Forum on Concepts and Approaches for Jupiter Icy Moons Orbiter

Science Capabilities & Workshop Goals

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Project Prometheus

Revolutionizing Space Exploration

Revolutionize space exploration using space nuclear electric power and propulsion to enable more robust and ambitious scientific missions and to stimulate future generations of explorers and students.

Key Program Components:

Energy Generation – allows for a range of power levels
- Radioisotope (milliwatts – kilowatts)
- Fission reactor (kilowatts–megawatts)

Conversion to Electricity – options dependent on end use
- Static: Thermoelectrics, Thermophotovoltaic
- Dynamic: Stirling free piston, Rankine (2-phase) & Brayton cycles (single-phase)

Electricity Utilization
- Nuclear Electric Propulsion
- Scientific Instruments – to be defined by scientific community

Jupiter Icy Moons Orbiter (JIMO)

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Nuclear Electric Propulsion

Nuclear Fission Reactor Research (DOE)

Objective: Research candidate reactor power systems suitable for planetary science applications

- *Finished comprehensive reactor concept screening activity*
  1) Heat pipe, 2) liquid metal, 3) gas
- Develop advanced nuclear fuels capable of supporting higher-temperature, higher power systems for more advanced, lightweight spacecraft

Power Conversion Research (NASA)

Objective: Research multiple high power thermal-to-electrical conversion technologies for nuclear electric propulsion (engineering unit - CY06)

  - Static (thermoelectric) and dynamic (Brayton & Rankine) conversion technologies

- *Competitively awarded 3 power conversion technology contracts (Boeing, JPL, NASA GRC, DOE Oak Ridge)*

Electric Propulsion Research (NASA)

Objective: Research multiple high-power (20-50 kWe & up to 250 kWe) electric propulsion technologies for nuclear electric propulsion (engineering unit - CY06)

- *Competitively awarded 2 electric propulsion technology contracts (NASA GRC, JPL)*
- Award very high power electric thruster research geared toward advanced electromagnetic thrusters for demanding, revolutionary science exploration missions requiring power levels of 250KWe or greater (CY04)

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Nuclear Fission Reactor Research

- Nuclear Reactor Test Facility and Support Equipment
  - Develop technical requirements and conceptual designs for safe, high-fidelity nuclear ground testing of space nuclear reactor power systems
  - Benefit: Lay groundwork for full power system testing and demonstration prior to flight operations
- Enhance Non-Nuclear Testing Capability
  - Provide system upgrades for non-nuclear thermal simulation of nuclear reactor cores for variety of candidate design concepts
  - Benefit: Provide capability to thermally exercise systems before committing to final nuclear design
- Autonomous System Development
  - Develop concept of operations enabling autonomous space nuclear power system operation
  - Benefit: Provide means of safe and reliable operations in the outer solar system
- Advanced Fuels Development
  - Develop fuels and associated cladding and structures capable of high temperature operations, explore thermal propulsion systems capable of high thrust operations
  - Benefit: High temperature fuels will lead to lighter more capable science exploratory spacecraft, advanced thermal propulsion could lead to shorter trip times to outer solar system planets of interest

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Nuclear Reactor Heat-to-Electrical Power Conversion

Closed Brayton

- Heat engine with inert gas in rotating turbo-alternator
- High eff. (20-25%)
- Relative high maturity, but not flight proven
- Engine prototypes built at 2 and 15 kW
- Scales well to high power, but large radiator
- Well suited for high voltage applications
- Turbine Inlet 1150K (superalloys), Temp ratio ~3.0

Mature Technology with Growth Potential

Free-Piston Stirling

- Heat engine with reciprocating piston & linear alternator
- High eff. (20-30%)
- Relative high maturity, but not flight proven
- 55 W Tech Demo Convertor (TDC) currently in flight dev't for 100 W class RPS
- Well suited for low to medium power applications
- T_{hot} 925K (superalloys), Temp ratio ~2.0

High Efficiency & Scales Well to Low Power

Rankine

- Heat engine with two-phase fluid in rotating turbo-alternator
- Moderate eff. (10-20%)
- Most work completed during 60's SNAP-8 Program (50 kW Mercury Rankine)
- K-Rankine scales well to 100's of kW (e.g. SNAP-50, MPRE)
- Turbine inlet 650K (organic fluids) to 1400K (Potassium), Temp ratio ~2.0

Potential for Low Mass, but Materials Issues

Thermoelectric

- Electrical potential produced by dissimilar materials exposed to temperature diff.
- Low eff. (4-7%)
- Flown on SNAP-10A (500 W), baselined for SP-100 (100 kW)
- SiGe or PbTe unicouples flight proven in RTG at power <300 W
- Segmented TE projects 10-15% eff.
- T_{hot} 1300K (refr. alloys), T_{cold}~600K

Flight Proven with Long Life, but Low Efficiency

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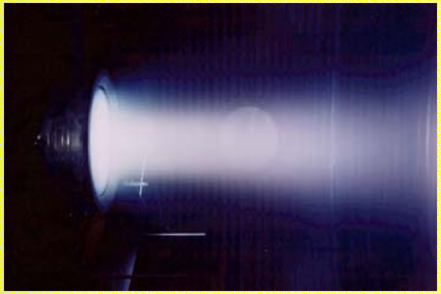
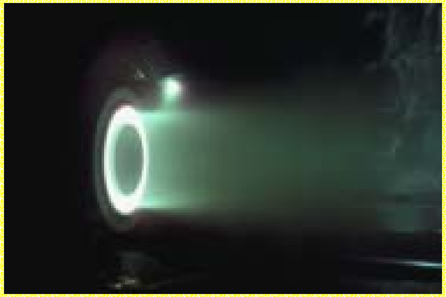
Electric Propulsion Research

• Utilizes electric power to ionize propellant and accelerate it to produce thrust



Electrostatic
Ion

Isp = 2500 - 15,000 sec
Power = 10W - 30kW
Efficiency = 60 – 80%
Mature at 2.3kW
Scales well



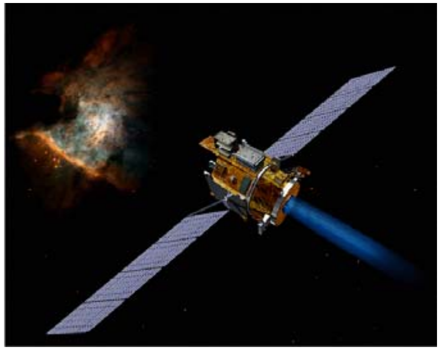
Electrostatic
Hall

Isp = 1500 - 3500 sec
Power = 100W - 50kW
Efficiency = 45 – 60%
Mature at 1.5kW
Scales well

Electro-magnetic
MPD, PIT, VASIMR

Isp = 2000 – 10,000 sec
Power = >100kW
Efficiency = 35 – 50%
Immature
Scaling not understood

Successfully Flew on 1997 Deep Space-1 Mission to Comet Borelly (2.3 kW unit)



Electrostatic – accelerates ions through applied electric field
Electro-magnetic – ions accelerated via combined electric and magnetic fields

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Radioisotope Power Systems Development

Objective: Reestablish, and strengthen, capacity to conduct science-driven, long-lived, Solar System and planetary surface exploration using radioisotope power systems

- Only 1 un-fueled radioisotope power system in current inventory (2006 Pluto mission)
- 30 safely flown by NASA on 19 missions

Multi-Mission RTG (MMRTG) Development (DOE)

<u>Objective</u>: Develop flight hardware to operate in space and on planets with atmospheres using state-of-practice technology

<u>Flight Candidates</u>: Baselined for Mars Mobile Science Laboratory (CY09 launch), NASA New Frontiers Program missions.

Stirling Radioisotope Generator (SRG) Development (DOE)

<u>Objective</u>: Develop flight hardware for more efficient power generation (space and on planet with atmospheres) by incorporating a Stirling convertor

<u>Flight Candidates</u>: Backup for Mars Mobile Science Laboratory (CY09 launch); NASA New Frontiers Program missions

Power Conversion Technology Research (NASA)

<u>Objective</u>: Develop higher efficiency heat-to-electrical power conversion technology

- Enables higher power, lower mass, and/or lower Plutonium-238 usage
- *Competitively selected 10 power conversion technology contracts*

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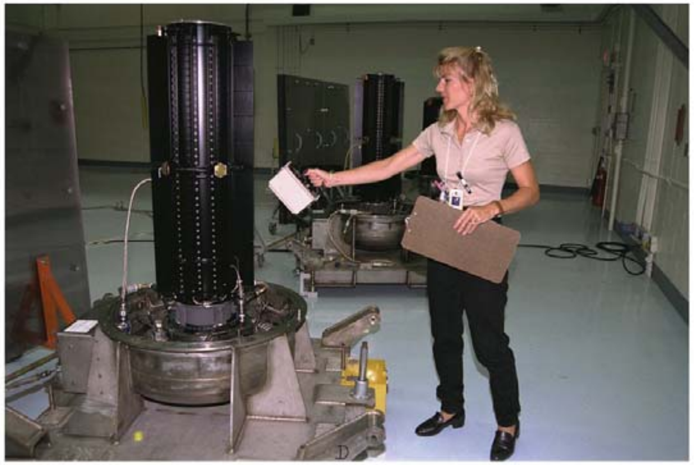
Multi-Mission RTG Development

MMRTG shores up lack of small nuclear power sources in U.S. inventory for civil space applications and deep space missions by end of this decade.

- Provides approximately 120 Watts of electrical power for scientific instruments and spacecraft operations.
- Minimal use of new technology – based on same power conversion technologies used on RTGs for Viking, Galilleo and Cassini programs but with half the power output and Plutonium requirements.



MMRTG is low risk and based on technologies proven on previous applications, such as the Cassini mission. (RTG shown here)

- Capable of operations on the surface of planets and moons with atmospheres (e.g., Mars, Titan) and in deep space independent of distance from Sun.
- Provides continuous all-day/all-night operation at any location and latitude.

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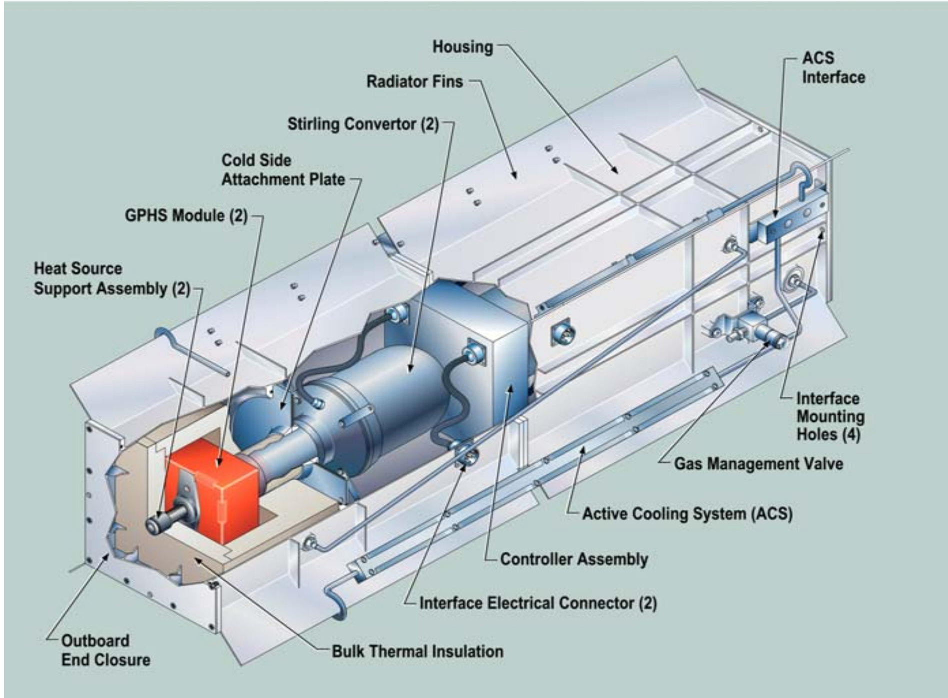
Stirling Radioisotope Generator (SRG) Development

New, advanced radioisotope power source (RPS) to support Mars surface exploration and deep space missions by end of this decade

- Provides approximately 120 Watts of electrical power for scientific instruments and spacecraft operations (same as MMRTG)
- Employs highly efficient Stirling dynamic energy conversion process which reduces Plutonium requirements substantially over current static conversion technologies



Stirling Radioisotope Generator (SRG) under development by Lockheed-Martin, Stirling Technologies and NASA Glenn

- Capable of operations on the surface of planets and moons with atmospheres (e.g., Mars, Titan) and in deep space independent of distance from Sun
- Four-fold reduction in Plutonium requirements for a given power level
- Dynamic energy conversion well-proven on Earth and in flight with small cryocoolers

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Advanced Power Conversion Research & Technology

- Research and technology projects that will enable development of high-efficiency, high-specific power RPS for wide range of future mission applications
- Improved RPS could greatly expand the capabilities and options available for future small-scale science missions
  - 100 Watt-scale systems: Follow-on to current MMRTG and SRG developments (e.g., 2nd generation SRG)
  - Milliwatt (~0.010 W) to Watt-scale systems: Small electric power supplies for Mars network science, remote sensing stations and very small spacecraft
- Factor of 2 to 5 improvements in power conversion beyond SOA in converter reliability, lifetimes, power levels, and overall efficiency

Development of milliwatt-scale radioisotope power supplies could provide tremendous capabilities to future Mars and deep space missions

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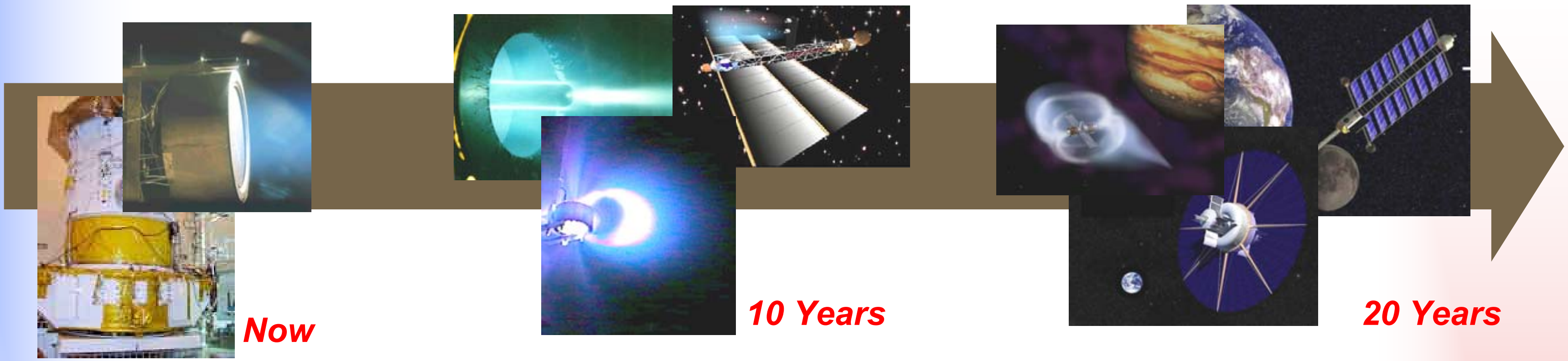
Jupiter Icy Moons Orbiter (JIMO)

- JIMO will be the first flight mission to use nuclear power and propulsion technologies.
- This mission will set the stage for the next phase of exploring Jupiter and will open the rest of the outer Solar System to detailed exploration.
- Project Office located at JPL

Many Technologies Extend to a Broad Range of Future Space Exploration Missions



- **Many of the technology, fabrication, and ground-based capacities developed for the first space nuclear propulsion mission have direct application to follow-on missions**
  - Nuclear fuel and clad & fabrication capacity
  - Nuclear reactor design, analysis, and qualification methodology and software
  - Neutron and gamma shield, and neutron reflector & fabrication capacity
  - Radiation-tolerant nuclear reactor instrumentation and control & fabrication capacity
  - Space nuclear reactor power system autonomy
  - Power conversion & fabrication capacity
  - Low mass, large-scale radiation-tolerant thermal radiators & fabrication capacity
  - High power density electrical power control and distribution & fabrication capacity
  - High power electric propulsion & fabrication capacity
  - Safety and launch approval procedures, National Environmental Policy Act procedures and actions
  - **Ground test facility and support equipment (both for zero-power critical testing, and potential full power testing)**

Evolvable technologies for follow-on science driven exploration missions

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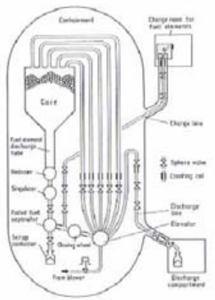
Applications Beyond NASA and Space Exploration

High Temperature Nuclear Fuel for Potential Future High-Temp Gas-Cooled Nuclear Plants

Uranium Nitride (UN) Fuel Pellets



High-Temp Gas Cooled Reactor Concept

High Reliability, Autonomous Systems & Controls (Reactor Control Technology) Potentially Apply to Broad Array of Autonomous Systems

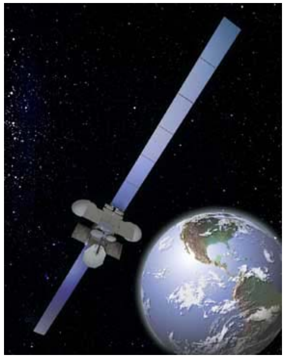
Autonomous Vehicles

High Temperature (Refractory) Materials for Reactor and Power Conversion Fabrication

Brayton Cycle Turbo-Alternator

3-Stage Potassium Turbine

Lightweight Advanced Thermal Radiators for Civil and Defense Communication Satellites



Civil Communications Satellites

Defense Communications Satellites

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Organizational Principles

- Organize for safety and mission success
- Establish clear lines of responsibility and authority
- Enable focus on mission systems engineering and optimization
- Enable responsiveness to science mission customers
- Utilize the capabilities of industry, academia, and the US Government via a competitive process to achieve innovative solutions and optimal cost and performance
  - Utilize capabilities of US Government to manage and implement this program
    - DOE regulatory responsibility and authority (Atomic Energy Act) for the development and operation of systems using special nuclear material (e.g., reactors)
    - DOE authority to indemnify developers of reactors and related activities
    - NASA has unique and extensive experience in the launch and operation of deep space spacecraft
  - Utilize capabilities of NASA
    - GRC, JPL, KSC, MSFC
  - Utilize the capabilities of instrument developers and scientists throughout the world
    - Universities
    - Industries
    - NASA centers and DOE laboratories

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Conclusion

- **Project Prometheus will enable a new paradigm in the scientific exploration of the Solar System. As in any scientific investigation we cannot predict what we will find and what impact it will have. We will be surprised!**

- **We hope and expect the JIMO mission will be the first of a new generation of missions characterized by more maneuverability, flexibility, power and lifetime and even greater scientific opportunity.**

- **Project Prometheus organization is established at NASA Headquarters:**
  - **Organization established to manage our three major elements**
  - **We have accomplished much in the short time since we began**
    - **Awarded five NRA's for nuclear propulsion research and ten for power conversion for radioistope power sources**
    - **Awarded three study contracts to industry led teams for study of the JIMO spacecraft**
    - **Assembled teams of dedicated scientists engineers and managers**
- **We know this will be difficult technically and politically and the support of all is essential. Each person involved [and committed] will help us toward our goals.**

- **Challenges are many, time is short, but the rewards are great. We can and will make a great impact on our knowledge of our home- the solar system.**

- *It is easy to go nowhere. . It requires no energy and has no risk except that of being left behind . To go forward and run ahead is a supreme test. – unknown*
- *Discovery comes as a result of positive discontent, a constructive dissatisfaction. In fact one may quite truthfully say that there is no discovery when one is content. -Myron Allen*