydrogen). The spectroscopic data suggest the presence of a newly identified regime of energetic mixed gas hydrogen plasma systems, called resonant transfer (RT) plasmas. The data also suggest that these RT plasma systems have unique characteristics that warrant further exploration for propulsion applications. Preliminary calculations suggest that a microwave RT plasma thruster could achieve performance several orders of magnitude greater than chemical rocket propulsion. Accordingly, the NASA Institute for Advanced Concepts (NIAC) has funded a study aimed at assessing the potential of RT plasmas for propulsion applications. This paper will discuss the results of the NIAC Phase I study including spectroscopic characterization of the RT plasma, development of RT plasma thruster hardware and preliminary test firing of two separate RT plasma thrusters.

Mars Exploration with Directed Aerial Robot Explorers

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Abstract. Under funding from the NASA Institute for Advanced Concepts (NIAC), Global Aerospace Corporation is developing a revolutionary system architecture for exploration of planetary atmospheres and surfaces from atmospheric altitudes. A key element of this innovative system architecture is the Directed Aerial Robot Explorer (DARE) platfrom, which essentially is a long-duration autonomous balloon with flight path control capability that can deploy swarms of miniature probes over multiple target areas. Trajectory control is enabled by a lightweight aerodynamic surface (a wing) suspended vertically on a long (several km) tether below a balloon that uses the relative wind between the two altitudes to generate lift. This lifting force can nudge a balloon relative to its trajectory in the ambient winds at float altitude. Balloon guidance capability offers unprecedented opportunities to obtain high-resolution targeted observations of both atmospheric and surface phenomena. Multifunctional micro probes, deployed from the balloons once over the target areas, can perform a multitude of scientific functions, such as atmospheric profiling or surface exploration, and then relay their data back to the balloon or to an orbiter. The DARE architecture enables low-cost, low-energy, long-term global exploration of planetary atmospheres and surfaces. A conceptual analysis of DARE capabilities and science applications for Mars is presented. Initial results of simulations indicate that a relatively small trajectory control wing can significantly change planetary balloon flight paths, especially during summer seasons in Polar Regions. This opens up new possibilities for high-resolution observations of crustal magnetic anomalies, polar layered terrain, polar clouds, dust storms at the edges of the Polar caps and of seasonal variability of volatiles in the atmosphere.

Market Driven Space Exploration

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Abstract. Market driven space exploration will have the opportunity to develop to new levels with the coming of space nuclear propulsion and power. NASA's recently established Prometheus program is expected to receive several billion dollars over the next five years for developing nuclear propulsion and power systems for future spacecraft. Not only is nuclear propulsion and power essential for long distance Jupiter type missions, but it also is important for providing greater access to planets and bodies nearer to the Earth. NASA has been working with industrial partners since 1987 through its Research Partner Centers (RPCs) to utilize the attributes of space for market driven research in Low Earth Orbit (LEO). Plans are now being made to utilize the RPCs and industrial partners in extending the duration and boundaries of space flight to create new market driven opportunities for exploration and discovery. The trend is for more industrial involvement in space. Private investment is now considering setting up shops in LEO for commercial purposes. Nuclear propulsion and power will hasten the opportunities for private investment in exploration beyond LEO. There are factors that will influence the degree of market driven space exploration. One is the relative emphasis to be placed on human exploration. Another is the capacity of the Prometheus spacecraft to handle market driven payloads. Still another is the ability of the RPCs and commercial ventures to convince the Prometheus and solar system exploration projects to consider market driven space exploration. The objective of this paper is to show the progression of market driven space research and its potential for supporting space exploration given nuclear power and propulsion capabilities.

High Temperature Interaction Between H_2o and Hydrothermal Reduced Ilmenite

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Abstract. Among a large number of chemical and physical processes that have been proposed for the oxygen production from lunar materials in the last years the hydrothermal reduction of ilmenite occupies a prominent place. The research work carried out in our laboratory during the past years has been dealing also with the study of the mechanism and kinetics of the ilmenite reduction involving different reducing agents such as CH_4 and NH_3. They all show different mechanisms, even though the final structure of the reduced sample exhibits a similar vein-like morphology. It appeared of interest to study the reverse process of oxidation with H_2O foreseeing the possibility to produce a catalyst to be utilized in controlled ecological life support systems (CELSS). The present work reports the experimental results obtained at temperature of 1070 and 1223 K utilizing a Ugine-Setaram Thermobalance coupled with a mass-spectrometer. The experimental data show that the process of oxidation of reduced ilmenite with water is feasible at high temperature giving rise to the formation of FeO and Fe_2O_3 at different stages of oxidation. The process occurs according to the reactions:

$Fe(s), TiO_2(s)$ (reduced ilmenite)$+H_2O(g)=FeO(s)+TiO_2(s)+H_2(g)$

$2\ FeO(s), 2\ TiO_2(s)+H_2O(g)=Fe_2O_3(s)+2\ TiO_2(s)+H_2(g)$

The oxidative process has been investigated as a function of water partial pressure in an argon carrier and as a function of the granulometry of the powder. An analysis of the residue before and after the oxidation process shows some peculiarities in the morphology of the condensed phase that will be discussed in the paper.

GEMS: A Revolutionary Concept for Planetary and Space Exploration

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Abstract. A novel observing system known as Global Environmental MEMS Sensors (GEMS) offers the potential to significantly improve the ability to take in situ measurements for a variety of space missions. The GEMS concept features devices with completely integrated sensing, power, and communications with characteristic dimensions of just millimeters. Thousands of these low-cost devices could potentially be deployed together from a spacecraft to enable distributed sensing in planetary and other space environments. The deployment of such probes is analyzed and discussed for various scenarios on Mars that would provide measurements with unprecedented spatial and temporal resolution. The extended coverage provided by the arrays would improve the ability to calibrate remote sensing data while also extending the areas traditionally measured by localized landers. The unique features of such a system could significantly improve the capabilities for planetary and space exploration in the near and far term.

Radio Waves for Space Based Construction

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Abstract. This paper follows up on work presented at STAIF2003, on the use of potential fields in automatic construction of massive objects of desired shape in Space. In STAIF03, we showed the commonality between the theories for acoustic and optical positioning/shaping methods. Using this theoretical framework, we developed a simple engineering estimation scheme to predict the acceleration per unit intensity. The radiation pressure is achieved by interaction of electromagnetic waves and particles of a given dielectric material and size. The theory was limited to the Rayleigh domain, where particle size is less than 5% of the wavelength, and isotropic scattering could be assumed. With this theoretical framework in hand, we now consider how radio waves could be utilized in a Space-based construction project.

In the test case project, the question of how to construct a safe radiation shelter for humans, in the Near-Earth Object (NEO) region is considered. NEO material, pulverized to 10cm diameter particles, is formed into desired shapes using the radiation pressure exerted by coherent radio beams on scattering dielectric objects. The forcefield is produced by solar-powered transmitter/antenna carrying spacecraft, which position themselves to set up a resonant field of the desired mode. Cylindrical shells are formed as the particles drift into position, with an average acceleration of the order of a millionth of an Earth G. Once in position, the particles are fused by solar-powered energy beams through a sintering process. Results show that 50m diameter, 50m-tall cylinders can be formed in the course of 12 to 13 hours per cylinder.

The paper also begins the consideration of tradeoffs between solar collector area, number of resonators, and capacitive storage-discharge of energy in the fabrication process. This work was sponsored under a NIAC Phase 1 Grant. The technical monitor is Dr. Robert Cassanova.

Unit Costs for Lunar-Derived Propellants

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Abstract. The estimated propellant production cost per metric ton will be derived and presented for solar system transportation waypoints. Background on recent and ongoing space resource propellant supply models will be presented, with a review of architectural assumptions, costs and expected markets. Integrated economic and engineering models (see Duke, et.al., 2002, Lamassoure, et.al., 2003, and Blair, et.al., 2002) estimate production costs, expected productivity of the mining and processing system, reusable transportation element behavior, fuel depot activity and revenues based on projected market conditions. Results of these economic models are used to derive total and marginal unit costs for propellant at fuel depot facilities for the purpose of facilitating the commercial development of space and to aid program and logistic planning for human space exploration missions.

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Technical Feasibility of Lunar Base Mission Scenarios

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Abstract. Throughout decades of space activities lunar exploration and development has been the subject of a number of advocates. These advocates encompass those in government, military, national or international space agencies, and space advocacy groups. Advocates of lunar exploration and base establishment have put forward a number of rationales. The rationales include science, resource exploitation, the study of our universe, the search for a greater understanding of the origins of life, militaristic reasons, settlement, and continued manned and robotic space exploration.

On the basis of these rationales, scenario types proposed for establishing a lunar base are identified and investigated in this paper. Scenario types encompass lunar science, In-Situ Resource Utilization (ISRU), power generation base for use on Earth or in space, military base, developmental test-bed for advancing technologies for future space exploration, lunar base used as a way-point, transfer station to other planetary bodies, and lunar settlement or colony. The future realization of these types is assessed on the basis of how technical variables influence the particular scenario under consideration.

Realization of the scenarios is assessed according to the feasibility of enabling technology variables, which include transportation, life support, structures, and power systems. To this end, a feasibility index is developed and discussed in the paper. This index takes into consideration the state of development regarding the critical enabling technologies and the level of influence of each variable as it pertains to each scenario type. Influence is a function of the criticality factor for each technical variable. Criticality is defined as the level of influence of each variable on the particular scenario in terms of how that variable (i.e., enabling technology) either enables or constrains the scenario outcome. The feasibility index identifies variable criticality involved in each scenario type and ascertains how those variables differentiate in levels of influence depending upon the projected lunar base development.

A Site Selection Technique for Martian Habitats

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Abstract. Beginning with a map of the entire planet of Mars and graphically accumulating areas of interest informed by astrobiology, geology and other mission parameters, this author developed a series of possible habitat sites to support a traverse mission through Utopia Planitia, Isidis, and Elysium Planitia using Ian L. McHarg's (1969) sieve mapping method.

Shell Worlds: An Approach to Making Large Moons and Small Planets Habitable

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Abstract. The main problem with terraforming worlds is finding planets with workable initial parameters: large enough, temperate enough, wet enough, the day/night cycle not too long or too short, having a magnetic field, etc. We propose a novel method of creating habitable worlds for humanity by enclosing airless and sterile planets, moons, and even large asteroids within engineered shells supported by breathable atmospheres. Beneath the shell an earthlike environment could be formed similar in almost all respects to that of Earth except for gravity, regardless of the distance to the sun or other star. These would be natural worlds, not merely large habitats, stable across historic timescales at least, each comprising a full self-sustaining ecology, which might evolve in interesting and distinct directions over time. It is proposed that advanced civilizations would come to prefer created shell worlds to "natural" planets due to the stability of a world without an active core and design possibilities for living spaces. This approach requires no fundamental breakthroughs in science or physics but does require progress in energy production, space transportation, and environmental and materials sciences.

Extraterrestrial Subsurface Technology Test Bed: Human Use and Scientific Value of Martian Caves

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Abstract. Caves and subsurface voids on Mars and other bodies can provide significant advantages when used for human habitat and operational space. They are also targets for significant scientific investigations. We have developed a suite of technology concepts to make utilization of extraterrestrial caves feasible. Our goal is to provide a solid foundation of information and options so that mission planners may realistically consider the subsurface option in development of mission scenarios.

We have concentrated on identifying the primary challenges of functioning in the extraterrestrial cave environment. Employing concepts like inflatable cave liner habitats, foamed-in-place airlock technologies, and microrobotic self-deploying communication, mapping, and data transmission networks, we are developing solutions to meet those challenges and demonstrate the feasibility of cave use on Mars.

We present the results of field trials of an incave mission simulation in several Earth caves as a proof-of-concept demonstration. These trials during the summer and fall of 2003, culminate in a high fidelity simulation scheduled for January 2004. Concepts and prototypes were developed during a completed Phase I and on-going Phase II NASA Institute for Advanced Concepts (NIAC) study.

A Continuous Method for Mining Regolith on the Moon or Mars

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Abstract. Future space missions to planetary bodies, both manned and robotic, will require the efficient utilization of in-situ resources to ensure longevity and success. In Situ Resources Utilization (ISRU) and In Situ Support Equipment (ISSE), while requiring the development of new technologies and methods for commodity extraction, will still rely upon some method of mining technology for the harvesting and transformation of the raw materials prior to processing.

The Northern Centre for Advanced Technologies Inc. (NORCAT), in partnership with Electric Vehicle Controllers Ltd. (EVC), is presently engaged in the development and adaptation of existing mining technologies and methodologies for use extra-terrestrially as precursor and enabling technologies for ISRU and for use as ISSE in support of longer term missions. More specifically, NORCAT and EVC are developing a concept for mining regolith from the lunar or Martian landscape. The Canadian team, consisting of NORCAT, EVC, UTIAS, and XTI, in cooperation with the University of Missouri-Rolla and the Colorado School of Mines is developing hardware for a regolith harvesting system. Although the technologies under development may be considered generic to any planetary surface, this group's focus is the development of a fuel depot system using regolith harvested from the lunar south pole.

This presentation will focus upon the mining equipment development and will update the audience on concepts and progress.

Electric Power Development on the Moon from In-Situ Lunar Resources

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Abstract. The long-term exploration and colonization of the solar system for scientific research and commercial interests depends critically on the availability of electrical energy. In addition, the long-term potential for humans to settle space requires self-sufficiency, and therefore, self-sustaining electrical power systems. This can be attained on the Moon by utilizing the indigenous resources present there through the fabrication of solar cells using thin film growth technology and the vacuum environment of the Moon. Thin film solar cells will be fabricated directly on the surface of the Moon through the transportation of only the tools needed to fabricate the cells and not the transportation of the vast arrays of cells themselves. The deployment of a ~200kg crawler on the surface of the Moon with the capabilities of preparation of the lunar regolith for use as a substrate, evaporation of the appropriate semiconductor material for the solar cell structure, and deposition of metallic contacts and interconnects, will allow for the emplacement of a lunar electric power system that can reach 1 MW in several years of crawler operation. Initial growth of the thin film solar cell will proceed with raw materials brought from Earth. These first cells can be made of more easily fabricatable CdS/CdSe (as compared to silicon). With an initial installation of ~100 kW capacity (6 months of operation) a regolith processing facility can then be emplaced on the Moon which will extract the needed raw materials from lunar regolith so as to feed the solar cell crawler for the fabrication of silicon solar cells by using the electrical power generated by the initial cell fabrication. This unique approach for the emplacement of an electric power system on the Moon would require the transportation of a much smaller mass of equipment to the Moon than would otherwise be required to install a power system brought to the Moon, and would result in a power system that was repairable/replaceable through the simple fabrication of more solar cells.

Designing for Human Space Exploration

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Abstract. A generalized concept design model is presented for human spaceflight systems. Mass, power, volume, and cost is discussed as key design parameters. This model can be based on historical systems if desired. The design philosophy of past systems can be used to formulate likely system characteristics. Alternatively, designs using advanced technologies can be incorporated to hypothesize future system characteristics and assess impacts.

The inputs to the model consist of: crew number, mission duration, and payload size, power, and mass. Payload refers to any space hardware that is not related to the crew, crew systems, or supporting bus hardware. This creates sizing information for the space system expressed in size, power, and mass. Cost information is then generated using the facility mass as the primary input parameter.

Examples to be discussed include space hotels, multi-use space business parks, space stations, interplanetary transfer vehicles, and planetary surface habitats as well as others. Space hotels can be evaluated using crew as the primary input parameter and minimizing accompanying payloads. By changing the basic design philosophy, a hotel can vary from having Spartan quarters to luxurious and spacious rooms. Various designs can then be compared to determine relative size and cost. This information can be quite useful when determining how much to charge customers for their transport and stay on orbit.

Other useful information is presented that has been derived from this model. The Apollo program is compared to the NASA Mars Design Reference mission (circa 1998). Interplanetary space system designs are examined to show differences and commonality for future crewed missions to the inner and outer planets.

Developing the Cosmos Through Innovative Government – Private Partnerships

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Abstract. This paper examines novel approaches to utilizing advanced technologies in the development of the space frontier. One of the prime factors holding back the robust development of space is insufficient investment in the technologies necessary to make it a reality. The key to success in bringing needed space development technologies to maturation lies in bringing technology investors together from government industry and academia. An aggressive road map for developing space will require a diverse set of technologies. In most cases, components or whole systems, are of intense interest to industry or other government agencies. By having each investor contributing to the part of the technology development of interest to them, development of space systems can be put together at a cost far below what would be required to develop for a stand-alone effort. The NASA Space Partnership Division has been employing this technique to leverage a $30M NASA investment into a nearly $100M advanced technology development effort focused on developing the space frontier.

Benzene Production on Mars

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Abstract. The Methane to Aromatics on Mars (METAMARS) system is an *in situ* resource utilization (ISRU) technique that converts methane produced from the carbon dioxide in the Martian atmosphere to low hydrogen content liquid aromatic fuels for an Earth Return Vehicle, thus greatly increasing the leverage of the hydrogen imported from the Earth. More importantly, the METAMARS system reduces the amount of hydrogen imported from Earth by a factor of four, leading to dramatic reductions in mission cost. This project involves design and construction of two fully functional oxygen/aromatic hydrocarbon production facilities (brassboard and protoflight) sized to produce 1 kg of bipropellant per day. Because aromatic fuels contain only about one hydrogen atom per carbon atom, the METAMARS system gives extremely high leverages on the order of 53 in the production of fuel and oxidizer for a Mars Sample Return (MSR) mission and human Mars missions. In addition, there are extensive potential commercial applications for the technology in converting trillions of cubic feet of stranded natural gas into easily transportable liquid aromatic products. Pioneer Astronautics has demonstrated multigram benzene production from carbon dioxide using an instrumented recycling brassboard system at rates comparable to those needed for a Mars Sample Return mission. This paper will discuss the design, construction and operation of the brassboard system.

Use of Gravity Simulator in the International Space Station for Mars Terraformation

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Abstract. The future international manned exploration of planet Mars will require some independency of food and oxygen supplies to the crews on Mars. Vegetables, growing inside secure vessels on the Martian ground, are the best candidates for supplying a quasi-continuous production of proteins, salt minerals, water and oxygen to the astronauts working in a semi-permanent possible future living facility at Mars' surface. But, for this achievement, it is fundamental a long-term (some years of) primary study of the strong influence of lower levels of visible light and high levels of ultraviolet, carbon dioxide atmosphere, very dry soil and lower gravity (as compared to Earth's one) field present on Mars on microbes' and vegetables' development. Mars terraformation is the name for a possible, secure, controlled (within a greenhouse) introduction of some very resistant species of bacteria, algae, and plants, and greenhouse gases on Mars for the beginning of a long, gradual change of the Martian environment (e.g., Martian soil and atmospheric temperature profiles close to the ground), increasing in some degrees the air and soil's temperatures for the transformation of sites with permafrost into liquid water and the release of oxygen molecules into the atmosphere All influent characteristics of Mars, except gravity, can be simulated on Earth's surface. In this paper I suggest the study of effects of simulated Mars' 0.38 g gravitational field on microbes, algae and plants, to determinate if they can develop normally at that field strength, by the use of variable centrifuges (in the ESA-built European Modular Cultivation System and Biolab, or other similar hardware) to be future aboard the International Space Station (ISS) Biological Research Facility, which is being developed. I also suggest a future construction of a greenhouse facility on Mars for a secure and controlled begin of its terraformation. The ISS can be of much valuable use for a solid planning of the future international manned Mars exploration for the firm possible future international terraformation of that planet, for Human use.

Requirements for Space Settlement Design

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Abstract. When large space settlements are finally built, inevitably the customers who pay for them will start the process by specifying requirements with a Request for Proposal (RFP). Although we are decades away from seeing the first of these documents, some of their contents can be anticipated now, and provide insight into the variety of elements that must be researched and developed before space settlements can happen. Space Settlement Design Competitions for High School students present design challenges in the form of RFPs, which predict basic requirements for space settlement attributes in the future, including structural features, infrastructure, living conveniences, computers, business areas, and safety. These requirements are generically summarized, and unique requirements are noted for specific space settlement locations and applications.

Is Extraction of Methane, Hydrogen and Oxygen from the Lunar Regolith Economically Feasible?

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Abstract. The extraction of oxygen from the lunar regolith is relatively straightforward and has been studied extensively. Extraction of hydrogen is also straightforward, but because the concentration of hydrogen is so low (~50 ppm), the economics is problematical. However, a process for extracting hydrogen may also extract carbon, which is typically present at the 100 ppm level. A small amount of available oxygen can be extracted in the same process, through the hydrogen or carbon reduction of iron oxide in the regolith. Thus, a combined process is possible in which methane and oxygen are the end products. Methane has advantages over hydrogen in terms of storage and liquefaction energy requirements. We show that the combined hydrogen and carbon content of a given quantity of lunar regolith, if converted to methane and used in a methane/oxygen engine, can lift more payload off of the Moon than a hydrogen/oxygen engine utilizing hydrogen and oxygen extracted from the same amount of regolith. We examine the conditions under which it might become economically feasible to utilize these minor constituents of the lunar regolith. It is concluded that improved excavator, extractor, and power technologies could make the extraction economically feasible. This would open practically any place on the Moon as a source of rocket propellant.

A Prototype Bucket Wheel Excavator for the Moon, Mars and Phobos

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Abstract. Excavation of surface regolith material is the first step in processes to extract volatile materials from planetary surface regolith for the production of propellant and life support consumables. Typically, concentrations of volatiles are low, so relatively large amounts of material must be excavated. A bucket wheel excavator is proposed, which has the capability of continuous excavation, which is readily adapted to granular regolith materials as found on the Moon, in drift deposits on Mars, and probably on the surface of asteroids and satellites, such as Phobos. The bucket wheel excavator is relatively simple, compared to machines such as front end loaders. It also has the advantage that excavation forces are principally horizontal rather than vertical, which minimizes the need for excavator mass and suits it to operations in reduced gravity fields. A prototype small bucket wheel excavator has been built at approximately the scale of the rovers that are carried to Mars on the Mars Exploration Rover Mission. The prototype allows the collection of data on forces exerted and power requirements for excavation and will provide data on which more efficient designs can be based. At excavation rates in the vicinity of one rover mass of material excavated per hour, tests of the prototype demonstrate that the power required is largely that needed to operate the excavator hardware and not related strongly to the amount of material excavated. This suggests that the excavation rate can be much larger for the same excavation system mass. Work on this prototype is continuing on the details of transfer of material from the bucket wheel to an internal conveyor mechanism, which testing demonstrated to be problematic in the current design.

The Space Elevator: Status Report As A Means For Building Space Settlements

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Abstract: A space elevator is a physical connection from the surface of the Earth to a geostationary Earth orbit (GEO). Its' center of mass is located at GEO such that it orbits the Earth in sync with the Earth's rotation. The vision for the space elevator is that it is perhaps the only concept known that could lower the cost of access to space below $10 per pound and increase the lift capacity to orbit far beyond conventional systems, making it possible to consider construction of large, massive, space settlements in GEO. This presentation will provide a brief background on the space elevator concept, provide an update on some of the research work that has been done by NASA and its affiliates on the space elevator concept, and conclude with an overview of planned activities in the near future that could help make construction of a space elevator possible.

Robotic Lunar Ecopoiesis Test Bed: Bringing the Experimental Method to Terraforming

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Abstract. The notion of ecologically terraforming another planet (aka *ecopoiesis*) has been discussed by a number of scholars. Some theoretical treatments of various aspects of ecopoiesis have appeared in the literature. However, experimental terraforming studies have been rare to non-existent. This is not surprising because of the planetary scale and long durations typically discussed. We describe a concept to perform basic ecopoietic experiments in a test facility constructed on the lunar surface. Such a facility can provide long-term observation of organisms and their ecological, physiological, and evolutionary interactions in a low gravity environment. Salient features of extraterrestrial environments (e.g. the 0.38g Mars gravity) can be simulated more easily in the lunar milieu than on Earth while providing much greater access for experimenters than ecopoiesis experiments on Mars. Besides application of these proposed studies to possible future terraforming efforts, basic evolutionary and ecological processes could be studied under extreme selection pressures including fractional gravity, high radiation, and with a variety of atmospheres, soils, and other parameters. Novel, genetically engineered and selectively bred organisms could be tested in such a facility without concern for accidental release into Earth's environment.

Space Tourism: Recent Progress and Future Prospects

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Abstract. The feasibility of space tourism depends centrally on the cost of traveling to and from space. Until recently this has remained extremely high, thereby preventing space tourism services from developing. It has been widely believed that this high cost is an inherent problem of space flight. However, recent events have demonstrated that the current high cost is not an unavoidable physical necessity, but is at least partly due to the influence of near-monopoly government space agencies. Despite having used $1 trillion to develop a range of technologies useful for space activities, these have made no effort to reduce the cost of travel to and from space, which remains the same as it was when Yuri Gagarin first flew to low Earth orbit in 1961.

Recent growth of private activities aimed at realising passenger space travel has created the prospect of achieving sub-orbital space flights at less than 1% of the cost of comparable flights performed by Nasa in 1961. Once sub-orbital tourism starts it seems likely to grow rapidly, and to lead on to the development of orbital passenger vehicles. Thereafter the prospects for further growth will be excellent due to the very large unsatisfied demand revealed by market research. In addition, the basic technology of accommodation facilities in orbit is already well-developed having more than 30 years of accumulated experience involving four different space station designs. Orbital accommodation is also technically much easier to build and operate than launch vehicles; this will facilitate expansive development, with ever-larger and more interesting facilities in orbit, followed rapidly by lunar tourism services.

The economic effects of the growth of space tourism will be very positive, both for the companies from a wide range of industries which will be involved, and also for world economy and society as a whole. Unemployment is currently at historically high levels world-wide, due specifically to insufficient development of new industries. By turning governments' cumulative investment of $1 trillion to commercially valuable use, space tourism offers a unique means of pulling both the space industry and the world economy out of deepening recession.

Public-Private Model for Lunar Settlement

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Abstract. Since the beginnings of the space age, mission concepts and plans directed at lunar base development have been proposed. With the exception of Apollo, which was driven by cold war geopolitics, these concepts and plans have remained either on the political agenda or as proposed ideas for the commercial sector. This paper examines why this has been the case; why has there not been political formulation and implementation of lunar base missions or implementation of commercial development of the Moon? This paper assesses the issues facing those in both the public and private sectors who view lunar development as a desirable goal and offers suggestions, based on public-private partnerships, as to how to make that goal a reality.

There are several issues that have entrapped lunar development ideas on both the political and business agendas. First, lunar development advocates focus on scientific and technological benefits of lunar development, while providing weak links to economic competitiveness and national security issues that are of interest to political decision-makers in order to support new, revolutionary large-scale programs. Arguments based on unspecified technological spin-offs are ineffective. Further political rationales for lunar base development are constrained due to the weak public support for space in general and to reduced budgets and downsizing in government support for research and development (R&D). Second, public policy evolves on an incremental basis. Thus, past policies and practices change slowly and usually in response to a particular crisis or focusing event that warrants public attention. Third, albeit lunar commerce enjoys a prestige status in the private sector, as numerous companies in various stages of development have plans to carry out commercially viable robotic ventures on the Moon, plausible business plans for lunar settlement, catering to scientific, mining, and tourism projects, remain elusive and in the more distant future. The business plans that have been proposed for lunar settlement lack realistic return on investment calculations to make the venture attractive to investors and the private capital markets. These plans fail to properly identify and quantify sustainable long-term markets for the proposed ventures. Fourth, further compounding the prospects for commercial sector interest in lunar development is an environment of uncertainty concerning policy and legal regimes.

Public-private partnerships are essential to deal with these issues and to enable prospects for lunar development. This implies the existence of political support and government funding as well as aspects in the lunar development that would attract investor interest and private capital. At issue, is how to fashion a synergistic relationship. To this end, a number of ideas are put forward and discussed. These ideas range from the establishment of stable government-sponsored markets whereby the public sector undertakes the risk for R&D and formulates policy and legal regimes that would facilitate public-private lunar development, lunar development on the basis of dual-use technologies that have applicability to both the public and commercial sectors, and business plans for private sector ventures directed at lunar development activities that entail realistic return on investments and similar benefits for the public sector.

Pioneer Rocketplane: A Space Tourism Vehicle

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Abstract. The Pioneer XP is a four-seat fighter-sized vehicle powered by two jet engines and two rocket engines, enabling it to reach altitudes of 350,000 feet. The XP will operate from ordinary airfields within the well-established rules and practices for experimental aircraft. The XP does not use any launch assist. It reaches about 2,000 ft/s at 350,000 feet altitude. Safety, existing aircraft rules, and the constraints of cost and schedule force the Pioneer Rocketplane team to select oxygen and kerosene as the main propellants, to use a simple and reliable propellant feed system, to employ safe, already certificated aircraft components, and to plan on an incremental flight test approach. Although we plan to fly the aircraft soon, affordably, and safely, Pioneer is also developing an aircraft that can be upgraded to higher performance in the future. The thermal protection system, the wing propellant tanks, and the other systems are designed with the possibility of eventual upgrade in mind from the beginning, so that the option for the long-range aircraft can be preserved without requiring expensive reinvestment after the XP flies. It is our intention not merely to reach 350,000 feet, but to do it with an aircraft that is traceable to not only a satellite launch system but also a long-range transport aircraft in follow-on versions.

Review of Claims of Interaction Between Gravitation and High-Temperature Superconductors

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Abstract. Recent reports have claimed that high-temperature superconductors can interact with gravitation under certain conditions such that the weight of test masses changes in non-relativistic experiments. One prominent report, unique in being peer-reviewed, is by Podkletnov and Nieminen (1992). This paper was followed by a report (not peer reviewed) of large-amplitude gravitational wave generation in a laboratory (Podkletnov and Modanese, 2003). Common to these reports is the claim that the observed gravitational field may be modified using YBa2Cu3O7– ä (YBCO) below its superconducting critical temperature, Tc ~ 93K and in a magnetic field B ~ 1T. Temperatures below 70K gave the largest effects. The first experiment used magnetically levitated YBCO rotated at ~ 5000 rpm; the second experiment did not spin or levitate the YBCO, but used a 2MV electrical discharge in a vacuum chamber. Several attempts have been made world-wide to replicate the first of these experiments, although no peer-reviewed reports have yet confirmed the observations. No known replications of the second experiment have been completed so far. A number of papers have presented theoretical models for the effects. This paper will review the current experimental and theoretical scientific evidence regarding these experiments, together with further tests implied by the published explanations. The discussion will include a classical suggestion (due to Landau and Lifshitz) that gravitational waves can modify gravitational fields, Aquino's theory based upon electromagnetic fields, and Desbrandes's calculation to explain the Podkletnov and Nieminen results on the basis of gravity waves emitted from the Cooper pairs inside a superconductor. The conclusions are that these experiments are extremely difficult to replicate and that no complete replication confirming the effects has yet taken place, but that equally no-one has conclusively disproved the existence of the effects.

Podkletnov E. and Nieminen R., "A possibility of gravitational force shielding by bulk YBa2Cu3O7–*x* superconductor," *Physica C*, **203,** 441-444 (1992).

Podkletnov E. and Modanese G., "Investigation of high voltage discharges in low pressure gases through large ceramic superconducting electrodes," *J. Low Temp. Phys.*, **132**, 239-259 (2003).

A Proposed Model for Capturing Gravitational Spin Anomalies

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Abstract. During the 2003 STAIF Conference, the author proposed a theory based upon gravitational anomalies, that would use a universal gravitation model with a radial force term coupled with angular momentum. This extended efforts from Murad and Baker, Dyatlov who explains angular momentum effects as consequences of a 'spin' field, and Jefimenko. Angular momentum may explain various spin asymmetries allowing the transfer of gravitational radiation directly into angular momentum observed in some anomalous gyroscope experiments; planets orbiting around the sun; moons orbiting larger planetary bodies; and planetary rotation direction. Moreover, a decrease in rotation of a rapidly spinning neutron star may be due to generating gravitational waves as the star loses energy and angular momentum in a tangential direction by changes within its gravitational field. Similarly a coalescing binary black hole "loses" up to 12% of its total angular momentum. A High-Frequency Gravitational Wave (HFGW) experiment using a mini-synchrotron could test this proposed theory. Results suggest Jefimenko's co-gravity field may represent the elusive 'spin' or 'torsion' field. If true, these new effects can have a revolutionary impact upon theoretical physics and Astronautics.

A Propellantless Propulsion Experiment Design and Testing Plan

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Abstract. A propellantless propulsion experiment design and testing plan are described. The concept was initially presented during the Space Technology and Applications International Forum of 2001 and the experiment was initially presented during the Joint Propulsion Conference of 2001. New information is provided on how the experiment relates to the Human Exploration of Development of Space, the results of peer reviews, a cost estimate performed by a major U.S. aerospace company, and an alternative magnet design to reduce the cost of the experiment and potentially improve the reliability of the system. Recent improvements in high power solid state switches and superconducting magnets may have made propellantless propulsion possible. Propulsion may occur during the non-steady state ramp-up of a very rapidly pulsed, high power magnet. Propulsion would not occur after the first 100 nanoseconds of each pulse, since the magnetic field will have reached steady state. The United States Department of Energy Office of High Energy Physics provided some of the funding for the developed a no maintenance superconducting magnet that can carry 2,000 amperes per square millimeter and a switch which can provide 100 nanosecond ramp-ups at a rate of 0.4 megahertz, and at 9,000 volts and 30 amperes.

The Superheavy Elements and Anti-Gravity

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Abstract. The essence of any propulsion concept is to overcome gravity. Anti-gravity is a natural means to achieve this. Thus, the technology to pursue anti-gravity, by using superheavy elements, may provide a new propulsion paradigm. The theory of superluminal relativity provides a hypothesis for existence of elements with atomic number up to Z = 145, some of which may possess anti-gravity properties. Analysis results show that curved space-time exists demonstrating both gravitic and anti-gravitic properties not only around nuclei but inside the nuclei as well. Two groups of elements ($Z < 64$ and $63 < Z < 145$) exist that demonstrate these capabilities. The nuclei of the first group of elements have the masses with only the property of gravity. The nuclei of the elements of the second group have the masses with both properties: gravity and anti-gravity in two different ranges of curved space-time around the nuclei. The hypothetical element with Z = 145 is the unique among all elements whose nucleus has only anti-gravity property. It is proposed that this element be named *Hawking*, in honour of Stephen W. Hawking.

A Vacuum Energy Experiment

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Abstract. A vacuum energy experiment is discussed, based on the dark energy research funded by the U.S. Department of Energy, Office of High Energy Physics. Ideally, the experiment may be able to detect whether the vacuum energy spectrum actually has a frequency-cubed distribution, if there are any resonances, and the spectrum cutoff. Such an experiment would explain why the observed vacuum energy density of 4 electron volts per cubic millimeter is 120 orders of magnitude less than the theoretical prediction (which assumes a frequency cubed distribution and a cutoff at the Planck mass of 22 micrograms). Resonances may occur at known particles (e.g., the proton). The experiment would be based on replicating the conditions of deep space (ultra-vacuum, isolation from the Earth's magnetic field, and cryogenic temperatures) and a customized, semiconductor detector. The potential extractable energy is estimated.

Design of a Quantum Source of High-Frequency Gravitational Waves (HFGW) and Test Methodology

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Abstract. The efficient generation of High-Frequency Gravitational Waves (HFGW) has been identified as the required breakthrough that will lead to new forms of space propulsion. The gravitational wave (GW) counterpart of the LASER, termed Gravitational-wave LASER or "GASER" is the quantum approach to high efficiency. Electrons, protons, muons, etc, all have charge and mass, if accelerated they usually loose energy through the very efficient electromagnetic (EM) channel. Cleverly engineered quantum systems may lockout the EM channel while keeping the gravitational channel open. A class of active materials for an electron GASER is identified along with their relevant physical properties. Means for creating coherence and population inversion are described and the expected performances of the device are derived. Additional properties of the active materials are considered to enforce the theoretical foundation of the device. A proof-of-concept device, operating at about 1 THz, is described. Experiments are proposed as a natural starting point of the research.

Mach Effect Mass Fluctuations and Stationary Forces in High Power Inductive-Capacitive Circuits

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Abstract. Mass fluctuations expected on the basis of the strong form of Mach's principle (the gravitational induction of mass) are briefly revisited together with their use to produce "propellantless" stationary thrusts in systems of high voltage capacitors that are "shuttled" by a means other than the applied high frequency electric field that produces the fluctuations. It is shown that the application of a suitable magnetic field orthogonal to the electric field in the capacitors should produce the thrusts sought – and already purportedly observed by Brito and others in systems of this sort (motivated by theoretical ideas that are wrong as they violate momentum conservation). Results of an experimental investigation of these systems in the context of Mach effect mass fluctuations are reported. Those experimental results suggest that a real thrust effect is indeed present. And theoretical considerations further suggest that these thrusts can be scaled to practical levels without serious difficulty.

Understanding Anomalies to Extract Vacuum Energy

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Abstract. An interesting project was revealed to the author during an association with several Russian scientists from Novosibirsk. These investigations examined and applied a theory to various anomalies to try and understand what these events may represent. Data were collected by Dmitriev to quantify these events and identify commonalties that indicate the anomalies might have a natural origin. Dyatlov created theories on the Polarized Inhomogeneous Physical Vacuum where he claimed that each anomaly possessed a distinct boundary separate from its surroundings. Within this inhomogeneous boundary, the theory suggests that the magnetic, electric, gravitic, and spin fields would be different from its surroundings. From these findings, he developed equations that resemble the London equations for a superconductor and are somewhat similar to those developed later by Puthoff. The importance of these events is that with additional understanding, they may offer a means for extracting energy from the physical vacuum. Moreover, one may speculate that these anomalies may represent a gravitational vortex or even a portal or a wormhole to look into potential travel within other dimensions.

Interstellar Propellantless Propulsion System Based On Machian Effects With Rotary Magnification

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Abstract. A propellantless propulsion system based on Machian Effects with Rotary Magnification (MERM) may provide a significantly easier and cheaper approach to interstellar flight than antimatter assisted inertial confinement fusion (AAICF) propulsion systems or laser sails. The purpose of this paper is to evaluate the potential of MERM propulsion for interstellar missions such as the Alpha Centauri Flyby.

Is Electromagnetic Gravity Control Possible?

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Abstract. We study the interplay of Einstein's Gravitation (GR) and Maxwell's Electromagnetism, where the distribution of energy-momentum is not presently known (The Feynman Lectures, Vol 2, Chapter 27, section 4). As Feynman himself stated, one might in principle use Einstein's equations of GR to find such a distribution. GR (born in 1915) presently uses the Levi-Civita connection, LCC (the LCC was born two years after GR as a new concept, and not just as the pre-existing Christoffel symbols that represent it). Around 1927, Einstein proposed for physics an alternative to the LCC that constitutes a far more sensible and powerful affine enrichment of metric Riemannian geometry. It is called teleparallelism (TP). Its Finslerian version (i.e. in the space-time-velocity arena) permits an unequivocal identification of the EM field as a geometric quantity. This in turn permits one to identify a completely geometric set of Einstein equations from curvature equations. From their right hand side, one may obtain the actual distribution of EM energy-momentum. It is consistent with Maxwell's equations, since these also are implied by the equations of structure of TP. We find that the so-far-unknown terms in this distribution amount to a total differential and do not, therefore, alter the value of the *total* EM energy-momentum. And yet these extra terms are at macroscopic distances enormously larger than the standard quadratic terms. This allows for the generation of measurable gravitational fields by EM fields. We thus answer affirmatively the question of the title.

An Experimental Program for Assessing High-Frequency Gravitational Wave (HFGW) Optical Applications and the Precursor HFGW Telescope

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Abstract. An experimental program related to High-Frequency Gravitational Wave (HFGW) optical applications is presented. The fact that gravitational waves are slowed in a superconductor and therefore refracted has been published in peer-reviewed scientific literature and has remained unchallenged for over a decade. The development of HFGW generators and detectors is a primary objective of multiple research efforts and its ultimate development is considered uncontroversial. The only speculation is when such laboratory HFGW generators will be available and operational. Thus it is appropriate to prepare test objectives to assess the optical applications of HFGW; especially to consider HFGW relic cosmic background, acknowledged by astrophysicists, which can be imaged by a HFGW telescope and sensed by recently developed and fabricated HFGW detectors. This experimental program concentrates on precursor or preliminary proof-of-concept, component-validation laboratory tests relating to the fabrication of a mosaic, high-temperature superconductor (HTSC) lens for a 100-meter diameter, f/0.5, precursor HFGW Telescope. This experimental device will involve lens grinding/polishing considerations, telescope fabrication, and insuring the overall structural integrity. A grasp or gain of 3x104 for the lens is computed to obtain sufficient concentration of the anisotropic, relic HFGW cosmic background flux for detection. Three HFGW detectors are described that have been fabricated. HFGW lenses hold great promise and can initially be utilized to observe the currently available HFGW cosmic background and then be utilized in HFGW generator/detector optical test benches. Test objectives for this latter application are also presented.

Precursor Proof-of-Concept Experiments for Various Categories of High-Frequency Gravitational Wave (HFGW) Generators

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Abstract. High-Frequency Gravitational Wave (HFGW) generators are separated into three general categories. Precursor, component-validation, laboratory experiments for each category except, possibly, the third are identified in general terms. The categories are: The electromechanical category includes micro- and nano-element,piezoelectric crystal, and multi-dielectric film HFGW generators.The high-temperature superconductor category includes gasers, impressed magnetic fields, and transformation of electromagnetic radiation into gravitational waves (Gertsenshtein effect) HFGW generators.The laser/plasma category includes laser-energized mirrors, synchrotron light, nuclear fusion, plasma toroid, and nonlinear optical-acoustical, molecular-level HFGW generators. A perusal of HFGW literature reveals that since the 1960s many authors have contributed designs of mechanisms and devices that relate to the terrestrial generation of gravitational waves. Only in the last few years, however, have any researchers demonstrated that their proposed devices were practical HFGW generators, capable of producing kilowatts of power, that were operational in a laboratory setting. These recent devices make use of new technology and generate high-frequency (GHz and above) gravitational waves using non-gravitational forces. Most of the generators considered in this paper have been recently discussed at the May, 2003, Gravitational Wave Conference at The MITRE Corporation, McLean, VA, which was the very first International Conference dedicated to HFGW and attracted twenty-five research papers from nine countries. Although no detailed experimental tasks are discussed, experimental test objectives in the form of a roadmap are proposed for each category.

Precursor Experiments Regarding the Generation of High-Frequency Gravitational Waves (HFGW) by Means of Using an Array of Micro- and Nano-Devices

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Abstract. The process by which High-Frequency Gravitational Waves (HFGW) are generated by means of the time rate of change of the acceleration of a mass or masses, termed a "jerk" or a "shake," has been developed and applications to space technology have been proposed. The quadrupole-approximation equation for the power, P, of the HFGW generated in watts is given by P = 1.76x10-52 (2rΔf/Δt)2 where r is the radius of gyration in meters of the system of masses undergoing a change in force Δf in Newtons divided by the time interval, Δt, of this force change in seconds, the jerk. In this paper a series of proof-of-concept, precursor experiments are identified. Three specific component-validation, laboratory experimental tasks are described: the first involves the generation of a series of microsecond, nanosecond, and picosecond current pulses utilizing off-the-shelf pulse generators and even shorter pulses utilizing state-of-the-art equipment. From the foregoing equation it is recognized that the power of the HFGW generation is inversely proportional to the square of the pulse length, Δt, so that short pulse length (and high frequency of a train of pulses) is most desirable. The second task is to utilize the aforementioned pulses to energize, jerk, or otherwise cause a third-time-derivative change in motion of a test mass, termed an energizable element. The third task involves the ability to measure the motion of the test mass at megahertz, gigahertz, terahertz and other higher vibrational or jerk frequencies. Specific off-the-shelf laboratory equipment and their cost are listed. The energizing elements will involve small coils, activated by current pulses and/or electromagnetic pulses, to energize a small magnet and laser pulses to energize a small mirror or energize other nano- or micro-devices. Once the mechanism for producing the jerk is validated in these tasks (by verifying that the energizing pulses or elements energize or jerk of the energizable element), then that mechanism can be replicated. Those replicated mechanisms can be utilized as micro- or nano-elements in devices that will be now capable of generating HFGW. In this regard, an attosecond-pulse-duration, 6 KW, HFGW generator is discussed.

A Review of Past Insights by Robert L. Forward, PhD: Emerging Technologies and Future Concepts

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Abstract. A review of various technologies discussed by Dr. Robert Forward is presented as a tribute to Dr. Forward, and is based on selections from his writings and those of subsequent investigators. Some emphasis is placed on the new frontiers of space propulsion, power and communication. Many of these concepts and technologies are presented within the STAIF 2004 "1st Symposium on New Frontiers and Future Concepts." These range from highly speculative notions to hardware that has now been demonstrated in space flight. Among these concepts and technologies to be discussed are future communications, antimatter propulsion, space elevators and tethers, beamed energy propulsion, and emerging gravity theories and concepts.

STAIF-2004 Abstract Book

Woodward Effect Experimental Verifications

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Abstract. The work of J. F. Woodward (Woodward 1982-to-2004) on the existence of "mass fluctuations" and their use in exotic propulsion schemes was examined for possible application in improving space flight propulsion and power generation. Woodward examined Einstein's General Relativity Theory (GRT) and assumed that if the strong Machian interpretation of GRT as well as gravitational / inertia like Wheeler-Feynman radiation reaction forces hold, then when an elementary particle is accelerated through a potential gradient, its rest mass should fluctuate around its mean value during its acceleration. Woodward also used GRT to clarify the precise experimental conditions necessary for observing and exploiting these mass fluctuations or "Woodward effect" (W-E). Later, in collaboration with his ex-graduate student T. Mahood, they also pushed the experimental verification boundaries of these proposals. If these purported mass fluctuations occur as Woodward claims, and his assumption that gravity and inertia are both byproducts of the same GRT based phenomenon per Mach's Principle is correct, then many innovative applications such as propellantless propulsion and gravitational exotic matter generators may be feasible. This paper examines the reality of mass fluctuations and the feasibility of using the W-E to design propellantless propulsion devices in the near to mid-term future. The latest experimental results, utilizing MHD-like force rectification systems, will also be presented.

A Novel View of Spacetime Permitting Faster-Than-Light Travel

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Abstract. Recent discoveries across many disciplines of physics have supported a driving need for a "new" science to explain the apparent relationship between phenomenon at cosmological scales and those at the quantum, subatomic level while still supporting the classical mechanics of motion, electromagnetism and relativity. A novel view of both the spacetime continuum and the universe is postulated that not only connects these fields of interest, but proposes a method to travel at superluminal speeds by examining the underlying equations of special relativity. The governing mathematics of special relativity describe a symmetrical continuum that supports not just one, but three, independent spacetimes each with a unique set of physical laws founded on the speed of light, c. These spacetimes are the subluminal (where $v/c < 1$), the luminal (where $v/c = 1$), and the superluminal (where $v/c > 1$) comprising a 'tri-space' universe. Relativistic symmetry illustrates that there can be up to three velocities (one for each spacetime) for a given absolute energy state. The similar characteristics of mass and energy in each spacetime may permit faster-than-light (FTL) travel through a quantum transformation/exchange of energy and mass (at the quark level or beyond) between the subluminal and superluminal realms. Based on the suggested characteristics of superluminal spacetime, the 'trans-space' method of FTL travel would allow a particle to traverse sublight space by traveling through the superlight continuum without incurring the penalties of special relativity or causal relations. In addition, the spacetime construct and superluminal realm of the 'tri-space' universe may offer a different perspective than the current ideologies that could better represent physical phenomena including universal expansion, the zero-point field, dark matter, and the source of inertia.

Relativistically Consistent Faster-than-Light (FTL) Communication Using Self-Referential Quantum States

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Abstract. A protocol using cross-entangled independent Einstein-Podolsky-Rosen (EPR) beams is developed as a means of sending information faster than light (FTL) by taking advantage of quantum nonlocality and indistinguishable particle statistics. Two observers bracket a central midpoint transmitter that contains dual EPR sources from which bits are encoded in packets of photon pairs. FTL communication occurs between the observers in a simplex mode. A reformulation of quantum mechanics is proposed that permits such communications, as well as wave function collapse, to be relativistically consistent, while also resolving the problem of causal ordering normally associated with spacelike connections. The issue of temporal paradox is handled separately at both the quantum and classical levels. Spacelike causal connections lead to closed loops in spacetime and causal self-reference. It is shown that such self-reference leads to nonlinearities in the evolution of the wave function that may be sufficient to lead to wave function collapse.

Paradox-Free FTL Travel in Higher Dimensional Spaces

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Abstract. This paper describes one possibility for rapid round-trip, paradox-free Faster-than-Light (FTL) travel between Earth and distant stars within the human lifetimes of those on-board the ships and Earth. It shows that such rapid transits would require dimensions beyond the 4 dimensions of flat or curved spacetime; with the added dimensions needed to give starships (their worldlines) room to "climb" and "descend" above the spacetime realms of Special Relativity (SR)—realms where nothing travels faster than the speed-of-light (c). The added dimensions would be associated with zero-point field gradients formed within the quantum vacuum by actions of specially conditioned em radiation emitted from accelerating ships. These gradients would result in: STL (slower-than-light) vehicle velocity within the perturbed vacuum surrounding the ship; FTL vehicle velocity with respect to the unperturbed vacuum and Earth; and invisible FTL vehicle travel in all observer-frames that move STL with respect to Earth. For one case of FTL travel, rapid transits to distant stars would result in starship disappearance from human sight after light speed is reached—followed soon thereafter by its reappearance trillions of miles away, in close proximity to its target star. And during the short interval of disappearance, the starship's worldline would "jump"over trillions of miles of distance—arching like a suddenly-formed rainbow within a "spacetimetau" realm of existence rises above the terrain of curved or flat spacetime. This paper concludes with possibilities for FTL thrust and lift by "polarizing" quantum vacuum or "warping" spacetime metric, and the resulting "hyperspace" navigation problems—which could compare in severity with those of FTL propulsion and control.

Quantum Tic-Tac-Toe as Metaphor for Quantum Physics

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Abstract. Quantum Tic-Tac-Toe is presented as an abstract quantum system derived from the rules of Classical Tic-Tac-Toe. Abstract quantum systems can be constructed from classical systems by the addition of three types of rules; rules of Superposition, rules of Entanglement, and rules of Collapse. This is formally done for Quantum Tic-Tac-Toe. As a part of this construction it is shown that abstract quantum systems can be viewed as an ensemble of classical systems. That is, the state of a quantum game implies a set of simultaneous classical games. The number and evolution of the ensemble of classical games is driven by the superposition, entanglement, and collapse rules. Various aspects and play situations provide excellent metaphors for standard features of quantum mechanics. Several of the more significant metaphors are discussed, including a measurement mechanism, the correspondence principle, Everett's Many Worlds Hypothesis, an ascertainity principle, and spooky action at a distance. Abstract quantum systems also show the consistency of backwards-in-time causality, and the influence on the present of both pasts and futures that never happened. The strongest logical argument against faster-than-light (FTL) phenomena is that since FTL implies backwards-in-time causality, temporal paradox is an unavoidable consequence of FTL; hence FTL is impossible. Since abstract quantum systems support backwards-in-time causality but avoid temporal paradox through pruning of the classical ensemble, it may be that quantum based FTL schemes are possible allowing backwards-in-time causality, but prohibiting temporal paradox.

Effect of the Vacuum Energy Density on Graviton Propagation

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Abstract. It has been known for some time that the value Λ of the vacuum energy density affects the propagation equation for gravitons - the analogue of photons for the gravitational field. (For historical reasons, Λ is also called "cosmological constant".) More precisely, if Λ is not zero, then a mass term appears in the propagation equation, such that m2=-Λ. As a consequence, the polarization states of gravitons also change, because a massless particle has only two polarization states while a massive particle has more. This effect of the Λ-term has been confirmed by recent calculations in a curved background. A real value for the mass (when Λ<0) will show up as a slight exponential damping in the gravitational potential, which is however strongly constrained by astronomical data. The consequences of an imaginary mass (for Λ>0) are still unclear; on general grounds, one can expect the onset of instabilities in this case. This is also confirmed by numerical simulations of quantum gravity which became recently available. These properties gain a special interest in consideration of the following. (1) The most recent cosmological data indicate that Λ is positive and of the order of 0.1 J/m3. Is this value compatible with a stable propagation of gravitons? (2) The answer to the previous question lies perhaps in the scale dependence of the effective value of Λ. It could then happen that Λ is actually negative at the small distance/large energy scale at which the quantum behavior of gravitational fields and waves becomes relevant. Applications for an advanced propulsion scheme is that local contributions to the vacuum energy density (remarkably in superconductors in certain states, and in very strong static electromagnetic fields) can change locally the sign of Λ, and so affect locally the propagation and the properties of gravitons. The graviton wavefunction, for different values of the parameters, may be characterized by superluminal phase velocity or by unitarity only in imaginary valued time. This may indicate a connection between gravitons and Faster-Than-Light travel.

A Gravitational Experiment Involving Inhomogeneous Electric Fields

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Abstract. Unification of gravitation with other forms of interactions, particularly with electromagnetic field will have tremendous impacts on technology and our understanding of nature. The economic impact of such an achievement will also be unprecedented and far more extensive than the impact experienced in the past century due to the unification of electricity with magnetism and optics. Theoretical unification of gravitation with electromagnetism using classical differential geometry has been pursued since the late nineteen twenties, when Einstein and Cartan used teleparallelism for the task. Recently, Vargas and Torr have followed the same line of research with more powerful mathematics in a more general geometric framework, which allows for the presence of other interactions. Their approach also uses Kähler generalization of Cartan's exterior calculus, which constitutes a language appropriate for both classical and quantum physics. Given the compelling nature of teleparallelism (path-independent equality of vectors at a distance) and the problems still existing with energy-momentum in general relativity, we have been motivated to undertake an experimental search for potential electrically induced gravitational (EIG) effects. This presentation details some of the practical concerns that relates to our investigation of electrical influences on laboratory size test masses. Preliminary results, appear to indicate a correlation between the application of a spatially inhomogeneous electric field and a appearance of a force on the test mass. The presence of such a force is consistent with the predictions of Vargas-Torr. More importantly, the effect is proportional to the sample mass, a scaling which is the unique signature of a gravitational effect.

STAIF-2004 Abstract Book

Woodward Effect Experimental Verifications

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Abstract. The work of J. F. Woodward (1990; 1996a; 1996b; 1998; 2002a; 2002b; 2004) on the existence of "mass fluctuations" and their use in exotic propulsion schemes was examined for possible application in improving space flight propulsion and power generation. Woodward examined Einstein's General Relativity Theory (GRT) and assumed that if the strong Machian interpretation of GRT as well as gravitational / inertia like Wheeler-Feynman radiation reaction forces hold, then when an elementary particle is accelerated through a potential gradient, its rest mass should fluctuate around its mean value during its acceleration. Woodward also used GRT and Mach's Principle to clarify the precise experimental conditions necessary for observing and exploiting these mass fluctuations or "Woodward effect" (W-E). Later, Woodward in collaboration with his ex-graduate student T. Mahood pushed the experimental verification boundaries of these proposals utilizing various experimental approaches including torque pendulums. If these purported mass fluctuations occur as Woodward claims, and his assumption that gravity and inertia are both byproducts of the same GRT based gravitational phenomenon per Mach's Principle is correct, then many innovative applications such as propellantless propulsion and gravitational exotic matter generators may be feasible. This paper examines the need for some kind of propellantless propulsion for interstellar flights, the reality of mass fluctuations and the feasibility of using the W-E to design propellantless propulsion devices in the near to mid-term future. The author's initial W-E tests along with the latest experimental results, utilizing MHD-like force rectification systems, will also be presented.

Power Chips for Efficient Energy Conversion

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Abstract. The Power Chips technology employs a gap of 4-10 nanometers in a gap diode to allow for efficient thermal conversion with very low thermal leakage. The design DT is on the order of 400 degrees single stage, with operation possible from 1 K to 1600 K, depending on configuration and meeting engineering challenges. Efficiency is projected to be in the range of 70% of Carnot-defined maximum. R&D work on this approach has been in progress since 1997. The main technical challenge of fabricating and maintaining the required gap has been overcome; thin film and packaging issues remain. The technology is anticipated to be ideal in terms of size, weight, efficiency, and reliability. Power Chips can be packaged identically as conventional thermoelectrics making them a drop-in replacement in many cases including RTGs. Applications for Power Chips include RTGs as well as thermal conversion from a waste heat stream or solar-thermal conversion.

Flyer Acceleration by Pulsed Ion Beam Ablation and Application for Space Propulsion

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Abstract. Flyer acceleration by ablation plasma pressure produced by irradiation of intense pulsed ion beam has been studied. Acceleration process including expansion of ablation plasma was simulated based on fluid model. And interaction between incident pulsed ion beam and a flyer target was considered as accounting stopping power of it. In experiments, we used ETIGO-II intense pulsed ion beam generator with two kinds of diodes; 1) Magnetically Insulated Diode (MID, power densities of <100 J/cm^2) and 2) Spherical-focused Plasma Focus Diode (SPFD, power densities of up to 4.3 kJ/cm^2). Numerical results of accelerated flyer velocity agreed well with measured one over wide range of incident ion beam energy density. Flyer velocity of 5.6 km/s and ablation plasma pressure of 15 GPa was demonstrated by the present experiments. Acceleration of double-layer target consists of gold/aluminum was studied. For adequate layer thickness, such a flyer target could be much more accelerated than a single layer. Effect of waveform of ion beam was also examined. Parabolic waveform could accelerate more efficiently than rectangular waveform. Applicability of ablation propulsion was discussed. Specific impulse of 7000~8000 seconds and time averaged thrust of up to 5000~6000N can be expected. Their values can be controllable by changing power density of incident ion beam and pulse duration.

The STAIF Advanced Propulsion Conference: Leave No Inquiring Mind Behind!

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Abstract. There are extremely unusual phenomena that surround us and there is a need to better understand how they will influence new conceptual and revolutionary propulsion systems. Mankind has toiled considerably pursuing chemical propulsion with only slight improvements in weight and performance. Ignoring a revolutionary new breakthrough, a different propulsion scheme that departs from conventional wisdom is necessary to create a truly long-range space-faring civilization. In this age of discovery, we are bravely questioning the conventional wisdom and its limitations. We search for new means to develop future propulsors that may be propellantless, operate based upon ambient fields, capable of developing high specific impulse, and still generate suitable high levels of thrust to break free from our earthly bonds. As scientists and engineers, we would like to report that although there are limitations to the amount of progress that mankind can make, there is considerable uncertainty about the future positive directions that will provide the necessary technology to take us to the stars. To address this, a symposium was created as a catalyst to fit within the confines of the STAIF forum. This format focuses upon the innovative use of existing technology, but more so, to examine anomalies and perform investigations within the fringes of mainstream physics that could both scrutinize and improve our understanding of things such as gravity, gravitational waves, and superconductivity. All of these could impact new frontiers and future concepts; these new innovative technologies could be applied to propulsion, electric power generation, and communications. Many of the concepts discussed were developed with very little capital investment. Within this structure, the presenter alongside with academic and laboratory investigators are given a voice to address their ideas amongst technical peers in an international setting to potentially gain leverage for future funding. These concepts are so diverse that one could argue that mankind is taking a closer step to reach an elusive destiny that often exceeds our grasp. As such, it is difficult to imagine the progress that could be achieved if adequate funding were made available to pursue even a few of these concepts.

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