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Project Prometheus: Program Overview

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Nuclear Power in Context of Spacecraft Applications

Enabling Aspects of Space Nuclear Power Systems

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-duration (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 band-width communications

Space-Based Nuclear Reactor Technologies

1960's Space Nuclear Auxiliary Power (SNAP)

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Presentation Overview

- History
- Nuclear Fission Reactors and Radioisotope Thermoelectric Generators
  - SNAP 10A (FS-4) Launched in 1965
  - Pre-Development (FS-4)
  - SNAP-50/SPUR space reactor programs from late-60's/early-70's

SP-100 Program Overview

- 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**

**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.*

**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
**Presentation Overview**

**Program Description**
- Program Description

**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 enable 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**
- Fission reactor (100-1000 kW is)

**Conversion to Electricity**
- Static Thermoelectric,
- Thermophotovoltaic
- Dynamic String, Rankine, Brayton

**Energy Generation**
- Radioisotope (milli to kilowatts)

**Electricity Utilization**
- Electric Propulsion
- Scientific Instruments
- Communications
- Auxiliary spacecraft/plant
- Habitats
- In-situ resource utilization

**Propulsion**
- High-power electric
- Nuclear thermal

**Space Exploration Missions**
- Jupiter icy moons orbit, JIMO, Mars Science Laboratory (2009), New Frontiers, Scout and others

**Future Prometheus Technology-Enabled Missions**
- Robotic, Human, and Human/Robotic

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**Presentation Overview**

**Technology**

- Technologies

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**PROJECT PROMETHEUS**

**Reactor Options Under Evaluation**

- Liquid Metal Cooled
- Heatpipe Cooled
- Direct Gas Cooled

- Liquid metal coolant (Li) transfers heat from core to power conversion heat exchangers.
- Requires high temperature liquid metal pumps.
- Requires lithium / helium gas separator.
- Requires pumped-loop flow system, potentially with freeze/thaw capability.

- 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.

- Core includes fuel pins and gas flow controls.
- Core provides thermal power via single HE/Xe pumped gas loop.
- Hot gas directly feeds single or multiple Brayton power conversion units.
- Brayton power conversion includes compressor for pumping gas back into core.

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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 erred, 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 Reactor Science and Engineering, June 19*
PROJECT PROMETHEUS
Heat-to-Electrical Power Conversion Technologies

- Electrostatic Ion
  - lp = 2500 - 15,000 sec
  - Power = 100W - 30kW
  - Efficiency = 60 - 80%
  - Mature at 2.5kW

- Electrostatic Hall
  - lp = 1600 - 3500 sec
  - Power = 100W - 50kW
  - Efficiency = 45 - 69%
  - Mature at 1.5kW

- Electro-magnetic MDP, PIT, VASIMR
  - lp = 2000 - 10,000 sec
  - Power = >100kW
  - Efficiency = 35 - 50%
  - Immature

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

PROJECT PROMETHEUS
Nuclear Electric Propulsion
Brayton - NSTAR Demonstration

- Successful Integrated Test Completed Dec 03
  - 2 kW Brayton Power Converter
  - 1100 V-dc Power Mgmt & Distribution
  - 2.3 kW Engr Model NSTAR Ion Thruster
- Fully Representative JIMO-type PMAC/PPU Architecture
  - Brayton Speed and Voltage Control with Parasitic Load Radiator (PLR)
  - 10:1 Transformer-Based Voltage Increase
  - Direct Feed of Rectified Output into Thruster Beam Supply
- Significance of Test
  - Demonstrated End-to-End Electrical Throughput from Brayton Alternator to Ion Thruster in Vacuum
  - Demonstrated High Efficiency AC-to-DC Conversion using Radiation Tolerant Transformer/Rectifier Approach
  - Demonstrated High Speed Load Switching from Ion Thruster to PLR During Thruster Re-Cycles
  - No Adverse Energy Deposition onto Thruster-Grids
  - No Harmful Transients on Brayton Rotating Unit
  - Design Techniques are Storable to JIMO Power Levels

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-restrained 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 a basis for much of the future program."

*From Michael J. S. Betton, Ph.D., Chair, Solar System Exploration Survey Committee, National Research Council to testify on to Senate Committee on Commerce, Science, & Transportation at a Science, Technology, and Space Hearing Space Exploration, Washington, July 20 2002*
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.

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.
**Presentation Overview**

- Identity
- Mission Elements
- Program Management
- Technology
- Future Directions

**Presentation Overview**

**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 fusion 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.

**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
    - Reliability & Safety
    - Launch Infrastructure
    - Crew size
    - Payloads
    - In-space repair
    - Maintenance & Assembly
    - Lunar/Mars Commonality
    - Power/propulsion issues
    - Acquisition Strategy/PM Tools
- Output:
  - Input to help structure follow-on BAA and RFP

**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
  - Methods 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

**Presentation Overview**

- History
- Mission Scope
- Progress
- Technology
- Updated Plans:
  - Jupiter Icy Moons Orbiter
  - Europa Clipper
- Safety

Pre-Decisional - for discussion purposes only
PROJECT PROMETHEUS
Safety is Paramount

- Space reactor design minimizes potential for inadvertent startup during all launch accident scenarios
  - Core of rare materials and geometry
  - Leakage from fuel separated from core
  - Small matrix structure removed before startup
- U-235 fuel and other materials pose very small radiological hazard prior to extended operations in space

Must be safe to launch

- Maximum use of non-nuclear power in all phases of development
  - High performance nuclear reactors in space
  - Operation at moderate power densities/temperatures
  - Use for energy and waste disposal
- Emphasis use of existing facilities and mature component technology

Must be safe to develop

- NASA applications restricted to "outbound" trajectories
  - Planetary protection requirements will be developed
- Highest commitment to safety required throughout all phases of development, deployment and operation
  - Engage the public to assure that safety concerns are addressed

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 mission or program and reasonable alternatives
  - Ensures: Environmental Assessment or Environmental Impact Statement (EIS), as appropriate
  - Risk provides opportunity for public engagement

- Presidential Directive/National Security Council Memorandum #45 (PDNSC-55) (as amended)
  - Purpose: Ensure informed decision-making at the Presidential level before launching a mission with radioisotope power systems or nuclear reactor
  - Ensures: NASA/DOE safety analyses, interagency safety evaluation, and nuclear safety launch approval by Director of OSTP or the President.

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

PROJECT PROMETHEUS
Conclusion

- Project Prometheus technologies can play a vitally important role in support of 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
  - 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
  - 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

PreDecisional - for discussion purposes only