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Project Prometheus: Program Overview

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Project Prometheus, NASA

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Nuclear Power in Context of Spacecraft Applications

Nuclear Fission Reactors and Radioisotope Thermoelectric Generators

- Operate continuously regardless of orientation or distance from the Sun
- Locations where solar power density is too low or solar power not readily or continuously available (lunar polar craters, high Martian latitudes)
- Operate for long durations (years to decades) at power levels from milliwatts to multi-hundred kilowatts
- Operate in harsh environments (radiation, weather, magnetic)
- Provide safe, light-weight, long-lived heat source
- Enabling new methods of space exploration
  - Deliberate trajectories, high-power science, large bandwidth communications

Space-Based Nuclear Reactor Technologies

1960's Space Nuclear Auxiliary Power (SNAP)

- SP-100 Program initiated in FY83, terminated FY1993
- Three agencies involved, each contributing funding separately
  - NASA and DoD had potential missions
  - DOE had potential technology
- SP-100 technology base was an evolution of SNAP-50/SPUR space reactor programs from late-60's/early-70's

PROJECT PROMETHEUS

Match the Power System to the Destination

Solar Electric Best Suited to Inner Solar System
- Also limited reach to large outer planetary bodies with aerocapture (Jupiter, Saturn, Uranus, Neptune only)

Radioisotope Electric for New Frontiers Class Solar System Missions
- 100-1000 W
- 5-30 kg payload
- MFT EELV - high energy earth departure

Nuclear Fission Electric for Large Flagship Missions to Outer Planets
- 100s – 1000s kg
- 1000 kg payloads
- SMFT EELV – low energy earth departure

SP-100 Program Overview
Radioisotope Missions
Used reliably on 24 missions since 1961
- 8 RTG Earth Orbit missions (Triumph, Nimbus, LES)
- 7 RTG planetary missions (Pioneer, Voyager, Ulysses, Galileo, Cassini)
- 2 RTG Mars missions (Viking 1 & 2)
- RTGs used on Apollo 11, Mars Pathfinder & MESR among others

Distances & Planets Are Not to Scale

PROJECT PROMETHEUS

History
- Program initiated in response to identified limitations of current paradigm for Solar System exploration
  - Solar power limits power budgets and can be of limited use in outer planetary system
  - Chemical propulsion can limit maneuverability and destinations
- Nuclear Systems Initiative included in President's FY03 Budget and renamed Project Prometheus in President's FY04 Budget

Presentation Overview

Vision for Space Exploration

THE FUNDAMENTAL GOAL OF THIS VISION IS TO ADVANCE U.S. SCIENTIFIC, SECURITY, AND ECONOMIC INTEREST THROUGH A ROBUST SPACE EXPLORATION PROGRAM

Implement a sustained and affordable human and robotic program to explore the solar system and beyond
Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.

Space Exploration Beyond Low-Earth Orbit:
- Conduct robotic exploration across solar system to search for life, understand history of universe, search for resources
- Demonstrate power, propulsion, life support capabilities for long duration, more distant human and robotic missions
- Conduct human expeditions to Mars after acquiring adequate knowledge and capability demonstrations

Pre-Decisional - for discussion purposes only
Presentation Overview

**Program Description**

- Electric Propulsion
- Auxiliary
- In-situ
- Communications

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**PROJECT PROMETHEUS**

**Objectives and Benefits**

Project Prometheus supports the Vision for Space Exploration by developing safe, reliable, long-lived, rugged power sources, from milli- to multi-kilowatt, using radioisotope and fission reactor power systems, and advanced propulsion systems that would enable more robust and ambitious science exploration not possible with current power and propulsion technologies.

**Direct Benefits**
- Radioisotope power systems enabled detailed and extended in situ scientific exploration of Solar System locations that cannot be explored in detail using solar or battery power, such as Mars, Europa, Titan, and the Neptune system.
- Nuclear fission power systems would enable unprecedented exploration of the solar system by providing the energy necessary to power high capability science instruments and advanced electric propulsion systems, as well as a variety of auxiliary and surface systems in support of future human missions.

**Indirect Benefits**
- Compelling stimulus to student interest in technical education from the combination of exciting new space exploration and nuclear propulsion development.
- Terrestrial systems, benefit from the development of advanced technologies required for space nuclear power and propulsion.

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**PROJECT PROMETHEUS**

**Key Technology Components**

- Energy Generation
  - Fusion reactor (100-1000 of kWe)
- Conversion to Electricity
  - Static: Thermoelectric, Thermophotovoltaic
  - Dynamic: Stirling, Rankine, Brayton heat pumps
- Propulsion
  - High power electric
  - Nuclear thermal
- Auxiliary
  - Electric
  - Nuclear
  - Thermal
  - Nuclear
  - High power electric
- Communications
  - Satellite communications
  - Communications
  - Auxiliary spacecraft
  - Spacecraft
  - Communications

**Future Prometheus Technology-Enabled Missions**

- Robotic, Human, and Human/Robotic

Future Prometheus Technology-Enabled Missions

*Ensuring safety is our paramount objective and all program activities will be conducted in a manner to achieve this goal.*

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**PROJECT PROMETHEUS**

**Reactor Options Under Evaluation**

- Liquid Metal Cooled
  - Core includes fuel pins and gas flow channels
  - Core provides thermal power via single or multiple Brayton power conversion units
- Heat Pipe Cooled
  - Modular core design with multiple heat pipes integrated with fuel pins
  - Heat pipes passively transfer heat from core to heat exchangers
  - Independent heat exchangers transfer heat from heat pipes to multiple independent power conversion loops
- Direct Gas Cooled
  - Core includes fuel pins and gas flow channels
  - Core provides thermal power via single or multiple Brayton power conversion units

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**PROJECT PROMETHEUS**

**Nuclear Fission Reactor Research**

**Paper Reactors, Real Reactors**

An academic reactor or reactor plant almost always has the following basic characteristics:

1. The reactor is in the study phase. It is not being built now.
2. It is simple, small, cheap, and light
3. It can be built very quickly
4. It is very flexible in purpose
5. Very little development is required. It will use nearly off-the-shelf components.

On the other hand, a practical reactor plant can be distinguished by the following characteristics:

1. It is being built now
2. It is complicated, large, expensive, and heavy
3. It is behind schedule
4. It takes a long time to build because of the engineering development problems
5. It is requiring an immense amount of development on apparently trivial items.

*The tools of the academic reactor-designer are a piece of paper and a pencil with an eraser. If a mistake is made, it can always be erased and changed.*

*If the practical-reactor designer errs, he wears the mistake around his neck; it cannot be erased. Everyone can see it.*

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*Admiral Hyman Rickover: The Journal of Nuclear Science and Engineering, June 19*
**PROJECT PROMETHEUS**  
Heat-to-Electrical Power Conversion Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed Brayton</td>
<td>Heat engine with inert gas in sliding turbo-alternator</td>
</tr>
<tr>
<td></td>
<td>High eff. (20-30%)</td>
</tr>
<tr>
<td></td>
<td>Relative high maturity, but not firm pressure</td>
</tr>
<tr>
<td></td>
<td>Engine prototypes built at 2 and 15 kW</td>
</tr>
<tr>
<td></td>
<td>Stacks well to high power, but large radiator</td>
</tr>
<tr>
<td></td>
<td>Well suited for high voltage environments</td>
</tr>
<tr>
<td></td>
<td>Turbine inlet 150K (auxiliary), Temp ratio &gt;3.0</td>
</tr>
</tbody>
</table>

**Thermoelectric**  
- Electrical potential produced by dissimilar materials exposed to temperature differences.
- Low eff. (4-7%)
- Placed on SNAP-10A (500 W), bezel-locked for SP-100 (100 kW)
- SiGe or Pt/Pt-Rh thermocouples tight in PtN at power 500 W
- Segmented TE projects 10-15% eff.
-heimer, 1000 (inh.
-therm., Temp =400K

**Electrostatic**  
- Accelerates ions through applied electric field
- Electric-magnetic - ions accelerated via combiner electric and magnetic fields

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**PROJECT PROMETHEUS**  
Nuclear Electric Propulsion

**HiPEP & NEXIS Thruster Beam Extraction Testing**

**NEXIS**  
- 16-25 kW
- 6500-7500 s  
- 75% Eff.
- 8000 Volt Grid
- Life: >1600 kg Xe  
- 7 to 11 years

February, 2004 - 27 kW, spa 8700 s,  
75% efficiency, 6000 V, 50N thrust

**HiPEP**  
- 20-50 kW
- 6000-6000 s  
- 75% Eff.
- 8000 Volt Grid
- Life: >2000 kg Xe  
- 7 to 11 years

February, 2004 - 30kW, spa 8300 s,  
75% efficiency, 7700 V, 68N thrust

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**PROJECT PROMETHEUS**  
Electric Propulsion Technologies

- **Electrostatic Ion**  
  - Ip = 2500 - 15,000 sec
  - Power = 10W - 30kW
  - Efficiency = 60 - 80%
  - Mature at 2.3kW

- **Electrostatic Hall**  
  - Ip = 1600 - 3500 sec
  - Power = 10W - 50kW
  - Efficiency = 45 - 60%
  - Mature at 1.5kW

- **Electro-magnetic MDP, PIT, VASIMR**  
  - Ip = 2000 - 10,000 sec
  - Power = >100kW
  - Efficiency = 35 - 50%
  - Mature at 1.5kW

**Electrostatic** accelerates ions through applied electric field
**Electro-magnetic** - ions accelerated via combiner electric and magnetic fields

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**Presentation Overview**

- **Jupiter Icy Moons Orbiter**
- Future Directions
- Space Science
- Communications
- Engagement
- Outreach

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**Decadal Survey**

- In 2002, the National Academy of Sciences conducted the Solar System Exploration Survey to prioritize technologies and missions.
- The Survey identified the following areas in which it believed that technology development is appropriate:
  - **Power**: Advanced RTGs and in-space nuclear fission reactor power source
  - **Propulsion**: Nuclear electric propulsion, advanced ion engines, aerocapture

  "The two most-constrained resources in the current generation of planetary spacecraft are onboard power and propulsion. Improvements in these two areas will enable the largest leaps forward in capability.

  - **The Survey identified a Jupiter Geophysical explorer as its top priority flagship mission**

  "The proposed Jupiter Icy Moons Mission will more than fulfill our goal of a flagship mission to further explore the subsurface oceans on Europa while simultaneously applying the new technologies that the Survey advocates as being critical for much of the future program."**


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• Technology
  - Develop a nuclear reactor powered spacecraft and show that it can be processed safely, launched safely, and operated safely and reliably in deep space for long-duration deep space exploration.

• Science
  - Explore the three icy moons of Jupiter – Callisto, Ganymede, and Europa – and return science data that will meet the highest scientific goals as set forth in the Decadal Survey Report of the National Academy of Sciences.
  - The high power and high data rate afforded by nuclear power will enable science data return far beyond current capabilities.
  - JIMO would be the first flight mission to use nuclear power and propulsion technologies applicable to future human exploration missions.

• Science
  - Explore the icy moons of Jupiter and determine their habitability in the context of the Jupiter system.
  - Europa, Ganymede, and Callisto very likely have global liquid water oceans beneath their icy crusts. ... one of the major discoveries in solar system science in the last decade.
  - There is spectral evidence for salts and organic materials on their surfaces, and geologic evidence that the Europan ocean may have been in contact with the surface in the geologically recent past (less than about 100 million years).
  - These bodies are among the most exciting in the solar system for geophysical, geochemical, and astrobiological exploration.

• Oceans:
  - Liquid water, Icy Crustal Structure and Active Internal Processes

• Astrobiology:
  - Volatiles, Organics and Surface Processes

• Jovian System Interactions:
  - Satellite Atmospheres, Surfaces and Interiors
**Presentation Overview**

- **Future Directions**

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**PROJECT PROMETHEUS**

**Evolution to Advanced Exploration Missions**

- Systems and techniques developed within Project Prometheus for robotic missions will provide:
  - advanced capabilities for scientific exploration,
  - address long term issues for development of nuclear systems,
  - demonstrate operation of fission systems in space

- Human surface exploration activities, mobile or fixed, could also require a new source of power (compact, all-weather, day and night), enabled by JIMO-developed technologies:
  - ample electric power to support a human crew
  - ample electric power to support in-situ resource utilization

- Human exploration transport vehicles could require a new source of power for auxiliary power supply and a new scale of power for propulsion systems.

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**Early Concept Definition (RFI)**

- **Solicitation:** Request for Information (RFI):
  - In support of Projects Constellation and Prometheus requirements development and acquisition strategy
  - Expected response from industry, academia, NASA centers, related commercial enterprises, etc.

- **Deliverables:**
  - Unfunded "White Papers" addressing key areas for further study and risk reduction

- **Purpose:**
  - Identification of areas for future trade studies & risk reduction activities
  - Identification of technical risk areas and cost drivers
  - Assessment of design drivers and other critical architecture considerations
  - Innovative concepts or considerations in key areas such as:
    - Sustainability
    - Affordability
    - Launch Infrastructure
    - Crew size
    - Reliability & Safety
    - Maintenance & Assembly
    - Lunar/Mars Commonality
    - Propulsion Issues
    - Acquisition Strategy/PM Tools

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**Concept Exploration & Refinement (BAA)**

- **Solicitation:** Broad Area Announcement (BAA):
  - In support of Projects Constellation and Prometheus requirements development and acquisition strategy
  - Expected response from industry
  - Multiple Awards/Varying Response Times

- **Deliverables:**
  - Architectural Trade Studies and Risk Reduction Analyses
  - Concepts for Lunar Missions and Architecture
  - Concepts for CEV
  - Methodologies for incorporating TECHMAT into CEV and Lunar Architecture
  - Recommendations for Streamlining Acquisition

- **Purpose:**
  - Advanced Development of Potential Risk Reduction Concepts
  - Support Systems Integration and CEV contract process
  - Continued pursuit of innovative concepts determined to be feasible/affordable based on Jan RFI results and recommendations

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**Presentation Overview**

- **History**
- **Future Exploration**
- **Technology**
- **Jupiter/Moon Orbiter**
- **Future Constellation**
- **Safety**

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**Output to help structure follow-on BAA and RFP**
PROJECT PROMETHEUS
Safety is Paramount

- Must be safe to launch
  - Space reactor designs minimize potential for inadvertent startup during all potential launch accident scenarios
  - Design with fail safe (forced reactor shutdown)
  - Uranium hex floride (UHF) heat source
  - U-235 fuel and other materials pose very small radiological hazard prior to extended operations in space

- Must be safe to develop
  - Maximum use of non-nuclear testing in all phases of development
  - High performance cold fusion reactors in space
  - Operations of moderate power densities and temperatures 
  - Prevention of accidental criticality while still in the Earth environment
  - Emphasis on existing facilities and mature component technology

- Reduce potential hazard to earth, space or planetary environments
  - NASA applications restricted to "outbound" trajectories and use in deep space
  - Planetary protection requirements will be developed

- Ensures safety concerns are addressed
  - The reactor would be specifically designed to prevent accidental criticality while still in the Earth environment
  - We are engaging NASA and DOE expertise in continuous safety management and risk assessment
  - NASA will fully comply with Environmental and Nuclear Safety Launch Approval Processes Applicable to the Use of Nuclear Power Systems in Outer Space

- National Environmental Policy Act (NEPA)
  - Purpose: Ensure NASA considers the potential environmental impacts of a proposed program or project and reasonable alternatives
  - NEPA Environmental Assessment or Environmental Impact Statement (EIS), as appropriate
  - Provides opportunity for public engagement

- Presidential Directive / National Security Council Memorandum #25
  - Purpose: Ensure informed decision-making at the Presidential level before launching a mission with radioisotope power systems or nuclear reactors.
  - Ensures NASA/DOE safety analyses, interagency safety evaluation, and nuclear safety launch approval by Director of OSTP or the President.

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Presentation Overview

- Communications, Engagement & Outreach

PROJECT PROMETHEUS
Designing for Safety

- NASA has over 30 years' experience in the successful management of radioisotope power systems (RPS)
- Working with DOE, we would apply that safety experience to the design, manufacture, and flight of a fission reactor
  - The reactor would be specifically designed to prevent accidental criticality while still in the Earth environment
  - We are engaging NASA and DOE expertise in continuous safety management and risk assessment
  - NASA will fully comply with Environmental and Nuclear Safety Launch Approval Processes Applicable to the Use of Nuclear Power Systems in Outer Space

- National Environmental Policy Act (NEPA)
  - Purpose: Ensure NASA considers the potential environmental impacts of a proposed program or project and reasonable alternatives
  - NEPA Environmental Assessment or Environmental Impact Statement (EIS), as appropriate
  - Provides opportunity for public engagement

- Presidential Directive / National Security Council Memorandum #25 (PD/NSC-25) (as amended)
  - Purpose: Ensure informed decision-making at the Presidential level before launching a mission with radioisotope power systems or nuclear reactors.
  - Ensures NASA/DOE safety analyses, interagency safety evaluation, and nuclear safety launch approval by Director of OSTP or the President.

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PROJECT PROMETHEUS
Communicating with Our Customers and Stakeholders

- Goal is to ensure open, honest, pro-active, inclusive, dialogue and communication with the public, media, educators, legislators and others
- Focus on Project Prometheus-specific technological and programmatic goals within the context of NASA scientific and exploration goals
- Provide for proactive, cooperative engagement with a broad range of potential stakeholders including environmental organizations
- Include technology education and outreach programs and materials available to all citizens

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PROJECT PROMETHEUS
Conclusion

- Project Prometheus technologies can play a vitally important role in supporting robotic and human exploration of the Solar System
  - Safety is the absolute highest priority; NASA has over 30 years of demonstrated safety record in the launch of radioisotope power systems
  - We can recapture work done for past programs and move forward quickly
- We believe the technologies being developed by Prometheus could enable a new paradigm in human and robotic exploration
  - Project Prometheus is a logical outgrowth of previous technology development programs and will fill an important gap in capability
  - The proposed JIMO mission will be the first of a new generation of missions characterized by more maneuverability, flexibility, power and lifetime
  - Project Prometheus is also leading the Agency in new approaches to communication, engagement, and outreach
  - We can make a great contribution to the fulfillment of the Nation's vision for space exploration
  - Space reactor designs minimize potential for inadvertent startup during all potential launch accident scenarios
  - Design with fail safe (forced reactor shutdown)
  - Uranium hex floride (UHF) heat source
  - U-235 fuel and other materials pose very small radiological hazard prior to extended operations in space

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