NASA/TM—2003-212598

PROJECT PROMETHEUS

Two-Phase Flow, Fluid Stability and Dynamics Workshop

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"…the navigation of interplanetary space depends for its solution on the problem of atomic disintegration…"
Robert H. Goddard, 1907

Match the Power System to the Destination

Main Asteroid Belt | **Trojan Asteroids** | **Centaur Minor Planets** | **Trans-Neptunian Objects** | **Kuiper Belt Objects / Comets**

Inner Planets | **Jupiter and Moons** | **Saturn and Moons** | **Uranus and Moons** | **Neptune and Moons** | **Pluto/Charon**

Solar Electric Confined 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 Outer Solar System Missions

–Targets with low Mass

– 500 W Class RTG

– <50 kg payload

–Delta II Launchers

Nuclear Electric for Large Flagship Missions to Outer Planets

–Large Targets

–100 kW Class Reactor

–>500 kg Payloads

–Delta IV Launch Vehicles

RTG for Surface Lander

Project Prometheus

Overview

- Safety is the absolute highest priority
- Key components of Project Prometheus
  - Radioisotope power systems development
  - Nuclear propulsion research
  - Jupiter Icy Moons Orbiter (JIMO) development
- Project Prometheus is in addition to the In-Space Propulsion Program already in the baseline

Project Prometheus will enable a new strategic approach to planetary exploration and is likely to play a key role in NASA's future

PROJECT PROMETHEUS

Objectives and Benefits

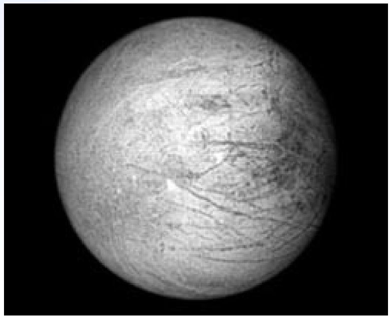
Revolutionize space exploration using space nuclear power and propulsion to enable reaching and studying natural laboratories of the Solar System, and to stimulate future generations of explorers and students.

Direct Benefits

- **Nuclear Power** (radioisotope) enables 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 Propulsion** enables unprecedented exploration of the Solar System, including locations that cannot be reached using chemical propulsion, and lays the foundation for potential 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, including next-generation nuclear power, **benefit** from the development of advanced technologies required for space nuclear propulsion.



Europa

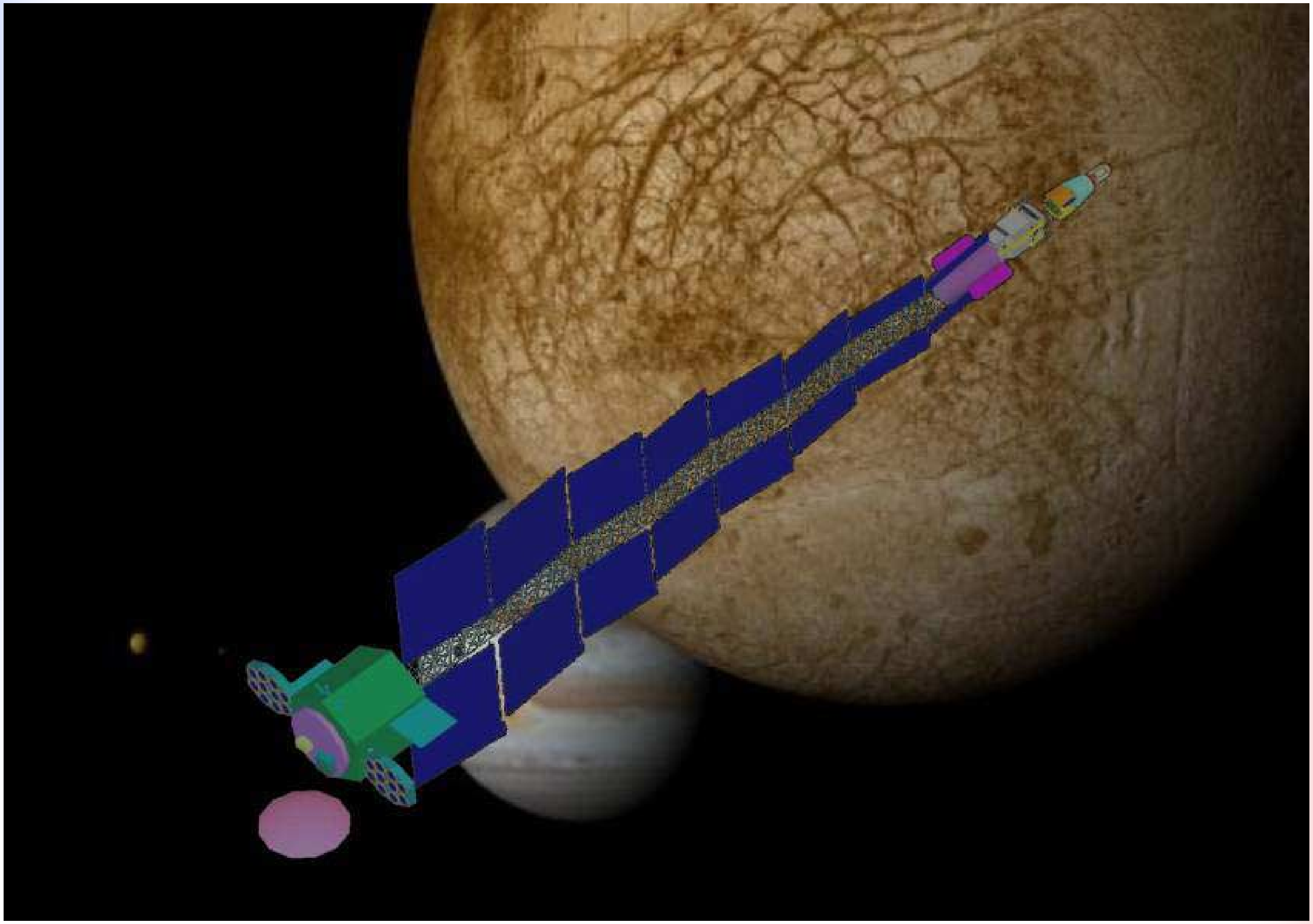
Neptune's Triton

Titan

NSP builds on NASA and DOE's history of safety in the use of nuclear power for space applications

Jupiter Icy Moons Orbiter

Conceptual Design, Animation



Jupiter Icy Moons Tour

Charting the Water Worlds of Jupiter

- Completely new level of exploration not possible with chemical propulsion orbiters:

  Full characterization of all three icy moons

- Interior structure and crustal thickness from geodesy, magnetics
  - Full range of remote sensing
    - Hi resolution imaging to study moons' history
    - IR and thermal spectral studies to search for organics, salts
  - Multi-frequency radar 'tomography' of icy crusts to depths of 30-40 km
    - Determine processes which 'bring the ocean to us'
    - Search for shallow liquid layers
- Mass and power margins enable complete investigation suite, orders of magnitude larger data return than single Europa Orbiter

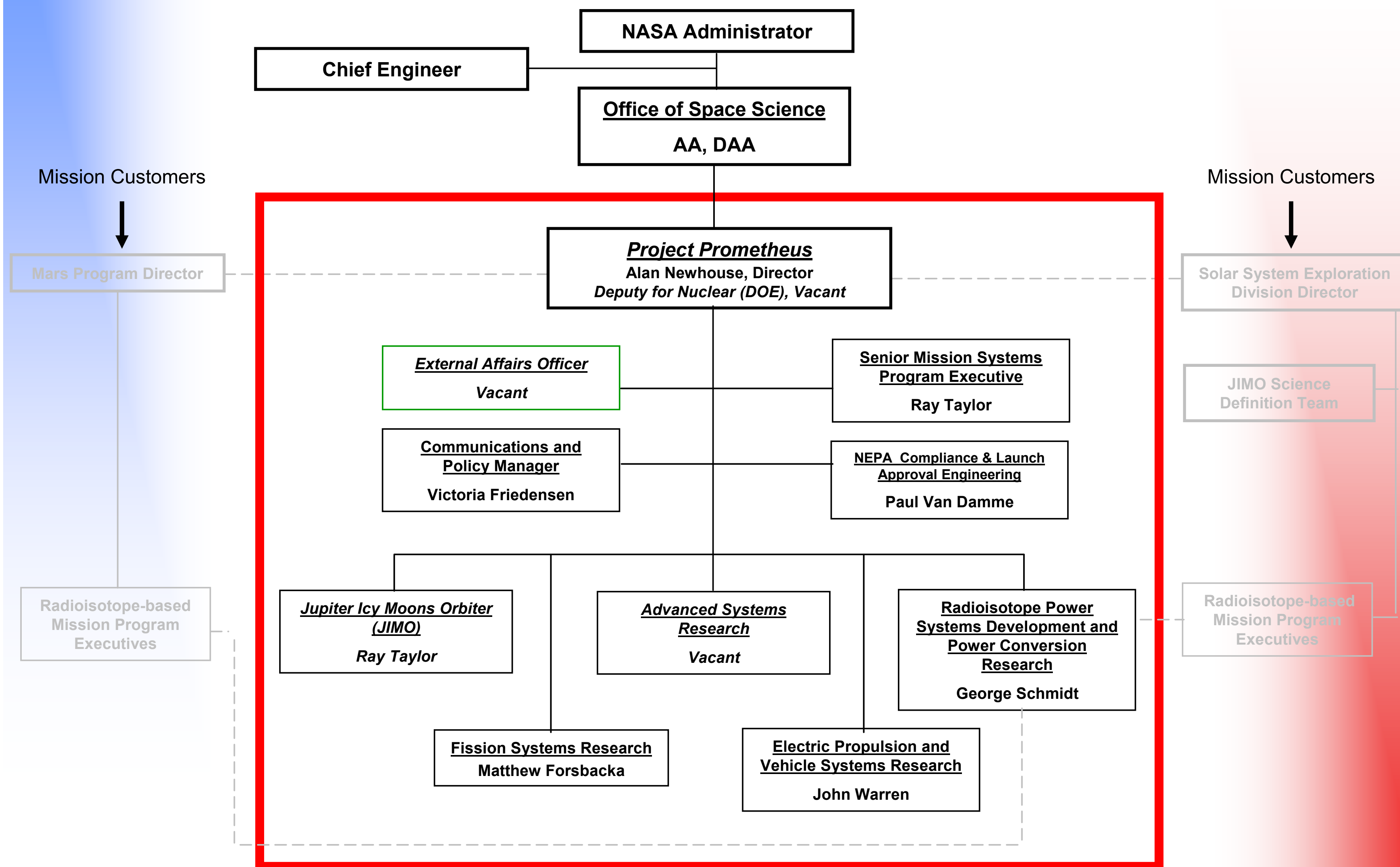
Jupiter Icy Moons Tour
Building for the Future

<u>Building for the Future</u>

- Orbital reconnaissance of all three icy moons sets the stage for next phase of exploration at Jupiter
  - Surface chemical and organic exploration
  - Probe to explore sub-surface
- Demonstrates capabilities to open the rest of the outer solar system to detailed exploration
  - Titan atmosphere and surface exploration
  - Neptune Orbiter, Triton exploration
  - Kuiper Belt tour
- Advances the ability to address multiple NRC Decadal Survey priorities with single missions

PROJECT PROMETHEUS

NASA Headquarters Organization



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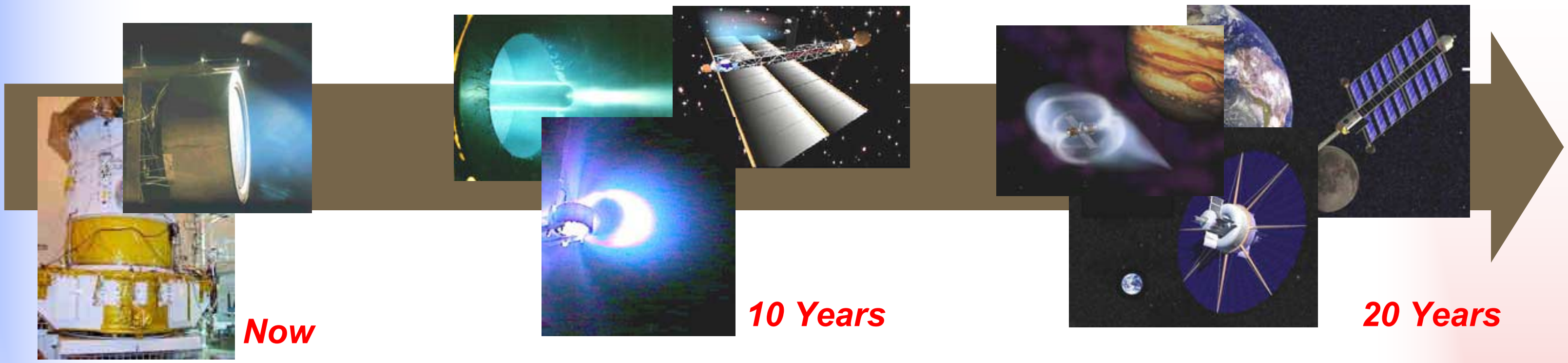
Many Technologies Extend to a Broad Range of Future Space Exploration Missions

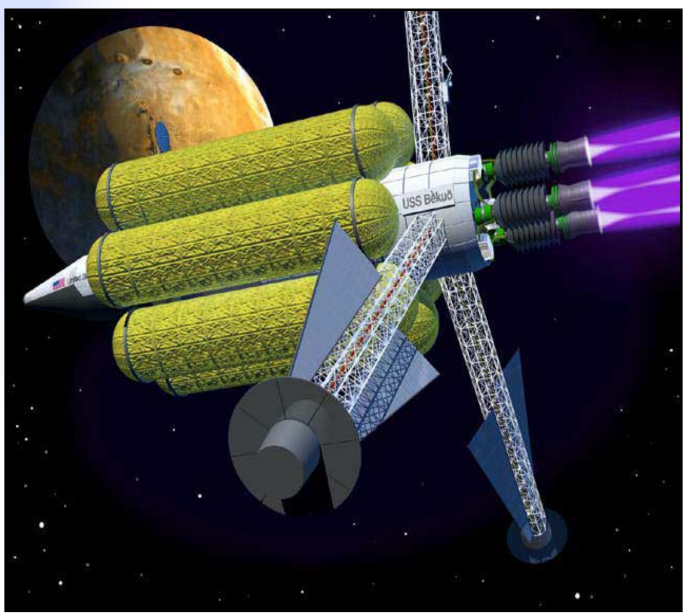


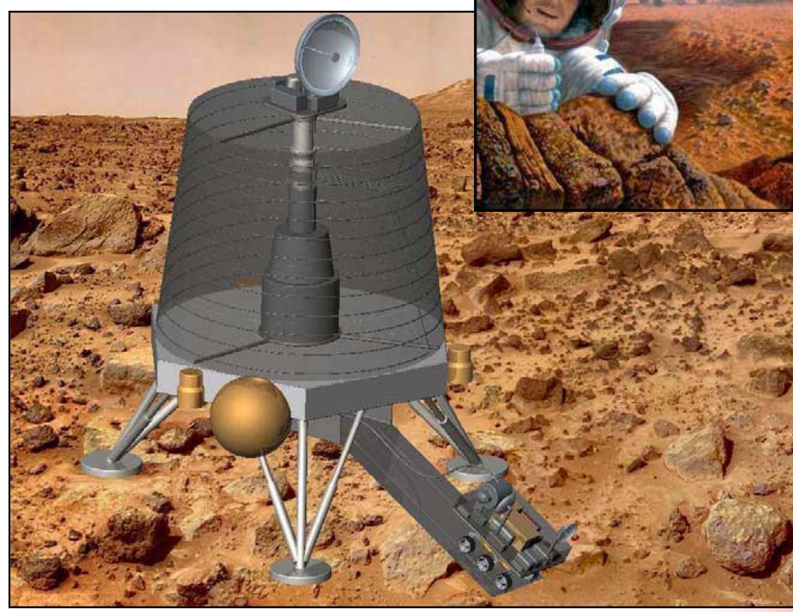
- **Many of the technology, fabrication, and ground-based capacities developed for the first space nuclear propulsion mission have direct application to follow-on missions**
  - Nuclear fuel and clad & fabrication capacity
  - Nuclear reactor design, analysis, and qualification methodology and software
  - 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

Potential Support to Human Space Exploration

- **Nuclear power and propulsion are key enablers of expanded human exploration**
  - Enables human exploration beyond earth orbit
  - Provides high power for human protection against charged solar particles
  - Provides abundant power at destination
  - Enables complex, long duration missions
- **Nuclear surface power is essential for extended reconnaissance of the Mars surface**
  - Long-range surface and sub-surface exploration
  - Human habitat and life support
  - *In-situ* manufacturing of consumables
  - *In-situ* propellant production



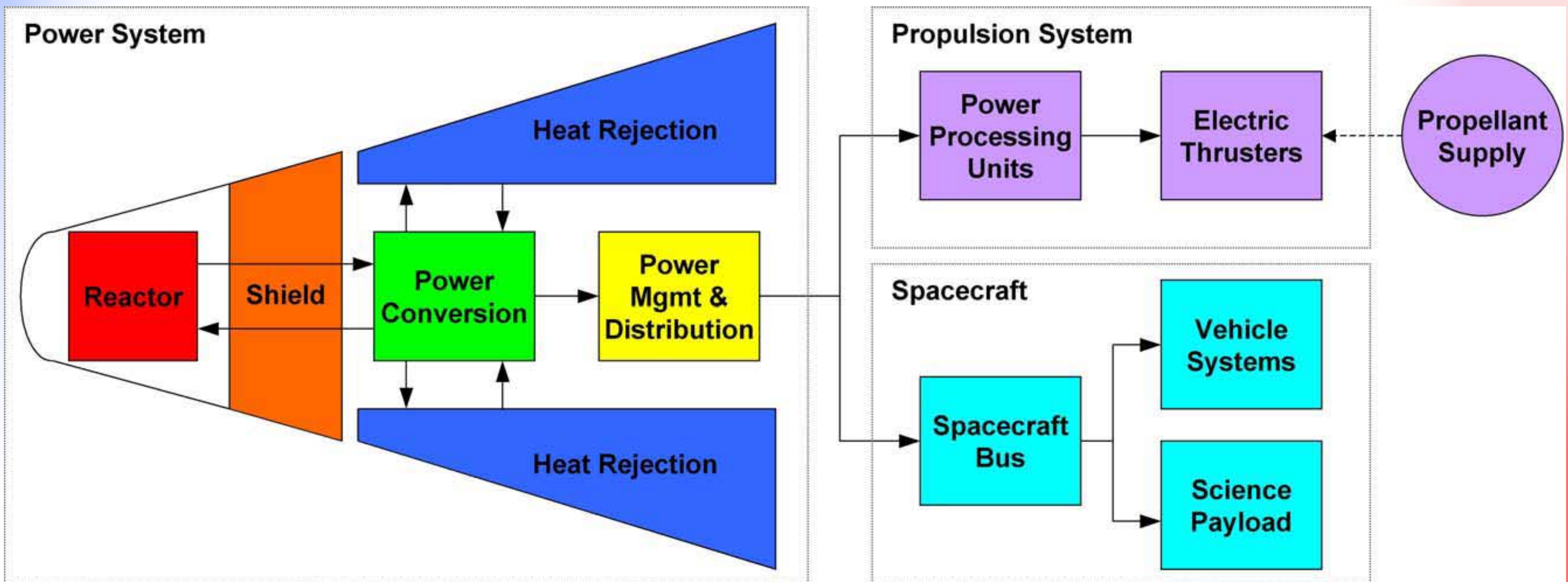


Conclusion

- **Project Prometheus will enable a new paradigm in the scientific exploration of the Solar System**
- **The proposed JIMO mission will start a new generation of missions characterized by more maneuverability, flexibility, power and lifetime**
- **Project Prometheus organization is established at NASA Headquarters:**
  - **Organization established to carry out development of JIMO, nuclear power (radioisotope), and nuclear propulsion research**
  - **Completed broad technology and national capacity assessments to inform decision making on planning and technology development**
    - NASA HQ Request for Information on nuclear propulsion
    - DOE/NASA evaluation of space reactor power system concepts
    - NASA / DOD workshop on solar power generation and power conversion
  - **Awarded five NRA's for nuclear propulsion research**
  - **Radioisotope power systems in development, and Plutonium-238 being purchased from Russia**
- **Formulated <u>science driven</u> near-term and long-term plan for the <u>safe</u> utilization of nuclear propulsion based missions**
- **Completed preliminary studies (Pre-Phase A) of JIMO and other missions**
- **Initiated JIMO Phase A studies by Contractors and NASA**

Microgravity Related Fluid Flow Topics

- Reactor
- Power Conversion
- Heat Rejection
- Propellant Management



Power Conversion Top-Level Requirements

- **Near-term (JIMO, other robotic missions):**
  - Up to 100 kWe to Electric Propulsion System (EPS)
  - 15-year operational lifetimes (10-yrs at 100% power, 5-yrs at 20% power)
  - Subsystem mass to enable achievement of system specific mass (alpha) ≤ 50 kg/kWe
- **Mid-term: (lower alpha, higher reliability, "2^{nd} generation JIMO"):**
  - 50 to 500 kWe to EPS
  - 15-year operational lifetimes (10-yrs at 100% power, 5-yrs at 20% power)
  - Subsystem mass to enable achievement of system specific mass (alpha) ≤ 30 kg/kWe
- **Far-term (potential for human mission applications):**
  - 2 to 10 MWe to EPS
  - 15-year operational lifetimes
  - Subsystem mass to enable achievement of system specific mass (alpha) ≤ 10 kg/kWe
  - Continued improvement of 50 – 500 kWe systems

(sample return, surface outposts & rovers, ISRU, etc.)

Power Conversion Options

X O

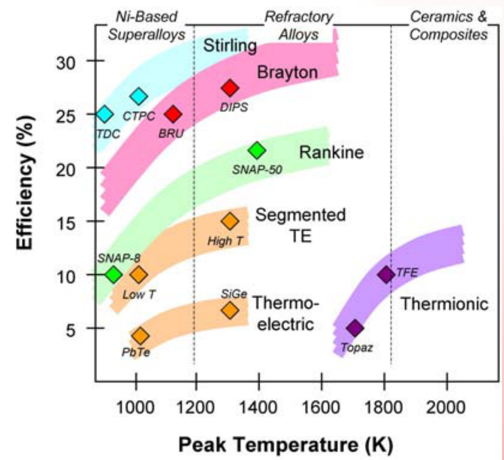
X

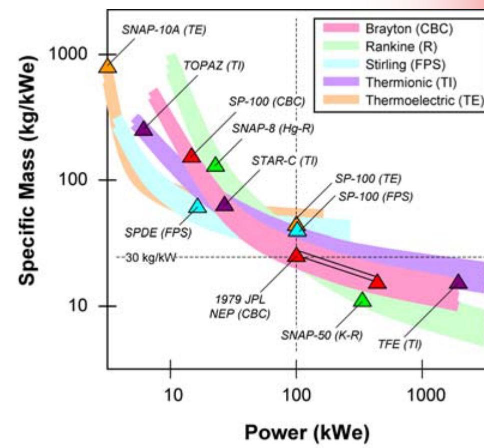
O

X O

X JIMO Trade-Space
O Code S NRA Award

- Closed Brayton Cycle
  - Heat engine with inert gas in turbo-alternator
  - ***Mature Technology with High Efficiency and Growth Potential***
- Free-Piston Stirling
  - Heat engine with reciprocating piston & linear alternator
  - ***High Efficiency & Scales Well to Low Power***
- Liquid Metal Rankine
  - Heat engine with two-phase fluid in turbo-alternator
  - ***Potential for Low Mass at High Power, has Technical Issues & no infrastructure***
- Thermoelectric
  - Electrical potential produced by dissimilar materials exposed to temperature difference
  - ***Flight Proven with Long Life, but Low Efficiency***
- Thermionic
  - Heated emitter passes electrons to cooled collector across very small Cs-filled gap
  - ***Extensive Database, but Life Issues Remain***



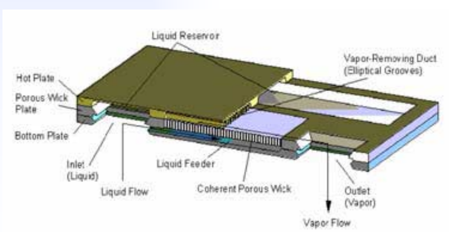


Heat Rejection

ISS Radiator

Carbon-carbon
Heat Pipe Radiator

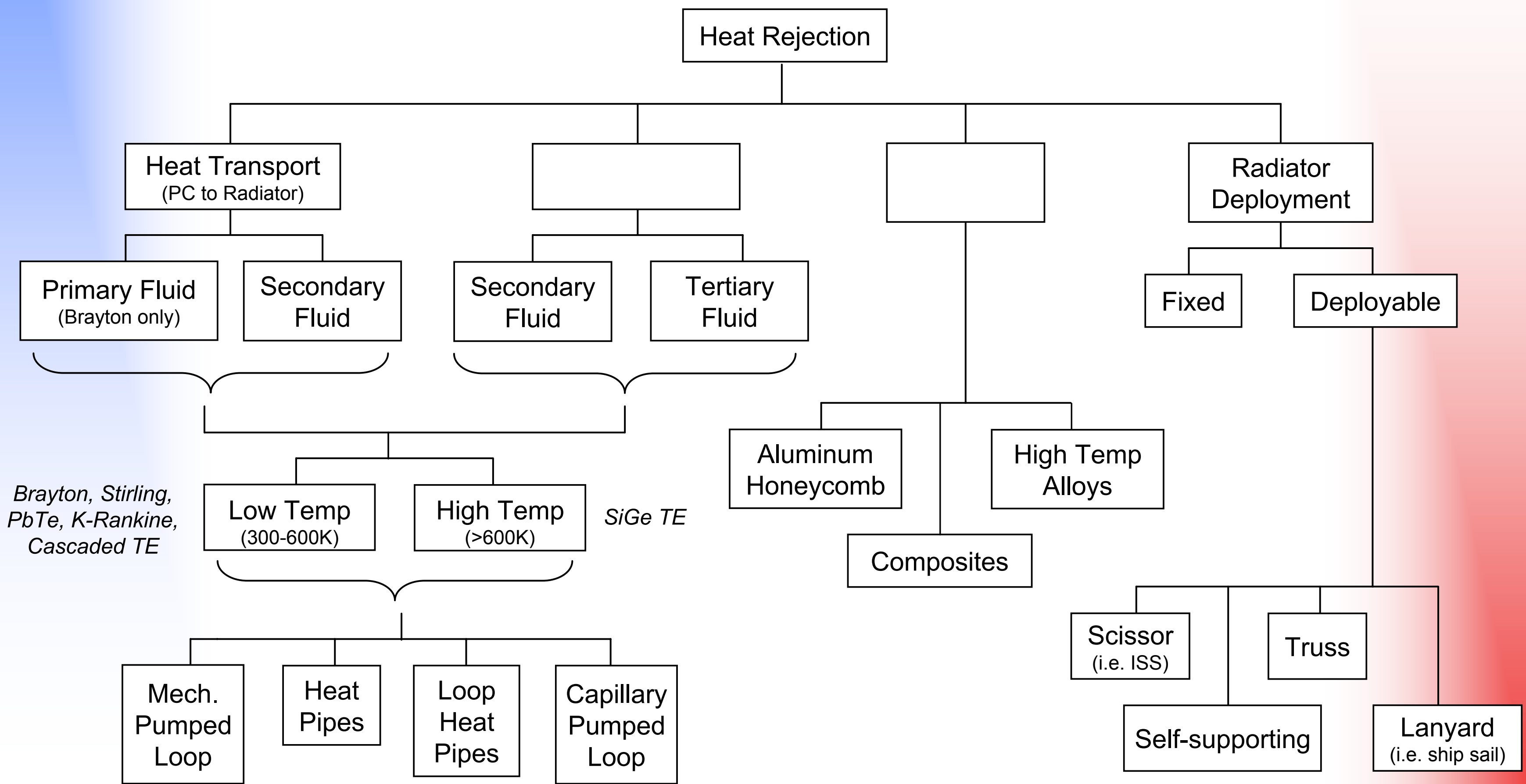
Annealed Pyrolytic Graphite
Space Radiator



Integrated Loop Heat Pipe
Evaporator

- Heat Transport
  - Mechanical Pumped Loop
  - Conventional Heat Pipes
  - Loop Heat Pipes, Capillary Pumped Loops
- Fluid Selection
  - Power Conversion Compatibility
  - Containment Material Compatibility
  - Freeze Tolerance
- Lightweight Radiator Surfaces
  - Composite Materials
  - Heat Distribution
  - Long Life, High Emissivity Coatings
  - Radiation Tolerance (Bonds, Coatings)
- Fault Tolerance/Survivability
  - Micrometeoroid Protection
- Deployment Mechanisms

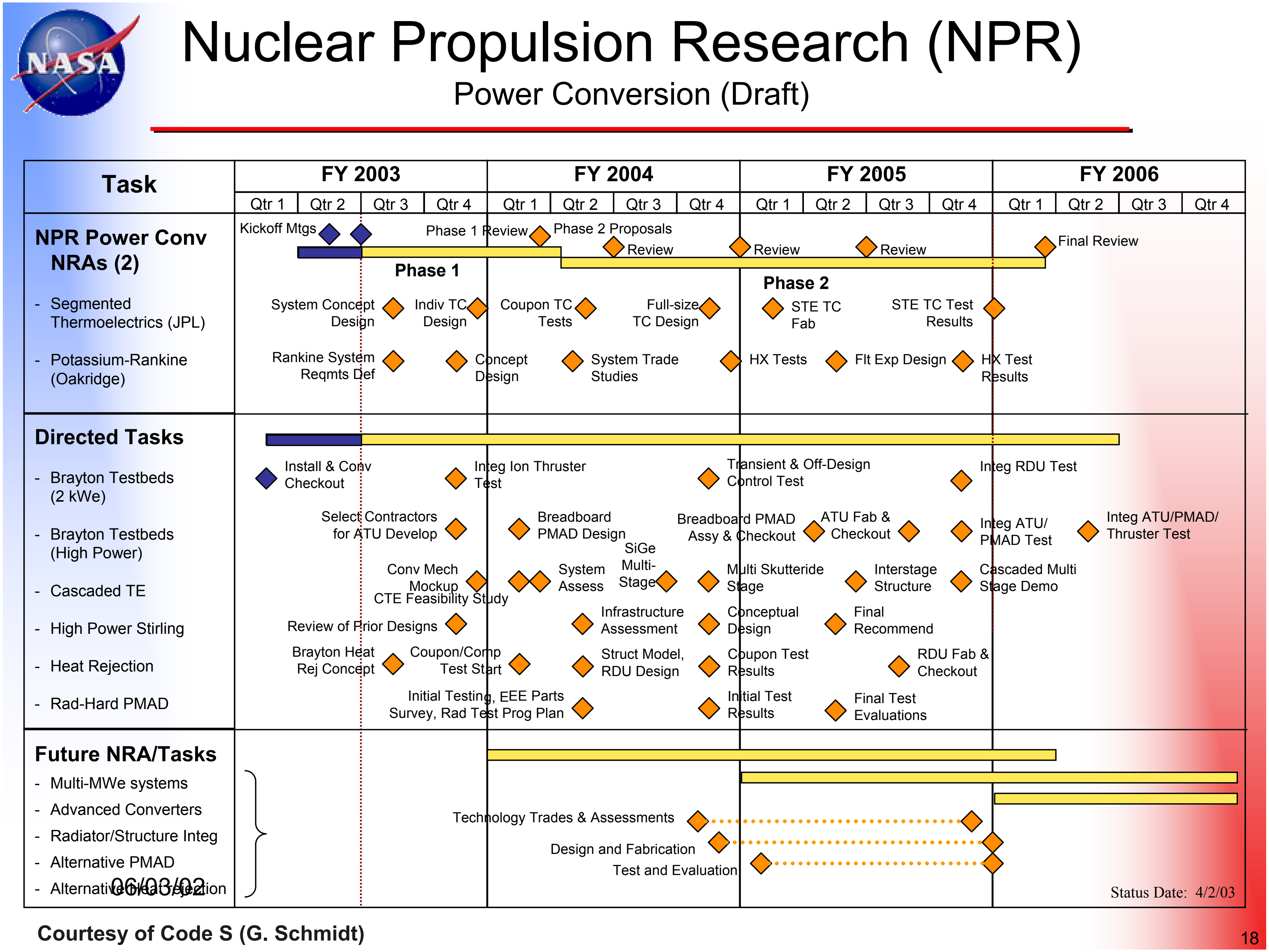
Heat Rejection Trade Tree



Heat Rejection Technology for Advanced Systems

- **Critical Needs:**
  - Mass Reduction with Lightweight Materials
  - Long Life Component Development (Pumps, Mechanisms, Coatings, etc.)
  - Power Conversion Compatibility and Integrated Thermal Testing

- **Current Funded Activities:**
  - Heat Rejection Systems Modeling and Development (GRC/JPL)
    - Heat Rejection Concepts
    - Materials and Fluids Studies
    - Thermal and Structural Design Models
    - Design, Fabricate, and Test Radiator Demonstration Unit (RDU) for 2 kWe Brayton
  - SBIRs (GRC)
    - Carbon-Carbon Radiators (Allcomp)
    - Annealed Pyrolitic Graphite Radiator (K-Technology)
    - Pulsed Thermal Loops (TDA)


Nuclear Propulsion Research (NPR)
Power Conversion (Draft)
Task
FY 2003
FY 2004
FY 2005
FY 2006
Qtr 1
Qtr 2
Qtr 3
Qtr 4
NPR Power Conv NRAs (2)
- Segmented Thermoelectrics (JPL)
- Potassium-Rankine (Oakridge)
Kickoff Mtgs
Phase 1 Review
Phase 2 Proposals
Review
Review
Review
Final Review
Phase 1
Phase 2
System Concept Design
Indiv TC Design
Coupon TC Tests
Full-size TC Design
STE TC Fab
STE TC Test Results
Rankine System Reqmts Def
Concept Design
System Trade Studies
HX Tests
Flt Exp Design
HX Test Results
Directed Tasks
- Brayton Testbeds (2 kWe)
- Brayton Testbeds (High Power)
- Cascaded TE
- High Power Stirling
- Heat Rejection
- Rad-Hard PMAD
Install & Conv Checkout
Integ Ion Thruster Test
Transient & Off-Design Control Test
Integ RDU Test
Select Contractors for ATU Develop
Breadboard PMAD Design
Breadboard PMAD Assy & Checkout
ATU Fab & Checkout
Integ ATU/ PMAD Test
Integ ATU/PMAD/ Thruster Test
Conv Mech Mockup
CTE Feasibility Study
System Assess
SiGe Multi-Stage
Multi Skutteride Stage
Interstage Structure
Cascaded Multi Stage Demo
Review of Prior Designs
Infrastructure Assessment
Conceptual Design
Final Recommend
Brayton Heat Rej Concept
Coupon/Comp Test Start
Struct Model, RDU Design
Coupon Test Results
RDU Fab & Checkout
Initial Testing, EEE Parts Survey, Rad Test Prog Plan
Initial Test Results
Final Test Evaluations
Future NRA/Tasks
- Multi-MWe systems
- Advanced Converters
- Radiator/Structure Integ
- Alternative PMAD
- Alternative heat rejection
Technology Trades & Assessments
Design and Fabrication
Test and Evaluation
06/03/02
Status Date: 4/2/03
Courtesy of Code S (G. Schmidt)
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Summary

- **Potential gravity-sensitive systems & components**
  – Liquid metal cooled reactor startup
  – Potassium-Rankine Conversion
    - Boiler
    - Liquid/vapor separator
    - Condenser
  – Heat Rejection
    - Startup and restart of heatpipes, loop heatpipes, capillary pumped loops
  – Propellant management

- **In-house, Contractor and competed research tasks will address relevant issues**