

Agenda

- **Study Introduction**
- **Executive Summary of Results**
- **Cost Analysis**
- **Findings**



STUDY INTRODUCTION

Study Objective

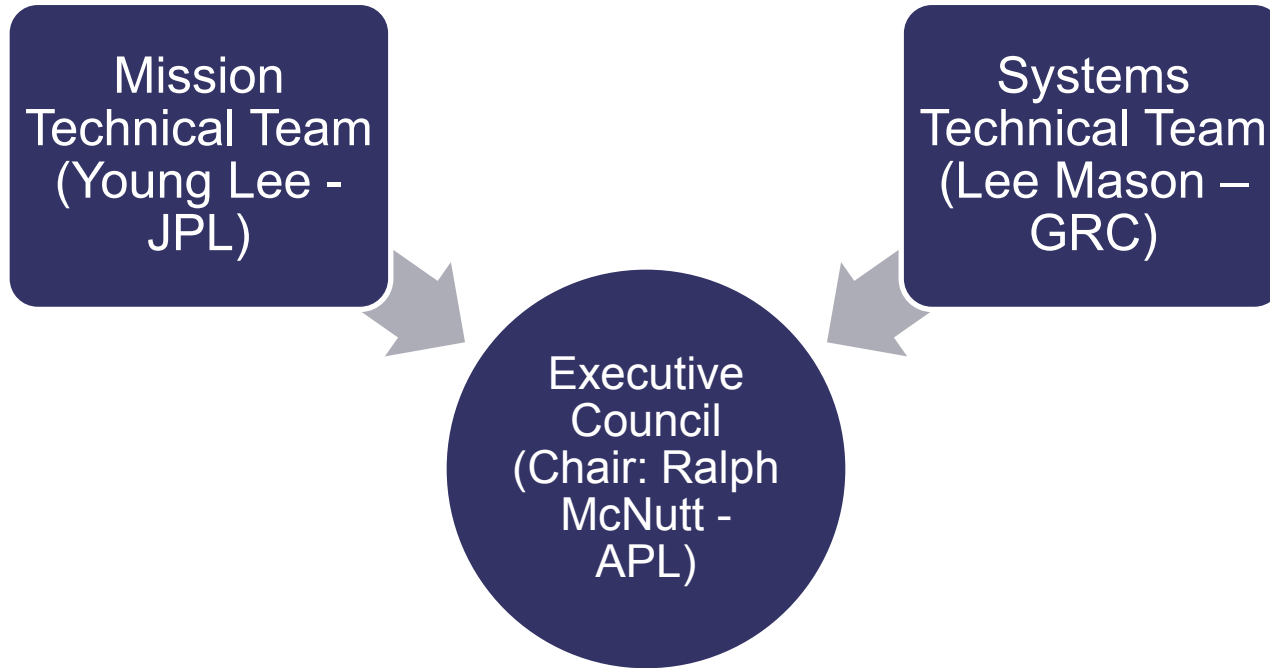
Identify **opportunities and challenges** of a sustainable provisioning strategy for safe, reliable, and affordable nuclear power systems that enable NASA Science Mission Directorate (SMD) missions and are extensible to Human Exploration and Operations Mission Directorate (HEOMD) needs in the **next 20 years**.

- from NASA Radioisotope Power Systems Program
Nuclear Power Systems Assessment
Terms of Reference
15 March 2014

Nuclear Power Systems Investment Study – Charge to Executive Council

- Long-term need to *develop more efficient systems*
- Planetary Science wants to *understand the potential for commonality* between Planetary RPS systems and components and initial investments in fission systems and components
- Study is intended to identify opportunities and challenges of a *sustainable, incremental, development strategy* for nuclear power systems to support SMD and initial fission capabilities for HEOMD
- Initial results by end of August, report by November 2014

Study Organization



Technical Tier Teams

Focus on addressing specific questions needed to be considered for overall plan development

Executive Team

Assimilate technical tier teams' reports and develop observations and findings

Composition Ensured Multiple Viewpoints Represented on Teams

Executive Council (EC) Membership (12)

- **Executive Council Chair:**
 - Dr. Ralph L. McNutt, Jr. The Johns Hopkins Applied Physics Laboratory
- **Members:**
 - Christopher Moore, HEOMD
 - Ryan A. Stephan, STMD
 - Leonard Dudzinski, SMD
 - Suzanne M. Aleman, NASA Nuclear Flight Safety Assurance Manager
 - Wade Carroll, DOE NE
 - Jerry McKamy, DOE NNSA
 - Kim R. Reh, JPL
 - Michael J. Amato, GSFC
 - Cheryl Reed, APL
 - Joseph A. Sholtis, Jr., Nuclear Safety Consultant
- **Executive Council Secretary:**
 - Kathryn K. Trase, GRC

NPAS System Team Membership (21)

Org	Name	Role
APL	Marty Fraeman	PMAD
DOE	Anthony Belvin	Reactors
	Dirk Cairns-Gallimore	RPS and Pu-238
GRC	Matt Dolloff	Consultant
	Marc Gibson	Fission Systems
	Lee Mason	Systems Study Team Lead
	Chip Redding	CAD
	Paul Schmitz	Systems Analysis
	Jeff Schreiber	Stirling
	Jim Withrow	Stirling Systems
	Wayne Wong	Consultant
Independent	Abe Weitzberg	Reactor Physics and Systems
INL	Steve Herring	Fission Systems
JPL	Sal DiStefano	Consultant
	Jean-Pierre Fleurial	Thermoelectrics
	Dave Woerner	Consultant
LANL	Patrick McClure	Nuclear Testing
	Dave Poston	Reactor Analysis
ORNL	Lou Qualls	Consultant
Y12	John Creasy	Reactor Fuel and HEU
	Chris Robinson	Consultant

NPAS Mission Team Membership (24)

Org	Name	Role
APL	Rich Anderson	ACE Study Lead/Mission Design
	Paul Ostdiek	ACE Study Lead/Mission Design
	Steve Vernon	ATLO Analysis/ConOps
DOE	Anthony Belvin	Space Nuclear Power Systems/Launch
GRC	Bob Cataldo	ATLO Analysis/ConOps
	Steve Oleson	Consultant
	Katie Trase	Consultant
	June Zakrajsek	Consultant/Stakeholder
GSFC	Donya Douglas-Bradshaw	Consultant/Stakeholder
INL	Steve Johnson	Nuclear Processing and INL, Operations
JPL	Brian Bairstow	System Engineering
	Greg Carr	Power System User -Ops
	John Elliot	Mission Concept (SMD)
	Jean-Pierre Fleurial	Consultant/Stakeholder
	Doug Isbell	Risk Communications
	Young Lee	Mission Study Team Lead
	Vicky Ryan	Launch Approval Engineering
	Dave Woerner	Consultant/Stakeholder
JSC	Michelle Rucker	Consultant/Stakeholder
	Kevin Watts	Mission Concept (HEO)
KSC	Larry Craig	Launch Ops
	Randy Scott	Nuclear Safety
	Chuck Tatro	Launch Ops
SNL	Ron Lipinski	Safety Analysis

Study Key Dates

- **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 Titan Saturn System Mission (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 Uranus Orbiter Probe (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 (KSC)**
- **Aug 13-14: System Team Face-to-Face Meeting #2 - Debrief UOP Quick-look Study Results (ORNL/Y-12)**
- **Aug 19: FPS Technical and Security Discussions (LANL)**
- **Aug 26-28: MST Face-to-Face Meeting #2 including UOP FPS Study Results Briefing (JPL)**
- **Sep 2-5: NPAS EC Final Review (Wash, DC)**
- **Nov 28 – NPAS Final Report**

Meetings at DOE and Launch
Facilities
Mission Studies at Collaborative
Engineering Centers



EXECUTIVE SUMMARY OF RESULTS

Executive Summary – Top Level (1)

- 1) Nuclear power systems would be **enabling*** for implementing many robotic mission concepts for the Science Mission Directorate (SMD) prescribed by the current Decadal Surveys
- 2) Given (1) current budget levels, (2) science community input in the current Decadal Surveys, and (3) NASA requirements as expressed to the Department of Energy (DOE – 2010), nuclear power systems are expected to be **needed** the decade following that of the current Decadal Surveys as well (i.e., into the 2030's)
- 3) Without significant budget increases in mission cost caps, projected, single-mission power requirements are unlikely to exceed $\sim 600 \text{ W}_{\text{electric}}$
- 4) Radioisotope Power Systems (RPS) with projected, NASA-funded, Pu-238 production levels, with thermoelectric converters fulfill a subset of SMD mission needs, but with little margin. Pu-238 is a precious resource and needs efficient utilization and preservation.
- 5) Ability to have programmatic (cost and schedule) flexibility would **need** maturation of more fuel-efficient advanced thermoelectrics and dynamic converters (Stirling) for flight, and likely additional spending in DOE infrastructure for increased Pu-238 production rate over time.

**No chemical, solar or other non-nuclear power supply known can fulfill this need*

Executive Summary – Top Level (2)

- 6) Converter technologies based upon advanced thermoelectrics and/or dynamic power conversion (Stirling) may have direct applicability to higher-power, space-nuclear Fission Power Systems (FPS) **likely needed** for human missions to Mars (Human Exploration and Operations Mission Directorate – HEOMD); various considerations may drive the approach, but common converter technologies for both FPS and RPS may be a promising provisioning strategy depending upon what modular FPS unit size is ultimately selected for projected HEOMD mission applications.
- 7) SMD has a **continuing need to maintain and advance RPS** for the next two decades **and to plan for increased Pu-238 production rate** over time
- 8) A novel, low-power, FPS critical experiment is being funded (FY15 – FY17) by NASA's Space Technology Mission Directorate (STMD) in cooperation with DOE to demonstrate technical feasibility; schedule and cost to first flight will remain uncertain until a system development project has been initiated but have been estimated to be no less than 10 years and \$550 M FY14\$ (with 30% contingency in current program ROM estimate)
- 9) For FPS, radiation background, low specific power, assembly, test, launch, and operations (ATLO), all present design challenges on robotic missions at the 1 kW_e power level; FPS-powered system mass would be larger than RPS-powered system mass at the 1 kW_e power level; this fission system may be consistent with a TRL level ~2 to 3 as compared with 9 for current RPS
- 10) SMD has no current requirements for a mission power system at the 1 kW_e level or higher, and so **no current requirement** for an FPS exists

Nuclear Power Requirements (1)

- Requirements assessed for nuclear power systems for Science Mission Directorate (SMD) for the next 20 years and their extensibility to currently expected power needs of the Human Exploration and Operations Mission Directorate (HEOMD)
 - Respond to Decadal Survey (Planetary Science Division, PSD) consensus requirements
 - » RPS is enabling for two Flagship recommendations, three additional Flagship candidates, and four New Frontiers candidates
 - › Power requirements range from 144 W_e to 625 W_e
 - › Lowest numbers for landers
 - › ~300 W_e for Discovery and New Frontiers
 - » RPS has been identified as enabling for nine potential Discovery missions – funded DSMCE studies (“Discovery and Scout Mission Capabilities Expansion” – 2007)
 - › Power requirements range from 130 W_e to 267 W_e
 - » Waste heat constraints mean that MMRTGs may not be able to enable all stated needs in the current planetary decadal survey

ALL known SMD requirements can be met with < 1-kW_e power systems

Nuclear Power Requirements (2)

- HEOMD Mars Design Reference Architecture 5.0 (and Addenda)
 - » No current requirements for Pu-238 based RPS systems
 - » Requires $\sim 35 \text{ kW}_e$ supply for surface system to generate electricity for propellant manufacture for Earth return of human crew from Mars surface
 - » Practical approaches are likely to require a Fission Power System (FPS, i.e. a nuclear reactor)
 - » Exact Mars human systems architecture have not yet been determined and could significantly alter nuclear system needs for future Mars HEO missions.
 - › Architecture trades – number of systems versus power output per system and reliability constraints remain undefined until no earlier than 2019
- Respond to Agency Mission Planning Model (AMPM)
 - » Planned cadence of Discovery and New Frontiers missions
 - » Use of nuclear systems to be allowed, but not determined until actual competition – hence, requirements are non-deterministic
- Enabling (i.e. required, necessary, and sufficient engineering solution)
 - » For current SMD requirements ($< 1 \text{ kW}_e$) Pu-238 based RPS systems are the preferred technical choice
 - » FPS systems in this range have a specific power (W_e/kg) lower than RPS by at least factor of 3

Sustainability

- Sustainable (i.e. affordable and for an affordable mission set)
- Mix of production for flight programs in the pipeline and advanced technology developments
- Knowledge retention
- Reviewed programs, costs, and outcomes for all public nuclear space from 1950 on
- Items of focus:
 - MMRTG (Multi-Mission Radioisotope Thermoelectric Generator – now on Mars powering Curiosity)
 - eMMRTG (enhanced MMRTG – advanced thermoelectric element manufacture being transferred to industry; “plug and play” for higher MMRTG efficiency)
 - Stirling convertors – dynamic power conversion potentially applicable to RPS and FPS – in development
 - HPSRG (High-power Stirling radioisotope generator) ~200 – 300 W_e
 - ARTG (Advanced Radioisotope Thermoelectric Generator) use of advanced, segmented thermoelectric elements to reach conversion efficiencies of ~15%

Fission Power System Possibilities for SMD

- **Technical**
 - Minimum reactor mass requires fast or epithermal reactor
 - United Nations Principles (Res. 47/68) and U.S. proliferation policy require U-235
 - Minimum shield mass requires highly enriched uranium (HEU) (>92% U-235 enrichment)
 - Use at ~1 to 10 kW_e is feasible but at low specific power (~2 W_e/kg at 1 kW_e)
- **Fuel availability**
 - HEU reserved for the combination of research, medical isotope production, and space reactors is 20 metric tons, of which a small fraction is set aside for space reactors
 - No additional HEU is currently foreseen as available due to long-range commitments and requirements; additional HEU for space applications would require reprioritization of existing commitments and revision of current allocations
- **Fuel and security costs of FPS versus RPS**
 - Fuel and sustainment costs currently estimated as far less for FPS than RPS
 - First FPS flight would cost additional ~\$30M NRE + ~\$40M RE for security at launch site (versus RPS)
- **Flight reactor costs remain unknown**
 - Only one U.S. reactor flown – SNAPSHOT using SNAP 10A in 1965 with limited lifetime
 - Funded STMD “KiloPower” effort investigating feasibility of simple, long-lived HEU reactor
 - Previous – albeit ambitious – space reactor development efforts cancelled when proposed costs and development times have been exceeded, typically when requirements changed or expanded and/or planned funding not provided



COST ANALYSIS

Mission Study Cost Findings

- Mission studies conducted looked at the Titan Saturn System Mission (TSSM) and the Uranus Orbiter Probe (UOP) Decadal Survey Studies

- 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

	Mission Costs Less Power System* (\$M)		
	UOP - RPS	TSSM - RPS	TSSM - FPS
Decadal Study	\$1,505	\$2,499	\$2,499
SRG Option A	\$1,511	\$2,436	\$2,634
SRG Option B	\$1,505	N/A	N/A
TE Option	\$1,514	\$2,411	\$2,661

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

- No significant total mission cost deltas were found trading against different RPS system
- Slight total mission cost increase (~\$200M) found using FPS instead of RPS

Non-Mission/Non-Systems Costs

- Sustainment* of NASA and Industry conversion capability supporting both RPS and FPS is \$7M/year for Stirling and Thermoelectric, individually
- Sustainment of LAE Capability at NASA/JPL- \$2M/year
- FPS Non-Mission/Non-Systems Cost - \$0/year (TBR)
- RPS Non-Mission/Non-System Costs:

Yearly, Recurring:

	FY14	FY15	FY16	FY17	FY18	FY19	FY20
Operations & Analysis Subtotal	\$48,100	\$49,600	\$53,100	\$54,000	\$57,500	\$59,500	\$60,000
FWPF	\$1,000	\$1,000	\$1,030	\$1,060	\$1,090	\$1,090	\$1,100

Non-Recurring:

	FY14	FY15	FY16	FY17	FY18	FY19	FY20
LANL: Hot Press & Furnaces	\$3,200	\$7,800	\$4,200	\$1,000	\$0	\$0	\$0
Pu-238 Supply Project	\$14,500	\$21,400	\$21,400	\$15,000	\$15,500	\$18,500	\$19,000

➤ **Post FY21 \$10M/year Operations & Analysis increases due to Pu-238 Supply**

* In-line work used to sustain



FINDINGS

Technical Findings – RPS specific

- **Nuclear power is enabling for SMD Missions for at least the next two decades**
 - Power requirements are $< 1 \text{ kW}_e$ for all current SMD plans
- **RPS is the only currently proven and available implementation approach**
 - Maintain and advance current RTG capability
 - Dynamic converters have best promise for significant efficiency increase for SMD future requirements ($\sim 300 \text{ W}_e$ generator). Needed for program resiliency, and responsible fuel resource utilization.
 - Continue development of advanced TE and Stirling converter technologies and evaluate options for increasing Pu-238 production past currently planned rates ($\sim 1.5 \text{ kg/yr PuO}_2$)
 - Independent technical assessment of ASRG should be conducted before new dynamic converter development is undertaken
 - Complete and realistic requirements need to be established up front
 - Near-term Stirling-converter flight demonstration should be considered
 - FPS are not applicable to most SMD mission concepts
- **Infrastructure and usage costs are well known**
 - Solid historical record
 - Enables budget and schedule planning with high confidence
 - Minimizes chances of missing budgetary targets

Technical Findings – FPS specific

- FPS could be used to implement larger SMD Flagship missions than currently envisioned if PSD budgets were to be increased significantly
- FPS is not required to implement envisioned SMD missions as long as RPS capability is maintained; FPS is a poor technical fit to the mission set and cannot fill all requirements in any case
- FPS are expected to be required and essential for implementing HEOMD missions
- FPS U-235 fuel supply is **limited** (a fraction of the ~20 MT account); fuel material and infrastructure costs to NASA have been currently estimated to be negligible
- Conversion technology being developed by SMD is applicable to, and should be highly beneficial for, both RPS and FPS
- FPS SNM* Security mission costs at the Cape during ATLO can be very significant (~\$70 M).
- Investment (~few \$M) is needed to explore the ATLO, Safety, Security, EDL trade space since it could impact FPS design
- FPS mission costs are not expected to vary much from historical costs for RPS NEPA or Launch Approval processes (based on current assumption set)
- STMD is making an investment (~\$15M) in an FPS pathfinder – KiloPower.
 - Develop and demonstrate small-fission technology
 - Provides important key decision point for this FPS approach at end of FY17
- Current FPS cost estimate fidelity significantly lags that of RPS for implementation; should increase with successful conclusion of STMD effort

*Special Nuclear Material

Sustainability Findings

- **Current Status:** Mars 2020, one Discovery mission, and one Flagship using MMRTGs* (a total of seven MMRTGs) could be powered with Pu-238 on hand (per DOE Memorandum of August 2013)
- **Future Projection:** AMPM calls for two Mars, two Discovery, and three New Frontiers missions between FY2021 and FY2033 (12-year period)
 - Assume 125 W_e (BOL) MMRTGs and, further, 1 on a Mars mission, 2 on a Discovery mission, and 3 on a New Frontiers (NF) mission
 - If all are missions are nuclear, then $\sim 2 \times 125 W_e + 2 \times 250 W_e + 3 \times 375 W_e = 1875 W_e$ total
→ Demand of 15 MMRTGs in 12 years
 - Pu-238 isotope production restart ~ 1.1 kg/yr → 9 fuel clads/year → 32 fuel clads/MMRTG
→ single 125 W_e MMRTG every 4 years → Supply of 3 MMRTGs in a 12-year period
 - All at a sustainment cost of $\sim \$75$ M/yr (Pu-238 plus hardware)
- **Supply versus Demand:** Needs to be monitored carefully by joint NASA and DOE activity
- Increase flight rate via two routes
 - More efficient converters (segmented thermoelectrics (JPL), Stirling (GRC)) - requires continued technology investment
 - Increased Pu-238 production (requires outfitting additional hot cell to reach 5 kg / yr)

***Use of MMRTG limits certain science missions that could be done**

General Observations

- Communications between all concerned divisions of NASA (SMD, HEOMD, STMD) and of DOE (NE, NNSA) must remain open in a timely and on-going fashion
 - Important for programmatic efficiency
 - Important for technology development
 - Important for achieving flight status
- Need for streamlining lines of authority and management for development of flight articles
- This study has identified communication issues which need to be strengthened as these efforts go forward including:
 - SMD and HEOMD should coordinate any future requirements, as they evolve, in a timely fashion
 - NASA nuclear investments should be coordinated both within NASA and with DOE in a united set of requirements

Take Away from NPAS Effort

- Nuclear power systems are required for many scientifically compelling SMD mission concepts $< 1 \text{ kW}_e$ (meets requirements now, and for the foreseeable decades)
- FPS is not a fit for currently projected SMD mission concepts
 - Would likely not enable non-orbiting mission (landers and/or rovers)
 - Would likely not, therefore, enable breadth and depth of Decadal science
- FPS has promise and is likely required for HEOMD surface missions
- Sustaining RPS capability requires continued technology development and plutonium (Pu-238) production and maintenance of the associated infrastructure by NASA
- To meet SMD science needs across cost classes (Discovery, New Frontiers, and Flagship) both thermoelectric and Stirling convertors are enabling for the foreseeable future
 - Continued investments are needed to advance these technologies
 - Enables compelling science output by achieving higher power output, balancing plutonium usage and production in support of an increased flight rate, remaining within mission budget constraints, and retiring mission risk.
 - Stirling power convertors have never been flown; opportunities for future technology flight demonstration of such convertors should be considered in support of dynamic converter technology maturation and risk reduction