The 2014 Nuclear Power Assessment Study (NPAS)

MISSION STUDY RESULTS INVESTIGATING ADVANCED RADIOISOTOPE POWER SYSTEMS AND FISSION POWER SYSTEMS

February 22, 2015

Young H. Lee¹, Brian K. Bairstow¹, Robert Cataldo², Richard Anderson³, Steve Oleson², and Steve Johnson⁴

¹Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena, CA 91009
²Glenn Research Center, 21000 Brookpark Rd, Cleveland, OH 44135
³Applied Physics Laboratory, 11100 Johns Hopkins Rd, Laurel, MD 20723
⁴Idaho National Laboratory, 1955 Fremont Ave, Idaho Falls, ID 83415
818-354-1326, Young.H.Lee@jpl.nasa.gov
Outline

• Mission Study Team’s Methodology
• Mission Study Objectives for New Power System
• Design Reference Missions (DRM)
• DRM Study Findings
• DRM ROM Mission Cost
• ROM Mission Cost Observations
• Instrument Sensitivity Assessment
• Mission Class Assessment
• Transition Point Analysis
• Mission Study Team Roaster
• Study member list from Collaborative Engineering Centers
Mission Study Team’s Methodology

- Formulate the Mission Study Team with representation from APL, DOE, GRC, GSFC, INL, JPL, JSC, KSC and SNL
- Plan mission studies with mission design centers for selected mission concepts with new power systems
- Develop DRM Study Ground Rules and Objectives
  - Do not revisit science goals and science payload
  - Do not make changes to launch vehicle or mission design
- Identify a set questions that need to be answered during mission design sessions
- Obtain RPS and FPS System Descriptions from System Team
- Assess identified DOE Activities for Nuclear-enabled Launch
  - Fueling, Acceptance testing, Transportation, KSC Nuclear Safety, KSC Initial Processing and KSC Ground/Launch Support
- Assess identified activities and concerns with new RPS and FPS
  - KSC ATLO and LV Integration, Nuclear Launch Safety and Security, Radiological Contingency Planning, Launch Approval Engineering Activities
- Generate mission ROM costs including each power system considered and its nuclear launch costs
- Perform applicability/commonality assessment to Science mission class (Discovery, New Frontier and Flagship) and HEO Mission Class
- Perform analysis on instrument sensitivities to new RPS and FPS environment
- Identify transition point of RPS to FPS for SMD missions
Mission Study Objectives for New Power Systems

- Perform Accommodation study
  - Use the point designs to compare and contrast nuclear power system capabilities
  - Investigate new power modes with higher power availability
- Understand potential future mission needs for Radioisotope Power Systems (RPS) and/or Fission Power Systems (FPS).
  - Consider power system efficiency and mission reliability requirements
- Understand the new nuclear power system’s impact to the Design Reference Missions (DRMs) from the end-to-end perspectives.
- Produce findings that could be translated into mission requirements:
  - System Mass
  - EOM Power
  - Number of Systems to be Integrated
  - Physical Dimensions
  - Thermal Management
  - Instrument Sensitivity to Radiation, Thermal, Vibration and EMI
  - Total Induced Dose (TID) Limitations for Avionics and Instruments
    » Radiation vaults/spot shielding, e.g.
  - ATLO/ConOps Considerations
    » Non-conventional S/C integration requirements, if any
    » Unique mission phase environmental and critical event requirements
- Generate ROM mission costs including each power system and ATLO options
- Identify applicability/commonality to Discovery, New Frontier and HEO Mission Class
- Perform analysis on instrument sensitivities to new RPS and FPS environment
- Identify transition point of RPS to FPS for SMD missions
Selected Design Reference Missions (DRM)

- Mission study DRM selection criteria
  - Enabled (or significantly enhanced) by nuclear power
  - Selected from the Planetary Science Decadal Survey Mission
  - Have good technical basis and science rationale with multi-faceted mission architectures
  - Have mission concept cost estimate exceeding cost cap since deferred missions subject to less perceived “favoritism” by science community

- Titan Saturn System Mission (TSSM) 2008 Concept
  - Complex mission with mission cost challenges
  - Total power 540 W_e EOM using 100 W_e ASRGs
  - RPS Study: JPL Team X Study Team
  - FPS Study: GRC Compass Team

- Uranus Orbiter and Probe (UOP) 2010 Decadal Survey Concept
  - 3rd ranked Flagship Mission concept
  - Total power 370 W_e EOM using 100 W_e ASRGs
  - RPS Study: APL ACE Lab
  - FPS Study: GRC Compass Team
DRM Study Findings – TSSM RPS

- Studied at 1 kW\textsubscript{e} power level to explore applicability of high power
  - **2008 Baseline**: 4 operating + 1 spare 2-GPHS ASRG (total power 540 W\textsubscript{e} EOM)
  - 2014 Option A: 3 operating + 1 spare 6-GPHS SRG (300 W\textsubscript{e} EOM each)
  - 2014 Option B: 3 operating + 0 spare 16-GPHS ARTG (350 W\textsubscript{e} EOM each)

- Closed mission design with dry mass increase of
  - 4% (Option A)
  - 1% (Option B)
  - Also looked at the baseline TSSM design using the most recent estimates for ASRG mass and power - 5% dry mass increase

- Made use of additional power
  - Decreased antenna from 4 meter to 2.25 meter, and increased TWTA from 35 W\textsubscript{e} RF to 140 W\textsubscript{e} RF to maintain data rate
  - Decreased battery size
  - Option A adopted a more robust thermal design
  - Option B was able to heat the tanks passively with radiated heat from the ARTGs
DRM Study Findings – UOP RPS

• Mission was extremely mass constrained, and exceeding the original mass would require revisit of mission design. The mission was studied at the original power level.

  • **2010 Baseline**: 3 operating + 0 spare 2-GPHS ASRG (total power $370 \ W_e$ EOM)
  • Option A: 2 operating + 1 spare 4-GPHS SRG (196 $W_e$ EOM each)
  • Option B: 2 operating + 0 spare 4-GPHS SRG (196 $W_e$ EOM each)
  • Option C: 2 operating + 0 spare 9-GPHS ARTG (189 $W_e$ EOM each)

• Option B fits into original mass constraint without other major spacecraft changes
  • Options A and C close to original mass constraint with a change to a 1.8 meter antenna (down from 2.5 meter) and downlinking to 34 meter DSN arrays
  • All options lower mass than baseline UOP design using the most recent estimates for ASRG mass and power

• UOP RPS findings could be useful in assessing power system applicability for New Frontiers Class mission due to its power requirements
DRM Study Findings – TSSM FPS

• Closed mission design on Atlas V 551 (baseline launch vehicle)
  • Launches at negative $C_3$ and needs 2-3 years of additional cruise time and increase from 15 kW$_e$ SEP system to 19 kW$_e$ SEP system
  • Dry mass increases by 30% (SRG FPS) to 55% (TE FPS) over baseline design

• Could return nearly double data
  • Double duty cycle of instruments, running more of them simultaneously during Titan orbit – no more science campaign necessary
  • Decreased antenna from 4 meter to 2.25 meter, and increased TWTA from 35 W$_e$ RF to 250 W$_e$ RF to increase data rate.

• Limited reactor operation duration
  • Can operate spacecraft off of SEP solar arrays,
  • Option to start reactor after Earth flyby about 5 years after launch
  • Shorter reactor operation time decreases radiation dose from FPS
DRM Study Findings – UOP FPS

• UOP FPS study was done via trajectory analysis and parametric models
  • Did not generate mission ROM cost

• Mission was very mass constrained
  • Replaced SEP design with NEP design, using 8+ kW<sub>e</sub> FPS

• No trajectories worked with constraints of Delta IV H, no Jupiter flybys and a 13 year max mission duration
  • *Must utilize Earth flyby or SLS to close mission design*

• Earth flyby at a 2,000 km distance could reduce required SEP power by half, down to 8.5 kW<sub>e</sub> reactor
  – Assumed a first-of-a-kind FPS would not use an Earth flyby with an operated reactor (2 years in this case) due to impact concerns.
  – Assumed Earth flybys of a subsequent flight-proven FPS would be assessed based on information available at that time.
Summary on DRM Studies Findings (1)

• TSSM studies explored utility of increasing power from 500 $W_e$ to 1,000 $W_e$
  • Able to simplify spacecraft design by replacing the 4 meter antenna with heavy gimbal and strict pointing requirements
  • Able to increase instrument duty cycles and data return
  • May enable different payload choices such as high power active instruments
    • Large RADAR or flash LIDARs for mapping and hazard avoidance
    • Complex instruments such as mass spectrometers

• UOP RPS study explored new RPS as a replacement for ASRGs at 300-400 $W_e$ power level
  • New RPS able to improve on ASRG performance, particularly compared to the 2014 ASRG mass and power estimates.
Summary on DRM Studies Findings (2)

• Power level sizing
  • TSSM study selected the 6-GPHS SRG and 16-GPHS ARTG to achieve a 1,000 W_e power level with a maximum of 4 units (including redundant units) to avoid configuration and integration issues.
    • TSSM could operate with 4-GPHS SRG and 9-GPHS ARTG by adding two additional units.
      • This would have minor mass and power impacts, but significant configuration and integration impacts.
  • UOP study selected the 4-GPHS SRG and 9-GPHS ARTG to achieve 370 W_e power with tight mass and configuration constraints.

• Redundancy policy a major driver
  • TSSM study SRG option included a redundant unit, which drove up mass compared to ARTG option.
  • UOP study looked at SRG options with and without redundant unit, and there was a significant mass impact.
DRM ROM Cost Generation Approach – Mission Concepts

• Mission studies conducted in parallel with system and nuclear mission launch costing exercises
  • Mission costs that were produced during design sessions exclude power system cost, nuclear-related ATLO costs, and launch services using NASA WBS structure
    • Used FY 2015 dollars
    • Used provided values for payload costs
    • Ignored any technology related items
    • Did not include ESA in-situ element costs
  • Focused on flight system costs to accommodate new power system
  • Inflated 2008 TSSM Study costs to FY15 for comparison purposes
  • Used 2008 cost estimates for 2008 ASRG Power System + ATLO + Nuclear Launch Cost, which do not include fuel costs or other DOE costs

• No total mission cost estimate for UOP FPS was produced
  • UOP FPS study focused on trajectory design and preliminary spacecraft sizing
Nuclear Mission Power System and Launch ROM Cost Generation Approach

• Key Inputs
  • Notional S/C configuration produced from DRM studies using System Team’s nuclear power system characteristics
  • ATLO Team’s nuclear power system integration options at KSC
  • DOE costs leveraged off of the 2011 MSL mission
  • NASA Work Breakdown Structure (WBS) was used to categorize the mission costs
  • Security costs were a bottoms-up estimate using DOE-INL labor rates and equipment costs. Any physical upgrades were leveraged off of recent DOE complex values.

• Assumptions
  – Normalized all costs to FY15
  – Used the mid-range number when ranges of cost data was provided by KSC
**TSSM 2014 RPS and FPS Study – Nuclear Mission Launch Cost Analysis Findings**

($FY15, $M)$

<table>
<thead>
<tr>
<th>Description</th>
<th>RPS (1 Unit)</th>
<th>RPS (1 kW&lt;sub&gt;e&lt;/sub&gt;)</th>
<th>FPS (1 kW&lt;sub&gt;e&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Unit</td>
<td>Existing Facility</td>
<td>TSSM</td>
</tr>
<tr>
<td></td>
<td>1 6-GPHS</td>
<td>1 16-GPHS ARTG</td>
<td>4 6-GPHS Stirling</td>
</tr>
<tr>
<td>A.0 NASA Management and Integration Costs</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>B.0 DOE Nuclear Powered Mission Support Costs</td>
<td>123</td>
<td>128</td>
<td>303</td>
</tr>
<tr>
<td>B.1 PuO&lt;sub&gt;2&lt;/sub&gt; Costs for RPS and HEU Costs for FPS</td>
<td>33</td>
<td>89</td>
<td>133</td>
</tr>
<tr>
<td>C.0 DOE/NNSA Security Costs</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>D.0 NASA Launch Approval Costs</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>E.0 NASA Launch Service Provider Costs</td>
<td>33</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>210</strong></td>
<td><strong>270</strong></td>
<td><strong>490</strong></td>
</tr>
</tbody>
</table>

- Included power system cost using FY 15 $M dollars
- Expect minimal change to cost for NASA LAE, LSP costs for FPS compared to RPS
- FPS costs for Security are significant (~$70M)
- One RPS-type discriminator is cost to fuel
## TSSM 2014 Study –
### Total Nuclear Mission Cost Analysis Findings

($FY15, $M)

<table>
<thead>
<tr>
<th>RPS</th>
<th>2008 ASRG</th>
<th>SRG (3+1) x 6-GPHS</th>
<th>ARTG 3 x 16-GPHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOM Power ($W_e$)</td>
<td>541</td>
<td>891</td>
<td>1,041</td>
</tr>
<tr>
<td>Mission Cost w/o nuclear components</td>
<td>2,499*</td>
<td>2,436</td>
<td>2,411</td>
</tr>
<tr>
<td>Power System + ATLO + Nuclear Launch Cost**</td>
<td>215***</td>
<td>490</td>
<td>590</td>
</tr>
<tr>
<td><strong>Total Mission Cost w/o Launch Vehicle</strong></td>
<td>2,714</td>
<td>2,926</td>
<td>3,001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FPS</th>
<th>Stirling</th>
<th>TE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stirling</td>
<td>1,015</td>
<td>1,015</td>
</tr>
<tr>
<td>TE</td>
<td>2,634</td>
<td>2,661</td>
</tr>
</tbody>
</table>

### Notes:
- *: 2008 TSSM Study costs inflated to FY 15 using 3% rate.
- **: Power System + ATLO + Nuclear Launch Cost is normalized using FY15 (Used the mid-range number when ranges of cost data was provided by KSC)
- ***: Uses 2008 cost estimates for Power System + ATLO + Nuclear Launch Cost – Launch Vehicle Cost, which do not include fuel costs or other DOE costs.
ROM Mission Cost Observations

- Total nuclear mission launch costs appear to be insensitive to nuclear power system type, once power system technology and infrastructure development is completed.

- The required mission power level may drive total mission costs for RPS missions that would need power levels above ~1 kW$_e$.

- Total mission cost comparisons between the TE and Stirling-based RPS missions did not reveal any significant cost deltas.

- One of the main discriminators for RPS options is the cost to fuel the generators.

- Total increases in non-nuclear mission cost (~$ 200 million) were found using FPS instead of RPS at the 1-kW$_e$ power level.

- Expect minimal change to the cost profile for NASA Launch Approval Engineering and Launch Services Program costs for FPS compared to RPS.

- Security costs for FPS are significant (~$ 70 million) compared to RPS.
Instrument Sensitivity Assessment

• Objectives
  • Assess the new RPS/FPS impacts on mission instruments
  • Assess the FPS induced environments to the mission instruments to ensure they are not impacting the measurement requirements

• Assumptions
  • Used 1 kW<sub>e</sub> FPS designs from System Team for TSSM and UOP Missions
    • 25 krad and 1e11 neutrons at 10 meter dose plane over 15 years
    • TSSM took advantage of longer separation distance and shorter operating time
    • Assuming UOP FPS mission has standard 10 meter dose plane and 15 year operation
    • Assuming vibration from Stirling FPS convertors similar to equivalent quantity of ASRGs
    • Assuming EMI from Stirling FPS convertors similar to equivalent quantity of ASRGs

• Focusing on specific TSSM and UOP missions for our analysis
  • Developing estimated requirements for validation for TSSM and UOP measurements
Instrument Impacts Summary

- Radiation and neutron impacts must be taken into account, in particular for instruments with optical detectors and instruments with high-voltage electronics
  - Dosage from standard FPS design is 25 krad
  - Total dose can be mitigated with shield design, boom length, reactor operation duration, spot shielding, and instrument robustness

- Thermal impact can generally be mitigated with shading and pointing

- Jitter is probably minor due to boom length, but must be considered during spacecraft design

- EMI impact on instrument is probably minor due to boom length

- Effect of FPS thermal and EMI output on spacecraft environment needs further study

- Do not anticipate significant changes in instrument impacts with new SRG and ARTG compared to ASRG and MMRTG
Considered Mission Class for Assessment

• **Discovery** Mission Class
  – Extremely cost sensitive especially for outer planet destinations, and needs RPS to be GFE.
  – Power needs from DSMCE ("Discovery and Scout Mission Capabilities Expansion" – 2007) are in range from $130 \text{ W}_\text{e}$ to $267 \text{ W}_\text{e}$ EOM.

• **New Frontiers** Mission Class
  – Cost sensitive, RPS cost of $50M or more is difficult to support.
  – Power needs from Decadal are in range from $170 \text{ W}_\text{e}$ to $750 \text{ W}_\text{e}$ EOM.

• **Flagship** missions
  – Less cost sensitive and need more power.
  – Most proposed mission power needs are in range from $150 \text{ W}_\text{e}$ to $1,000 \text{ W}_\text{e}$ EOM.
Some Mission Perspectives on RPS System Size

• Mission team assessed Discovery, DSMCE, and Decadal Survey Study for mission power level requirements.

• Launch vehicle integration of RPS units was assessed during our ATLO investigations:
  – The LV fairing is very likely limited to no more than 4 access doors and 2-3 would be preferred due to VIF accommodations.
  – Increasing the number of units mounted to the S/C increases installation complexity as well as accommodating mounting locations on the S/C becomes more difficult.
    » Could become health physics issue if installation times increase (higher radiological dose to workers)
  – Complexity to the S/C electrical bus and thermal management system could also increase.

• Thus the power system size has to factor these “constraints” as part of the system design methodology
Representative Power Ranges for SMD Mission Class

<table>
<thead>
<tr>
<th>Discovery</th>
<th>New Frontiers</th>
<th>Flagship</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiME, CHopper</td>
<td>New Horizons</td>
<td>Cassini Europa Clipper**</td>
</tr>
<tr>
<td>DSMCE</td>
<td>Juno*</td>
<td></td>
</tr>
<tr>
<td>200-300 W_e</td>
<td>300-600 W_e</td>
<td>600-1,200 W_e</td>
</tr>
</tbody>
</table>

* Non-RPS mission
** NASA has selected solar power as the current notional baseline for the Europa Clipper mission after the NPAS study was concluded

• Outer planet mission concepts have been designed to the constraints of available (limited) power systems
  – Powers have ranged from 100 up to 1,000 watts; instrument suits limited by available power

• Discovery, New Frontiers, and Flagship missions could all be supported by an RPS unit size of 300 W_e.
  – Discovery typically could use 1 unit.
  – New Frontiers could use 2 units.
  – Flagship could use 3-4 units.
Mission Class Assessment Summary (2)

• Human lunar and Mars missions could use FPS easily scalable to 10’s to 100’s kWe required for:
  – Habitation
    » 15-30 kW_e (ISS Loads currently ~60 kW_e)
  – ISRU
    » 10-35 kW_e
  – Exploration science
    » 2-10 kW_e
  – Crewed long-range exploration mobility needs/habitat backup
    » 2-5 kW_e (potentially RPS)

• No current HEOMD requirements for RPS
Potential Discriminators on the Transition Point of RPS to FPS

- Where does FPS come into play for SMD missions?
- At what point does it make sense to pursue FPS?

- What is the maximum amount or percentage of Pu-238 inventory NASA would be willing to devote to a single mission?
  - e.g., a single 1 kWₑ or 4 x 250 Wₑ SMD mission implementation
  - Pu-238 allocation between science and human missions
  - For reference: 54 GPHS (18 x 3) modules were flown on Cassini, the largest amount of plutonium flown to date

- Other factors to consider
  - FPS system availability/readiness meeting SMD mission requirements
  - System integration/location on a S/C (instrument/equipment interactions)
  - LV integration issues (including possible added facility and security needs)
  - Radiological differences (ground operations and security)
  - Availability/inventory of Pu-238 fuel
  - Total system/mission comparative costs
Estimate of Potential Total Power Available from Plutonium

• Assumptions
  – All 350 kg of Np-237 (isotope) have been converted to Pu-238 (isotope) with 80% efficiency.
      » Total supply is 280 kg of Pu-238 (isotope)
  – 110 g of Pu-238/clad -> can make 2,545 clads -> 636 GPHS modules can be made
      » ARTGs could produce @28 $W_e$(BOL)/GPHS = ~18 $W_e$
      » SRGs could produce @62 $W_e$(BOL)/GPHS = ~39 $W_e$
  – Consider the use of Am-241 separated from the Pu-weapons stockpile as a long range proposition that can add additional Pu-238 for use
      » Could be processed in the mixed oxide fuel production facility
        › The facility is currently under construction at SRS
      » Could be used as a viable and proven target (instead of neptunium) for production of very high purity (<< 1 ppm Pu-236) and high assay (>90 % Pu-238) Pu-238
      » The quantity of Am-241 available through this channel is at least 300 kg.
      » This would essentially double the quantity of Pu-238 that could be produced from the value presented above.
Transition Point Analysis - Mass

- RPS unit masses for 6-GPHS SRG and 16-GPHS ARTG were scaled up to large numbers of units to estimate mass at higher power levels.
- Power system mass seems to break even between $8 \text{ kW}_e$ and $10 \text{ kW}_e$. 

![Diagram showing mass vs power level with different symbols for 6-GPHS SRG, 16-GPHS ARTG, Stirling FPS, and TE FPS.](image-url)
Transition Point Analysis - Cost

• Mission costs for 6-GPHS SRG and 16-GPHS ARTG were scaled up to large numbers of units to estimate costs for missions at higher power levels.
  – These costs include RPS unit costs, RPS-related ATLO costs, and launch services costs.
  – Power system production and fuel related costs scale with number of units.
• As soon as there are multiple RPS units on a mission, costs are higher than estimated cost for one FPS unit
  – RPS costs exceed Flagship mission total cost target before 10 kW_e power level

**Nuclear Power Cost vs Mission Power Level**

![Graph showing nuclear power cost vs mission power level](image-url)
Summary Remarks on RPS to FPS Transition Point

• Power level breakpoint is subjective and mission dependent
• Identified three major discriminators:
  – Power System Mass
    » Mass breakeven appears to be between 8 kW_e and 10 kW_e EOM.
      › This does not take into account difficulties in integrating sufficient units of RPS to reach those power levels.
  – Amount of Plutonium used
    » Missions could use 6-GPHS SRGs or 16-GPHS ARTGs to generate over 1 kW_e EOM while using fewer than 54 GPHS modules total (amount used on Cassini)
  – Cost
    » Using current FPS cost estimates, cost breakeven is below 1 kW_e EOM.

• A prudent transition point seems between RPS and FPS for science missions to be around 1 kW_e
Mission Study Team Members

YOUNG LEE, NASA Jet Propulsion Laboratory, **LEAD**
RICHARD ANDERSON, Johns Hopkins University, Applied Physics Laboratory
BRIAN BAIRSTOW, NASA Jet Propulsion Laboratory
ANTHONY BELVIN, DOE Office of Space and Defense Power Systems
GREG CARR, NASA Jet Propulsion Laboratory
ROBERT CATALDO, NASA Glenn Research Center
LARRY CRAIG, NASA Kennedy Space Center
DONYA DOUGLASS-BRADSHAW, NASA Goddard Space Flight Center
JOHN ELLIOT, NASA Jet Propulsion Laboratory
JEAN-PIERRE FLEURIAL, NASA Jet Propulsion Laboratory
DOUG ISBELL, NASA Jet Propulsion Laboratory
STEPHEN JOHNSON, Idaho National Laboratory
RON LIPINSKI, Sandia National Laboratory
STEVEN OLESON, NASA Glenn Research Center
PAUL OSTDIEK, Johns Hopkins University, Applied Physics Laboratory
MICHELLE RUCKER, NASA Johnson Space Center
VICKY RYAN, NASA Jet Propulsion Laboratory
RANDY SCOTT, NASA Kennedy Space Center
CHARLES TATRO, NASA Kennedy Space Center
STEVE VERNON, Johns Hopkins University, Applied Physics Laboratory
KEVIN WATTS, NASA Johnson Space Center
DAVID WOERNER, NASA Jet Propulsion Laboratory
JUNE ZAKRAJSEK, NASA Glenn Research Center
Members from Collaborative Engineering Centers

GRC COMPASS Members:

STEVE OLESON, Lead
BRIAN BAILSTOW, Science and Payload, (JPL)
LAURA BURKE, Mission Design
BOB CATALDO, FPS ATLO Processing
ANTHONY COLOZZA, Thermal
STEPHEN JOHNSON, FPS ATLO Processing, (INL)
ROBERT JONES, Communications
RICH KELSCH, Structures
MIKE MARTINI, Mission Design
LEE MASON, Power
TOM PACKARD, Spacecraft Configurations
TOM PARKEY, Cost
PAUL SCHMITZ, Power
TIM VERHEY, Propulsion
STEVE VERNON, FPS ATLO Processing, Launch Vehicle, (APL)
JEFF WOYTACH, System Integration, Mission ConOps, Launch Vehicle

APL ACE Members:

RICHARD ANDERSON, Lead/Systems
HOLLIS AMBROSE, G&C
BETSY CONGDON, Mechanical
MARTY FRAEMAN, Avionics, Power
JASON GORCZYCA, S/C Design
LAUREN MEHR, Cost
BRIAN SEQUEIRA, Telecom
STEVE VERNON, ATLO
BRUCE WILLIAMS, Thermal

JPL Team-X Members:

AL NASH, Lead
DAVID HANSEN, Telecom
MICHAEL MERCURY, Systems
JONATHAN MURPHY, Deputy Systems
DHACK MUTHULINGAM, Power
JAMIE PIACENTINE, Configuration
LEIGH ROSENBERG, Cost
MATTHEW SPAULDING, Mechanical
ERIC SUNADA, Thermal
PAUL WOODMANSEE, Propulsion
BACKUP SLIDES
# NPAS TSSM 1 kWₑ RPS Study Options Summary

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>2008 ASRG</th>
<th>2008 Study with 2014 ASRGs</th>
<th>3+1 6-GPHS Stirling</th>
<th>5+1 4-GPHS Stirling</th>
<th>3 16-GPHS ARTG</th>
<th>5 9-GPHS ARTG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telecom</td>
<td>X/Ka, 4 meter antenna, 35W RF TWTA</td>
<td>X/Ka, 4 meter antenna, 35W RF TWTA</td>
<td>X/Ka, 2.25 meter antenna, 140W RF TWTA</td>
<td>X/Ka, 2.25 meter antenna, 140W RF TWTA</td>
<td>X/Ka, 2.25 meter antenna, 140W RF TWTA</td>
<td>X/Ka, 2.25 meter antenna, 140W RF TWTA -3 kg</td>
</tr>
<tr>
<td>Power</td>
<td>4 Operating + 1 Spare. 107 kg and 541 Wₑ EOM.</td>
<td>5 Operating + 1 Spare. 205 kg and 575 Wₑ EOM.</td>
<td>3 Operating + 1 Spare. 187 kg and 891 Wₑ EOM. Smaller batteries, non-RPS mass -5 kg.</td>
<td>5 Operating + 1 Spare. 192 kg and 965 Wₑ EOM. Smaller batteries, non-RPS mass -5 kg.</td>
<td>3 Operating + 0 Spares. 163 kg and 1,041 Wₑ EOM. Smaller batteries, non-RPS mass -5 kg.</td>
<td>5 Operating + 0 Spares. 161 kg and 945 Wₑ EOM. Smaller batteries, non-RPS mass -5 kg.</td>
</tr>
<tr>
<td>Structure</td>
<td>Composite and Aluminum for low mass, rigidity. 350 kg.</td>
<td>Effects of other subsystem mass increases not studied. On order of +20 kg.</td>
<td>Other subsystem mass increases drive mass +20 kg</td>
<td>Effects of other subsystem mass increases not studied. On order of +6 kg. Need to accommodate 6 units.</td>
<td>Effects of other subsystem mass increases not studied. On order of +6 kg. Need to accommodate 5 units.</td>
<td></td>
</tr>
<tr>
<td>Dry Mass (with margins)</td>
<td>3,224 kg</td>
<td>~3,400 kg</td>
<td>~3,350 kg</td>
<td>~3,360 kg Configuration and Thermal may add mass.</td>
<td>~3,270 kg</td>
<td>~3,270 kg Configuration and Thermal may add mass.</td>
</tr>
<tr>
<td>Subsystem</td>
<td>2010 Baseline 3xASRG</td>
<td>2010 Decadal with 2014 ASRGs</td>
<td>(2+1) x 4-GPHS Stirling SRG</td>
<td>(2+0) x 4-GPHS Stirling RTG</td>
<td>2 x 9-GPHS ARTG</td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------</td>
<td>-----------------------------</td>
<td>-----------------------------</td>
<td>----------------------------</td>
<td>----------------</td>
<td></td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>3 Primary + 0 Spare. 82 kg and 368 W_e EOM.</td>
<td>4 Primary + 0 Spare. 132 kg and 436 W_e EOM. (2014 est. output power lower than 2010)</td>
<td>2 Primary + 1 Spare. 110 kg and 588 W_e EOM. Minor shunt regulator component changes.</td>
<td>2 Primary + 0 Spare. 74 kg and 392 W_e EOM.</td>
<td>2 Primary + 0 Spare (plus 1 thermally isolating bracket each). 98 kg and 379 W_e EOM.</td>
<td></td>
</tr>
<tr>
<td><strong>Avionics</strong></td>
<td>Typical, Redundant APL Integrated Electronics Module, 32 Gbit recorder.</td>
<td>No change</td>
<td>Potential for minor modifications to command and telemetry interface.</td>
<td>Potential for minor modifications to command and telemetry interface.</td>
<td>Potential for minor modifications to accommodate additional temperature sensor inputs.</td>
<td></td>
</tr>
<tr>
<td><strong>G&amp;C</strong></td>
<td>Redundant Star Trackers, IMU, Sun Sensors, RWAs, Maneuvering Thrusters, Monopulse input from RF</td>
<td>No change</td>
<td>Removal of monopulse tracking as part of RF mass savings option</td>
<td>No changes required</td>
<td>Removal of monopulse tracking as part of RF mass savings option</td>
<td></td>
</tr>
<tr>
<td><strong>Telecomm.</strong></td>
<td>Dual Ka and X Band; 2.5 meter HGA; 40-W_e Ka, low EMI TWTA, Monopulse</td>
<td>No change</td>
<td>1.8 meter HGA; Removal of Monopulse; 14kg subsystem reduction</td>
<td>No changes required</td>
<td>1.8 meter HGA; Removal of Monopulse; 14kg subsystem reduction</td>
<td></td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td>“Thermos bottle” design with heat pipes, louvers, controlled heaters</td>
<td>Potential minor modifications for higher shunt power</td>
<td>Potential minor modifications for higher shunt power</td>
<td>No significant changes expected</td>
<td>Thermal isolating mounting brackets required. Relocation of components in ARTG thermal view likely required.</td>
<td></td>
</tr>
<tr>
<td><strong>Mechanical / Structural</strong></td>
<td>Aluminum structure, built around large HGA and large dual-mode propulsion system</td>
<td>Future analysis of layout &amp; mass props needed to account for placement of 4th ASRG &amp; mass increase</td>
<td>No significant structural changes expected</td>
<td>No significant structural changes expected</td>
<td>Future analysis of layout needed; Effects of ASRG radiant heat on nearby components to be studied.</td>
<td></td>
</tr>
<tr>
<td><strong>Orbiter Dry Mass MEV</strong></td>
<td>712 kg</td>
<td>~763 kg</td>
<td>~727 kg</td>
<td>~704 kg</td>
<td>~722 kg</td>
<td></td>
</tr>
</tbody>
</table>
## Comparison of the 2008 ASRG TSSM Study and 2014 FPS Concepts

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>2008 ASRG</th>
<th>1 kWe Stirling Reactor</th>
<th>1 kWe TE Reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Science</strong></td>
<td>108 kg, 182 W&lt;sub&gt;e&lt;/sub&gt;, ~5 Tb Data Return</td>
<td>108 kg, 182 W&lt;sub&gt;e&lt;/sub&gt;, ~9 Tb Data Return</td>
<td>108 kg, 182 W, ~9 Tb Data Return</td>
</tr>
<tr>
<td><strong>Mission</strong></td>
<td>~13 year</td>
<td>~15 year (1 year Earth spiral-out)</td>
<td>~16 year (2 year Earth spiral-out)</td>
</tr>
<tr>
<td><strong>Launch Vehicle</strong></td>
<td>Atlas 551, short fairing. C&lt;sub&gt;3&lt;/sub&gt; of 0.6 km&lt;sup&gt;2&lt;/sup&gt;/s&lt;sup&gt;2&lt;/sup&gt; (6,250 kg Stage mass)</td>
<td>Atlas 551, <strong>long fairing</strong>. C&lt;sub&gt;3&lt;/sub&gt; of -14.8 km&lt;sup&gt;2&lt;/sup&gt;/s&lt;sup&gt;2&lt;/sup&gt; (8,300 kg Stage Mass)</td>
<td>Atlas 551, <strong>long fairing</strong>. C&lt;sub&gt;3&lt;/sub&gt; of -22 km&lt;sup&gt;2&lt;/sup&gt;/s&lt;sup&gt;2&lt;/sup&gt; (9,600 kg Stage Mass)</td>
</tr>
<tr>
<td><strong>SEP Stage</strong></td>
<td>~15 kWe, 500 kg Xe, 2+1 NEXT</td>
<td>~19 kWe, 1,400 kg Xe, 2+1 NEXT</td>
<td>~19 kWe, 1,800 kg Xe, 3+1 NEXT</td>
</tr>
<tr>
<td><strong>Orbiter Power System</strong></td>
<td>171 kg, &gt;13 year operation time</td>
<td>~500 kg, ~7 year [reactor NOT activated until after final Earth flyby (~7 years after launch)]</td>
<td>~700 kg, ~7 year [reactor NOT activated until after final Earth flyby (~7 years after launch)]</td>
</tr>
<tr>
<td><strong>Aerobraking</strong></td>
<td>4 meter antenna for drag area, Ballistic Coefficient 77 kg/m&lt;sup&gt;2&lt;/sup&gt; (2 month aerobraking campaign)</td>
<td>4.5 meter drag flap plus 2.25 meter antenna same 77 Ballistic coefficient (2 month aerobraking campaign)</td>
<td>4.5 meter drag flap plus 2.25 meter antenna 80 Ballistic coefficient (~2.1 month aerobraking campaign)</td>
</tr>
<tr>
<td><strong>Communications</strong></td>
<td>4 meter antenna, X/Ka, 25 W&lt;sub&gt;e&lt;/sub&gt;/35 W&lt;sub&gt;e&lt;/sub&gt; RF, 140 kbps</td>
<td>2.25 meter antenna, X/Ka, 70/250 W&lt;sub&gt;e&lt;/sub&gt; RF, 250 kbps</td>
<td>2.25 meter antenna, X/Ka, 70/250 W&lt;sub&gt;e&lt;/sub&gt; RF, 250 kbps</td>
</tr>
<tr>
<td><strong>Attitude Control System (Titan Ops)</strong></td>
<td>Four 25 Nms reaction wheels, LVHLH around Titan</td>
<td>Four 150 Nms reaction wheels, Gravity Gradient around Titan</td>
<td>Four 150 Nms reaction wheels, Gravity Gradient around Titan</td>
</tr>
<tr>
<td><strong>Total S/C Dry Mass (with margins)</strong></td>
<td>~3,200 kg</td>
<td>~4,200 kg</td>
<td>~5,000 kg</td>
</tr>
</tbody>
</table>
UOP 2014 RPS Study –
Non Nuclear Mission Cost Analysis Findings*

($FY15, $M)

<table>
<thead>
<tr>
<th>NASA WBS</th>
<th>Description</th>
<th>2010 ASRGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>01</td>
<td>Project Management</td>
<td>48</td>
</tr>
<tr>
<td>02</td>
<td>Systems Engineering</td>
<td>67</td>
</tr>
<tr>
<td>03</td>
<td>Safety &amp; Mission Assurance</td>
<td>43</td>
</tr>
<tr>
<td>04</td>
<td>Science/Technology (Phases A-D)</td>
<td>15</td>
</tr>
<tr>
<td>05</td>
<td>Payloads</td>
<td>274</td>
</tr>
<tr>
<td>06</td>
<td>Spacecraft</td>
<td>321</td>
</tr>
<tr>
<td>07</td>
<td>Mission Operations</td>
<td>156</td>
</tr>
<tr>
<td>09</td>
<td>Ground Data Systems</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>Systems Integration &amp; Test</td>
<td>57</td>
</tr>
<tr>
<td>DSN</td>
<td>Space Communications Services (DSN)</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>1,038</td>
</tr>
<tr>
<td>Project Management</td>
<td>467</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1,505</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>SRG Option A (2+1) x 4-GPHS</th>
<th>SRG Option B 2 x 4-GPHS</th>
<th>ARTG 2 x 9-GPHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>01</td>
<td>47</td>
<td>48</td>
<td>47</td>
</tr>
<tr>
<td>02</td>
<td>66</td>
<td>67</td>
<td>66</td>
</tr>
<tr>
<td>03</td>
<td>42</td>
<td>43</td>
<td>42</td>
</tr>
<tr>
<td>04</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>05</td>
<td>274</td>
<td>274</td>
<td>274</td>
</tr>
<tr>
<td>06</td>
<td>313</td>
<td>321</td>
<td>315</td>
</tr>
<tr>
<td>07</td>
<td>155</td>
<td>156</td>
<td>155</td>
</tr>
<tr>
<td>09</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>57</td>
<td>57</td>
<td>57</td>
</tr>
<tr>
<td>DSN</td>
<td>57</td>
<td>34</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>1,049</td>
<td>1,038</td>
</tr>
<tr>
<td>Cost Reserves</td>
<td>462</td>
<td>467</td>
<td>463</td>
</tr>
<tr>
<td>Total</td>
<td>1,511</td>
<td>1,505</td>
<td>1,514</td>
</tr>
</tbody>
</table>

*: Removed power system cost and removed estimated nuclear launch costs.
**TSSM 2014 RPS Study – Non Nuclear Mission Cost Analysis Findings**

($FY15, $M)

<table>
<thead>
<tr>
<th>NASA WBS</th>
<th>Description</th>
<th>2008 ASRG**</th>
<th>SRG (3+1) x 6-GPHS</th>
<th>ARTG 3 x 16-GPHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Project Management</td>
<td>130</td>
<td>124</td>
<td>124</td>
</tr>
<tr>
<td>2</td>
<td>Systems Engineering</td>
<td>48</td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>3</td>
<td>Safety &amp; Mission Assurance</td>
<td>86</td>
<td>82</td>
<td>82</td>
</tr>
<tr>
<td>4</td>
<td>Science/Technology</td>
<td>185</td>
<td>185</td>
<td>185</td>
</tr>
<tr>
<td>5</td>
<td>Payloads</td>
<td>260</td>
<td>260</td>
<td>260</td>
</tr>
<tr>
<td>6</td>
<td>Spacecraft</td>
<td>702</td>
<td>639</td>
<td>620</td>
</tr>
<tr>
<td>7</td>
<td>Mission Operations</td>
<td>294</td>
<td>294</td>
<td>294</td>
</tr>
<tr>
<td>9</td>
<td>Ground Data Systems</td>
<td>74</td>
<td>74</td>
<td>74</td>
</tr>
<tr>
<td>10</td>
<td>Systems Integration &amp; Test</td>
<td>56</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>DSN</td>
<td>Space Communications Services (DSN)</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td><strong>1,902</strong></td>
<td><strong>1,826</strong></td>
<td><strong>1,807</strong></td>
</tr>
<tr>
<td><strong>Cost Reserves</strong></td>
<td></td>
<td><strong>597</strong></td>
<td><strong>611</strong></td>
<td><strong>604</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>2,499</strong></td>
<td><strong>2,436</strong></td>
<td><strong>2,411</strong></td>
</tr>
</tbody>
</table>

*: Removed power system cost and removed estimated nuclear launch costs.

**: 2008 TSSM Study costs inflated to FY 15 without nuclear launch costs.
### TSSM 2014 FPS Study – Non Nuclear Mission Cost Analysis Findings**

($FY15, $M)

<table>
<thead>
<tr>
<th>NASA WBS</th>
<th>Description</th>
<th>2008 ASRG**</th>
<th>2014 Stirling FPS</th>
<th>2014 TE FPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Project Management</td>
<td>130</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>Systems Engineering</td>
<td>48</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>3</td>
<td>Safety &amp; Mission Assurance</td>
<td>86</td>
<td>86</td>
<td>86</td>
</tr>
<tr>
<td>4</td>
<td>Science/Technology</td>
<td>185</td>
<td>185</td>
<td>185</td>
</tr>
<tr>
<td>5</td>
<td>Payloads</td>
<td>260</td>
<td>260</td>
<td>260</td>
</tr>
<tr>
<td>6</td>
<td><strong>Spacecraft</strong></td>
<td><strong>702</strong></td>
<td><strong>792</strong></td>
<td><strong>806</strong></td>
</tr>
<tr>
<td>7</td>
<td>Mission Operations</td>
<td>294</td>
<td>307</td>
<td>313</td>
</tr>
<tr>
<td>9</td>
<td>Ground Data Systems</td>
<td>74</td>
<td>74</td>
<td>74</td>
</tr>
<tr>
<td>10</td>
<td>Systems Integration &amp; Test</td>
<td>56</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>DSN</td>
<td>Space Communications Services (DSN)</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td><strong>1,902</strong></td>
<td><strong>2,005</strong></td>
<td><strong>2,025</strong></td>
</tr>
<tr>
<td><strong>Cost Reserves</strong></td>
<td></td>
<td><strong>597</strong></td>
<td><strong>629</strong></td>
<td><strong>636</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>2,499</strong></td>
<td><strong>2,634</strong></td>
<td><strong>2,661</strong></td>
</tr>
</tbody>
</table>

*: Removed power system cost and removed estimated nuclear launch costs.

**: 2008 TSSM Study costs inflated to FY 15 without nuclear launch costs.
Key Dates Executed by Mission Study Team

- May 1: NPAS Executive Council Kick-off Meeting (Wash DC)
- May 28: Mission Study Team Face-to-Face Meeting #1 (JPL)
- June 6: Debrief of MST Face-to-Face Meeting #1 summary to EC (Virtual)
- June 9-12: Team X Session on TSSM Stirling-based RPS (JPL)
- June 11: MST ATLO Assessment Sub-team kick-off meeting (Virtual)
- June 16-July 7: COMPASS Sessions on TSSM FPS (GRC)
- June 19-20: ACE Session kick-off on UOP RPS (APL)
- June 23-24: INL Tour with NPAS EC Chair (INL)
- July 7: Team X Session with sub-team on TSSM TE-based RPS (JPL)
- July 9-10: System Team Face-to-Face Meeting #1 – Debrief TSSM Quick-look Study Results (GRC)
- July 15: TSSM 2014 RPS/FPS Study Results Briefing (Virtual)
- July 17-18: MST ATLO Sub-team Security Assessment for New RPS and FPS (KSC)
- July 21: NPAS EC Mid-Term MST Status Briefing (Wash DC)
- July 24: ACE UOP RPS Study complete (APL)
- July 31: UOP 2014 RPS Study Results Briefing (Virtual)
- Aug 4-15: COMPASS Session on UOP FPS (GRC)
- Aug 7: MST ATLO Sub-team Launch Ops Face-to-Face Meeting at KSC
- Aug 13-14: System Team Face-to-Face Meeting #2 - Debrief UOP Quick-look Study Results (ORNL/Y-12)
- Aug 26-28: MST Face-to-Face Meeting #2 including UOP FPS Study Results Briefing (JPL)
- Sep 2-4: NPAS EC Final Review (Wash, DC)