FY02 Highlights

- Overview
- Architecture Concepts
- *Exploration Hurdles*
  - Space Transportation
  - *Power*
  - Crew Health and Safety
  - Human and Robotic Operations
  - Space Systems
- Technology Planning
- Leveraging and Partnering
- Future Direction

Hurdles: Power

Human and robotic exploration beyond low-Earth orbit requires abundant, efficient and affordable sources of power for in-space, surface and transportation systems unavailable with current power systems.

***FY02 Accomplishments Addressing Power Hurdle*:**

- Conducted a collaborative solar power effort with the National Science Foundation (NSF) and the Electrical Power Research Institute (EPRI) – awards were recently announced from a combined NASA Research Announcement totaling over $3M
- Conducted system studies to define and evaluate nuclear power system options for surface and in-space applications
  - Developing requirements for the Nuclear Systems Initiative
  - Developed nuclear power module concept for an artificial gravity vehicle
  - Developed Callisto surface nuclear power concept – co-funded with Revolutionary Aerospace Systems Concepts (RASC) program
- Contracted with industry to conduct Brayton engine design studies – co-funded with Integrated Space Transportation Plan (ISTP)
- Provided seed investments for key nuclear and solar power technologies

Hurdles: Power –
Space Solar Power NRA

The Space Solar Power program is developing many of the power system technologies (e.g., low mass, high efficiency photovoltaics and power distribution; robust structures) that NEXT will be able to leverage.

The Space Solar Power program manages a focused portfolio of research and development investments, guided by systems studies with a high degree of leveraging of resources inside and outside NASA. The effort is guided by the revised Space Solar Power program strategic research and technology road maps resulting from the 1999-2000 Space Solar Power Exploratory Research and Technology program. The Space Solar Power program is focused on conceptual analysis of space solar power applications, including longer-term new space industries, as well as nearer-term Space Science and Human Exploration and Development of Space applications of space solar power; development of component technologies; ground demonstrations and the definition of technology flight experiments and demonstrations (and production of flight hardware, resources permitting). Activities within the Space Solar Power program will guide the further definition of space solar power and related technology road maps including performance objectives, resources, schedules, and multi-purpose applications (commercial, science, and other government) allowing informed future investment decisions.

The Space Solar Power program, another objective of which is to explore the feasibility of beaming large amounts of power from space to Earth, has completed a major collaborative effort with the National Science Foundation and the Electrical Power Research Institute. Awards were recently announced from a combined NASA Research Announcement totaling over $3M. This mutual endeavor solidifies the recognition of the significance and possible impact to solving the United State's future energy needs without contributing to worsening pollution conditions.

This chart shows the list of technical areas, principal investigators, and institutions involved in conducting research in critical areas to solve the foremost challenges of space solar power.

http://spacesolarpower.nasa.gov/home.html

Space Solar Power Technology Advanced Research & Technology Program

- **Goal:** Conduct preliminary strategic technology research and development to enable large multi-megawatt to gigawatt-class space solar power systems and wireless power transmission for government and commercial markets (in-space and terrestrial)
- New Projects selected for funding by collaborative NASA-National Science Foundation-Electrical Power Research Institute Space Solar Power program
  - Intelligent Cooperative Robots (PI: Si, Arizona State University)
  - Coordination of Robotic Teams (PI: Singh, Carnegie Mellon University)
  - Comnet Delays and Controlled, Networked Robots (PI: Abdalla, University of New Mexico)
  - Assembly Systems via Self-Reconfigurable Robots (PI: Shen, University of Southern California)
  - Advanced (Quantum Dot) Solar Cells (PI: Rafaelle, Rochester Institute of Technology)
  - Concentrator (Multi-Bandgap) Solar Cells (PI: O'Neil, ENTECH)
  - Microwave Power Beaming (PI: Pavlidis, University of Michigan)
  - Microwave Power Beaming (PI: Little, Texas A&M University)
  - Power Converter Design (PI: Enjeti, Texas A&M University)
  - Intelligent Diagnostics and Operation of Power Grid (PI: Johnson, Howard University)
  - Microchannel Cooling Technology (PI: Henderson, University of Cincinnati)
  - Comprehensive Economics/Environmental Analysis (PI: Macauley, Resources for the Future)

Hurdles: Power –
Nuclear Power and Propulsion Requirements

Studies of nuclear propulsion and power systems for human class missions have repeatedly identified significant benefits over chemical options:

- Reduced launch mass
- Mission simplicity with fewer elements
- Shorter trip times
- Safety (reduced space exposure time)
- Abundant surface power for in-situ resource production, habitation, and long range mobility

Accordingly, NEXT studied the application of nuclear technologies to greatly improve the safety and robustness of human exploration. Use of nuclear systems will require careful attention to a number of issues to assure its safety and beneficial use from launch to end of mission.

During FY02, NEXT began development of nuclear system concepts and derived system requirements to guide the technology road mapping.

Follow-on technology road maps specific to human exploration systems will be developed. It is the intent that other programs, such as the Nuclear Systems Initiative, and possibly other agencies will use these road maps to identify common or synergistic technology performance goals and the associated development timeframes.

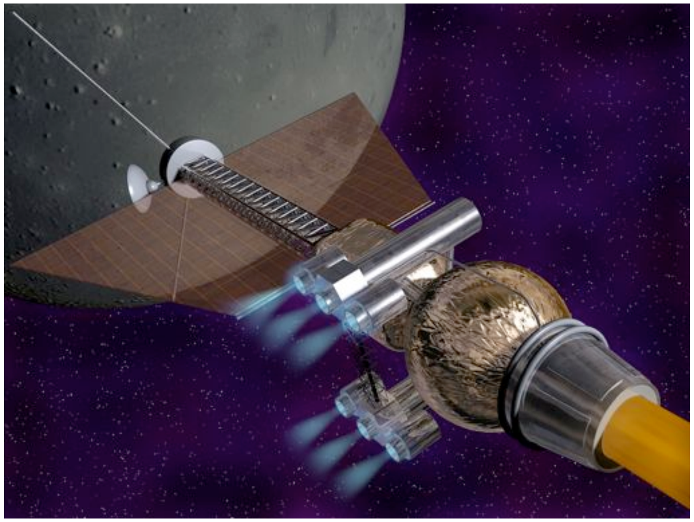
Nuclear Power and Propulsion Requirements

Scope

- Consolidate and communicate needs and requirements for nuclear power and propulsion systems and technologies (based on decades of previous study) in support of:
  - Transportation for human and robotic exploration missions
  - Surface power systems

Accomplishments / Results

- Developed mission requirements for crewed nuclear electric propulsion vehicles and power systems
  - Total electrical power for propulsion
  - Effective full power life
  - Specific impulse
  - Overall electric propulsion efficiency
  - Specific mass
  - Safety, reliability, restartability, and throttleability
- Developed mission requirements for nuclear surface power systems
  - User load profiles
  - Electrical power output
  - Lifetime
  - System mass
  - Deployability/remote emplacement
  - Planetary atmosphere and soil compatibility
  - Safety, reliability, throttleability, and restartability



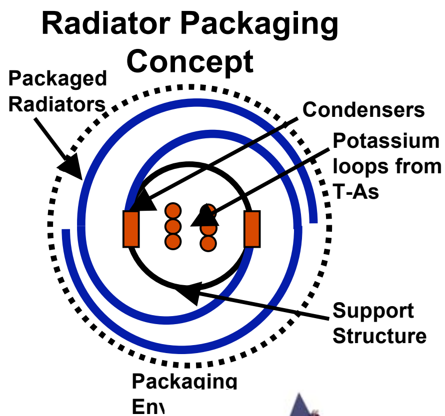
Hurdles: Power –
Nuclear Power Module Concept for an Artificial Gravity Vehicle

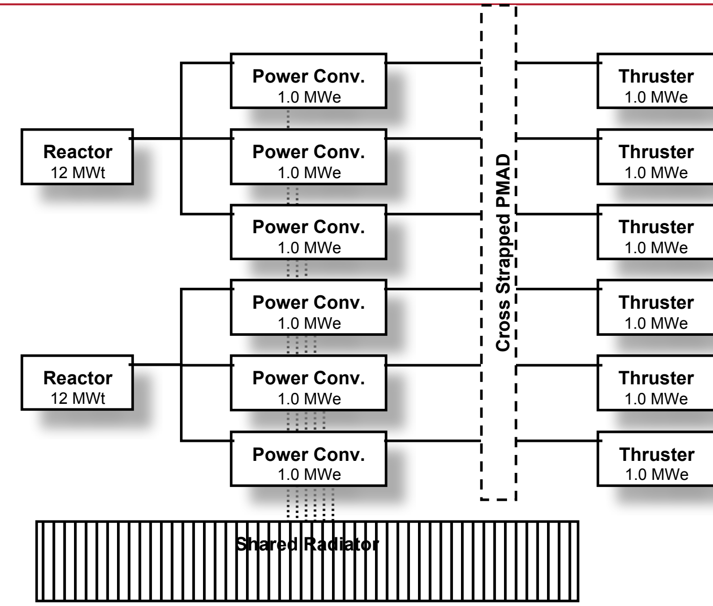
The reactor design used for assessment purposes was a 15 megawatt-thermal fast spectrum, boiling potassium reactor with a ceramic/metal core composed of uranium nitride in a tungsten/rhenium matrix (UN/W-25Re). The power system would utilize two such reactors, having a four-year life at full power operation. A potassium-Rankine power conversion system was chosen over other cycles, as this would result in lowest power conversion system mass at these power levels, the smallest radiators, and the lowest required reactor temperature. It was felt that these considerations outweighed the complexity of two-phase fluid management and liquid metal working fluids. The primary radiator would be 500 to 700 m^2 in area (assuming a rejection temperature of 1,000K), and would be composed of carbon-carbon composite heat pipes with metal liners and potassium working fluid. A tungsten/lithium hydride reactor shadow shield is used to reduce the radiation exposure to less than 1 rem/year at 100 meters.

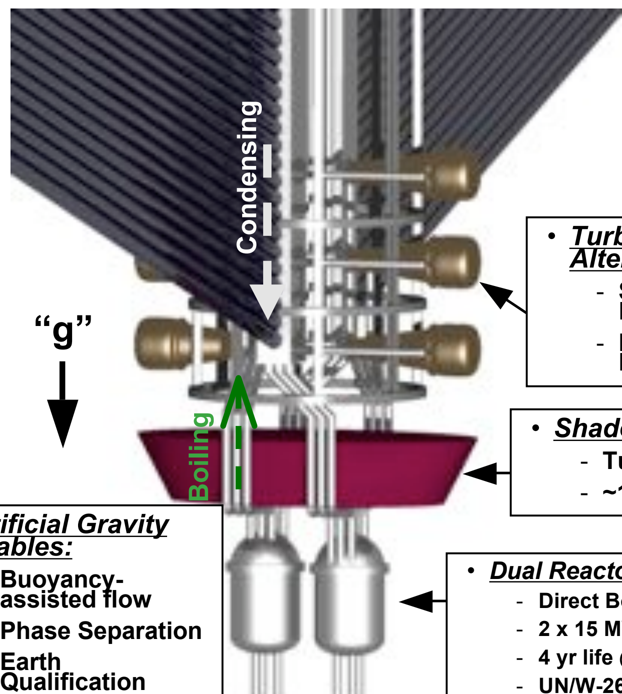
For system redundancy and potential compatibility with smaller power generation systems, the conversion system utilizes six one MWe turboalternators, each running from a separate fluid loop from one of the two reactors. The power output from the turboalternators would feed into a cross-strapped power management and distribution system and would subsequently power the electric thrusters. This system architecture provides for graceful degradation in the event of reactor, fluid loop, or turboalternator failures.

Nuclear Power Module Concept for an Artificial Gravity Vehicle

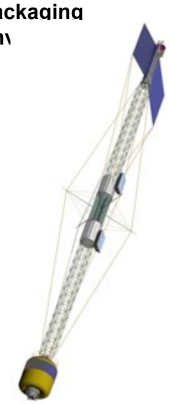
- **Rankine Conversion assumed due to:**
  - Lowest mass @ MWe powers
  - *Lowest radiator area*
  - Lowest reactor temperature
  - Adds complexities of 2-phase fluid management & liquid metals
- **Primary radiator (~500-700 m^2, ~1,000K) assumes technologies under previous development for advanced SP-100 radiators (reference Al Juhasz, NASA/GRC)**
  - Carbon-carbon composite heat pipe radiators, metal liner, potassium working fluid (5 kg/m^2).
  - Flexible woven "fabric" radiators
- **A potential deployment scheme has been identified**

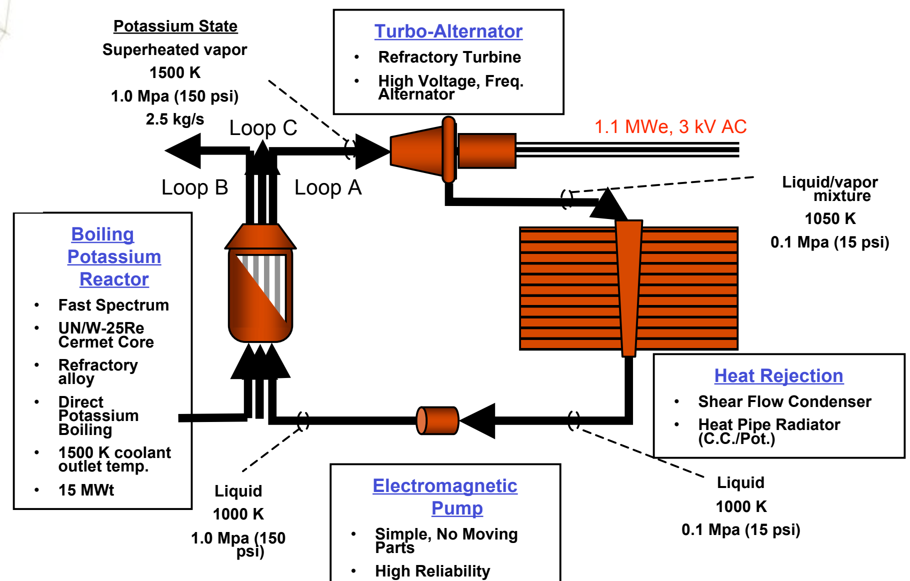






- ***Turbo-Alternators***
  - Six 1 MWe Loops
  - Potassium Rankine
- ***Shadow Shield***
  - Tungsten / LiH
  - ~1 rem/yr @ 100 m
- ***Dual Reactors***
  - Direct Boiling Potassium
  - 2 x 15 MWt
  - 4 yr life @ full power
  - UN/W-26Re Cermet fuel
- ***Artificial Gravity Enables:***
  - Buoyancy-assisted flow
  - Phase Separation
  - Earth Qualification





Hurdles: Power – Callisto Surface Nuclear Power System Concept

Power system concepts developed for previous Mars mission studies were adapted for conditions on Callisto (one of the Galilean satellites of Jupiter) since a high degree of commonality is possible and only a factor of two increase in power is required. The Callisto mission scenario is similar to the Mars mission scenario whereby cargo is pre-deployed and power and propellants are produced prior to crew arrival.

On the surface of Callisto, the required 250 kW of electrical power will be supplied by a 1-MW thermal nuclear reactor with a Brayton power converter. With shielding, this reactor will have a mass of 10,500 kg. The radiation it produces will require a 1 km separation from crew members. Transmission cabling will connect the reactor/converter system to the in-situ resource utilization plant and the surface habitat.

The elements of the power system include:

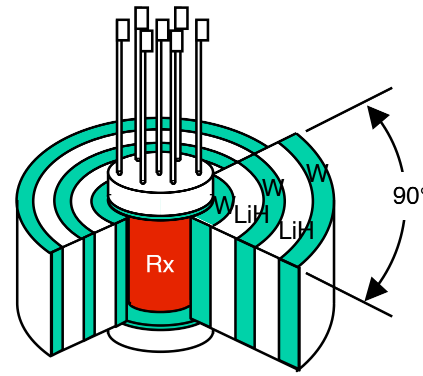
- A high temperature reactor that is either gas or liquid metal cooled, with an intermediate heat exchanger and instrument shielding for control drives
- Two Brayton power converters, each independent and sized for 100% power
  - 1,500° K turbine inlet temperature
  - 455° K compressor inlet temperature
  - 9% recuperator
- Radiators with pumped NaK coolant, Na or NaK heat pipes
- A 5,000 Vac alternator for 5,000 Vdc distribution
- Transmission cabling (for 1 km separation between the crew and reactor).

This power system concept study was primarily funded by the Revolutionary Aerospace Systems Concepts (RASC) program in support of the RASC FY02 Human Outer Planet Exploration study.

Callisto Surface Nuclear Power System Concept

Power System

- Nuclear reactor with Brayton power conversion
- 2x250 kWe
- 10,500 kg with shielding
- 1 km separation from crew systems
- Connected to in-situ resource utilization plant and surface habitat by cables



Power System/Reactor Mass Breakdown:

Power System Component	Mass (kg)
Reactor, Shield, HX (1 MWt)	1,600
Power Conversion (2x250kW units)	1,500
Heat Rejection (175 square meters)	500
PMAD (250 kWe, 5000 Vdc, 1 km)	400
Shielding for 1 km	6,500
Total	**10,500**


(Animation)

Hurdles: Power –
Brayton Engine Design Studies

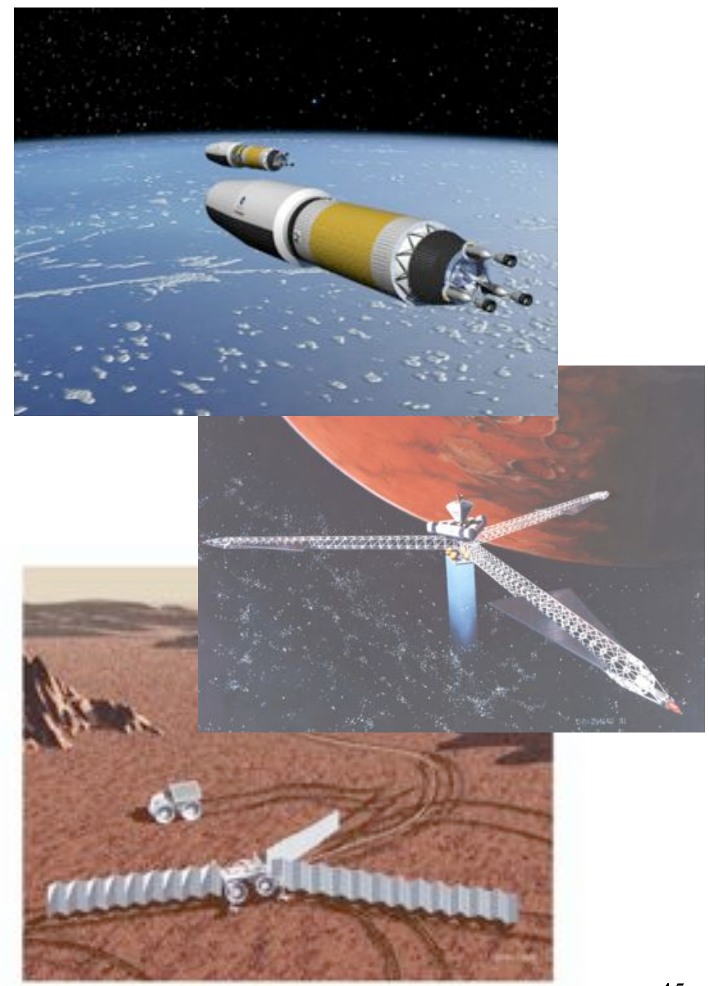
Brayton cycle heat engine technology is attractive because it has good efficiency; uses an inert, single phase working fluid; scales extremely well over a very wide range of power levels (from 100s of Watts up to megawatts); and is compact in size and integrates easily with different reactor cooling regimes. Past studies have shown Brayton engine applications may span a variety of mission architecture options – from powering rovers to providing electric propulsion – making it a highly versatile, multi-application technology.

Three contracts have been completed with three major space turbine manufacturers to evaluate the state-of-the-art in turbine technology for the design and manufacture of higher power, closed cycle Brayton engines. Contractors evaluated program schedule and cost against higher temperature materials and range of power output.

Brayton Engine Design Studies

Objective: To identify technology, schedule and cost for high output power systems.

- Three contracts completed for the design of a 25 kWe Brayton engine
  - Pratt & Whitney, Allison, and Boeing
- All concluded that a 4-5 year effort would be needed to design and build a 25-75 kWe class flight unit with current technology
- Advanced, higher temperature materials (>1300 K) require additional 2-4 years up-front development
- 25-75 kWe is the correct unit size for science nuclear electric propulsion, science and human bimodal nuclear thermal rocket, and Mars outpost and human missions



Hurdles: Power –
Power Technology Seed Investments

Investments to vastly improve the performance metrics of space power systems, e.g., Watts per m^2, kWe per kg, and Watt-hours per m^3, particularly for higher powered human missions, can have a significant impact in reducing mass and cost while enabling many classes of missions. The investments outlined here have contributed to advancing solar cell, array, and battery technologies; heat to electric energy conversion efficiencies; power management and distribution systems; and provided a first step to development of an autonomous control system.

High Voltage, Thin-Film Solar Arrays
This task is focused on resolving a significant issue affecting current NASA and commercial missions. On-orbit satellite failures have occurred due to the limited experience with high-voltage solar arrays in the space environment. Through this seed investment, techniques have been developed which have the potential to minimize future system failures.

Power Tile Technology
This activity is focused on the development of an advanced power system concept including solar cell, battery, and power management. This development activity also addresses thermal issues associated with loss of efficiency as temperature rises.

Power Beaming Technology
A new concept in wireless power transmission is being developed through the Space Solar Power program. In this concept, solar flux is trapped and directed into optical fibers which form a beam of energy.

2 kWe Brayton Testbed
NEXT is advancing Brayton power conversion technology through testing of an advanced electronic engine controller. This 2 kW flight configured Brayton testbed provides a tool for refining operations strategies, characterizing subsystem interfaces, and evaluating advanced component technologies.

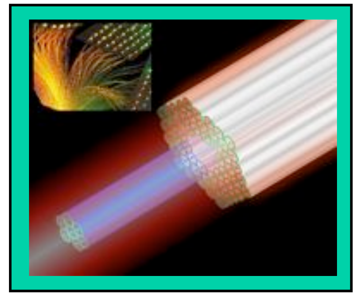
Hurdles: Power

Power Technology Seed Investments

High Voltage Thin Film Solar Arrays

- Thin-film solar arrays offer the potential of light weight, low cost, low stowed volume
- High voltage operation (~1,000 Volts) is critical to minimize mass and increase system performance

Power Beaming Technology



- A new concept in wireless power transmission utilizes solar flux trapped and directed into optical fibers which form a beam of energy
- Relevant to Space Science, Human Exploration and Development of Space, and commercial applications

Power Tile Technology

- The power tile is enabled by the synergistic combination of novel technologies: ultra-long life inorganic solid state Li batteries, thin-film nanowire based thermoelectric devices, and integrated power management.

2 kWe Brayton Testbed

- Initial startup after several years in storage
- Starting characterization testing
- Achieved 1,800 Watts output
- Operated up to 56,000 rpm
- Verified and evaluated new speed controller characteristics
- Operated over a range of turbine inlet temperatures

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