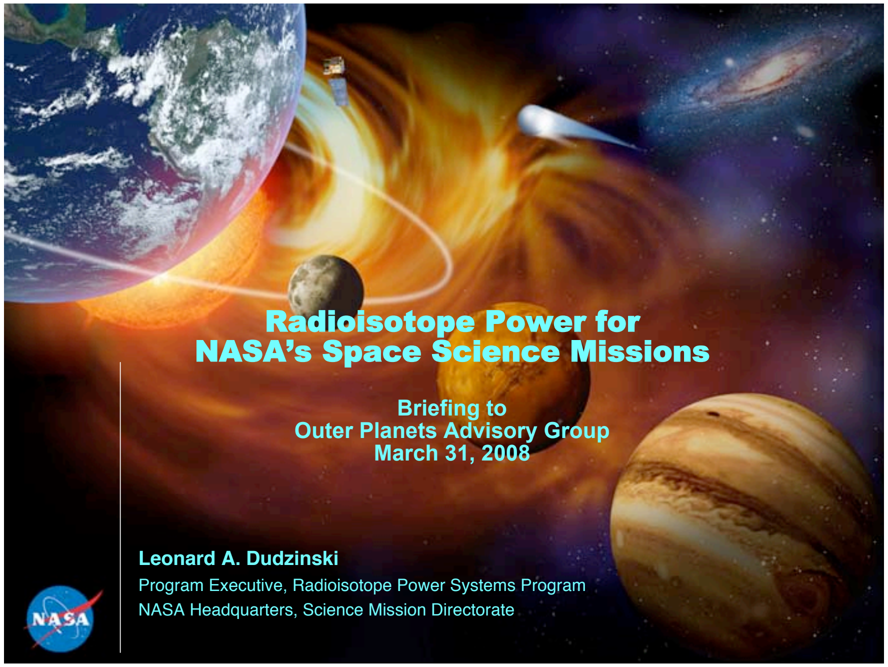


Radioisotope Power for NASA's Space Science Missions

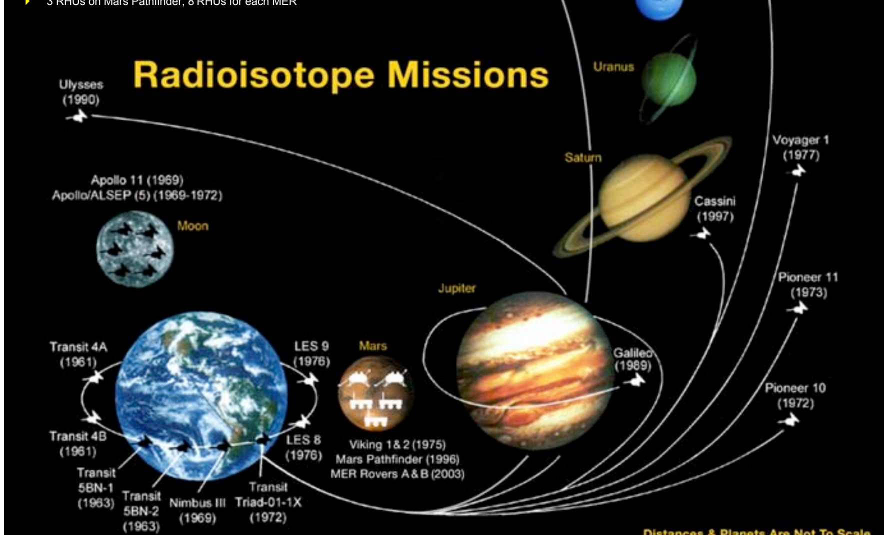
Briefing to
Outer Planets Advisory Group
March 31, 2008

Leonard A. Dudzinski
Program Executive, Radioisotope Power Systems Program
NASA Headquarters, Science Mission Directorate

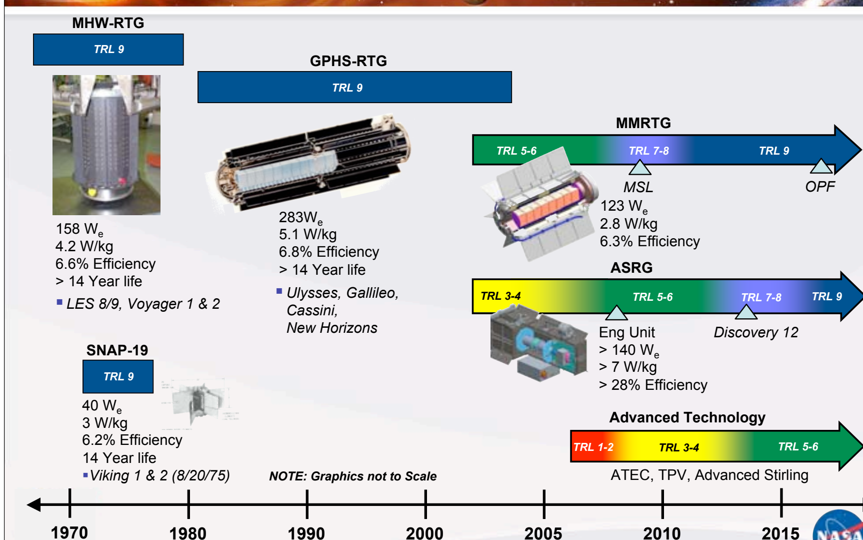
Outline

- RPS History
- RPS Technologies Performance Comparison
- RPS Availability Study
- Plutonium Shortage
- Discovery & Scout Mission Capability Expansion - Status
- ASRG Development - Status
- Plans for Discovery 2009 AO

- RTG's were used safely in 28 missions since 1961
  - 10 Earth orbit (Transit, Nimbus, LES)
  - 8 planetary (Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons)
  - 6 on lunar surface (Apollo ALSEP)
  - 4 on Mars surface (Viking 1& 2)
- 3 RHUs on Mars Pathfinder, 8 RHUs for each MER



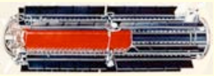
Radioisotope Power Systems Technology Evolution



RPS Development History

Current Technology

History of success

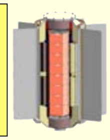


GPHS-RTG
- 285 W_e
- 6% Efficiency using SiGe Thermoelectrics
- 18 GPHS
- 4 W_e/kg (EOL)
- Vacuum applications

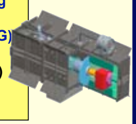
Flight Development

Flight system development managed by DOE
- Drivers: Multi-mission, Life & Reliability, Modular

Multi-Mission RTG (MMRTG)
- Lower risk, low efficiency (8 GPHS)
- 123 W_e, 6% Efficiency (PbTe/TAGS)



Advanced Stirling Radioisotope Generator (ASRG)
- ¼ Pu-238 as MMRTG (2 GPHS)
- > 140 W_e, >28% Efficiency



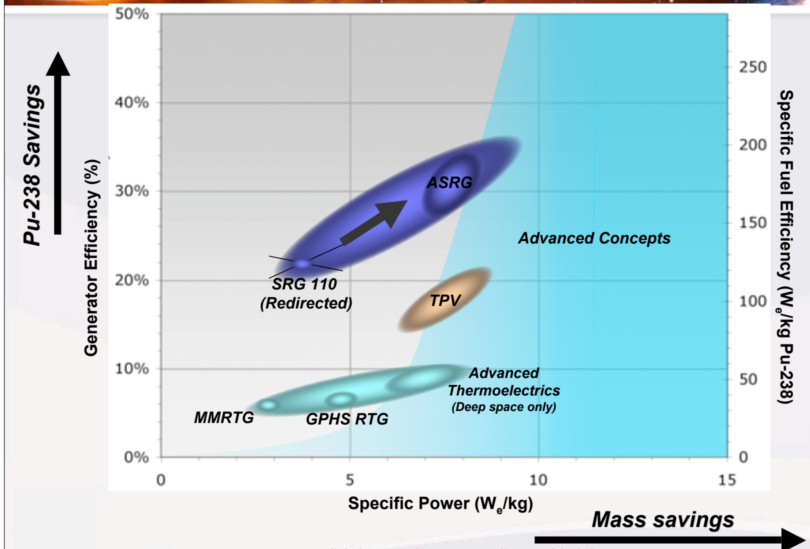
Advanced Technology

Radioisotope Power Conversion Technology (RPCT) Project
- Additional Drivers: Improved Performance, Lower Mass
- NRA extended phase

- Improve
  - Efficiency
  - Specific Power
  - Reliability
- Scalable
- Multi-mission capability

In-house Advanced Research
- GRC Stirling Development
- GRC Thermophotovoltaics
- JPL Thermoelectric Development

RPS Technology Comparison



Origin Of The ASRG and MMRTG

1995 — 2001 — 2004

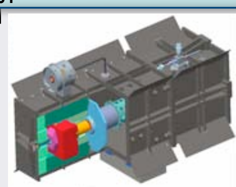
New NASA Directives

Do smaller missions
- (lower power)

Reduce the cost
- (smaller RPS)

Fly more often

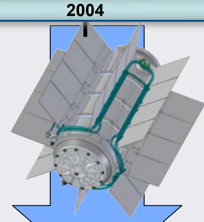
Joint NASA / DOE team reviewed:
- Missions planned
- Available RPS Options



SRG recommended to meet a range of space and surface missions at ~ 100 W_e

MMRTG recommended as backup

SRG-110 and MMRTG projects started under NSI / Prometheus



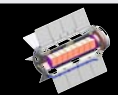
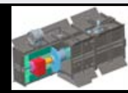
MSL Selects MMRTG Development transferred to MSL

Radioisotope Power System Application in Near Term Planetary Missions

Flagship / Mars / New Frontiers / Lunar / Discovery/Scout	Projected Launch Year	Power Req'm (W_e)	RPS Type	^{238}Pu Usage (kg)	
Mars Science Lab	2009	100	1 MMRTG	3.5	In Development
Juno (New Frontiers 2)	2011	No RPS requirement			In Development
Discovery 12	2014	250	2 ASRG	1.8	Under Study
New Frontiers 3	2016	250-600	2-4 ASRG	1.8-3.5	Directed Non-nuclear
Outer Planets Flagship 1	2017	700-850	7 MMRTG	24.5	Under Study
Discovery 13	2017	No RPS requirement			
Solar Probe	2020	200	2 MMRTG	7.0	Directed Non-nuclear

- Out year New Frontier mission opportunities will likely require 250-600 W_e RPS
- Future odd numbered Discovery mission opportunities may have an RPS option
- Next Flagship mission will be post 2025
- Radioisotope heater units may be required on these and other missions
- Other science missions not listed here may also require RPS

RPS System Performance Comparison

	MMRTG 	ASRG* 
BOM Net Electrical Power	123 W_e	140 - 160 W_e
Total Mass per Unit	44 kg	22 - 20 kg
Specific Power	2.8 W_e/kg	6.4 - 8 W_e/kg
Mass for >800 W_e FS Mission	308 kg (861 W_e)	132 kg (840 W_e)
RPS System Efficiency	~ 6.3 %	> 28%
W_e per kg Pu^{238}	35 W_e/kg	159 - 180 W_e/kg
Mass of Pu^{238} per Unit	3.52 kg	0.88 kg
Number of GPHS Modules	8	2
Development Cost	$94M	~$115M
Unit Cost	$36M	$20M
Hot / Cold-end Temperature	538°C / 210°C	640 - 850°C / 80°C
BOM Heat Output	1877 W_t	360 W_t

* *Range based on ASRG development options*

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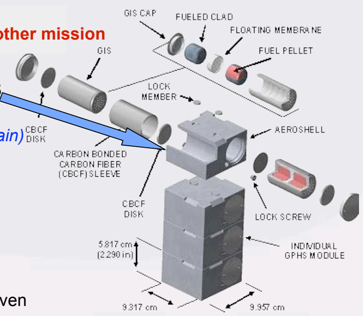
RPS Flagship Availability Study Summary Findings

- **Usable Pu^{238} inventory identified**
  - Assumes all Russian plutonium purchases made
  - Does not include new US production
  - **Enough for MSL, Discovery 12, OPF, and possibly one other mission**
- **Additional Issue: Losing vendor for Fine Weave Pierced Fabric (FWPF) material used to make GPHS**
  - DOE pursuing either a replacement material or a new method of procuring FWPF *(Cost & schedule impact uncertain)*
  - **Limits GPHS available to OPF**



- **MMRTG production rate: 1 per year (start 2010)**
  - TRL 7 in Jul 2008
  - 2 fueled MMRTG per year possible with full scale ASP line
- **ASRG production rate: 3 per year (start 2011)**
  - TRL 6 in Mar 2008, TRL 7 possible in 2010 if "Go Ahead" given
- **DOE issues**
  - Recommends NASA buys remaining Russian fuel
  - Recommends NASA funds continued uninterrupted production of Pu pellets after MSL MMRTG is fueled
  - DOE seeks authorization for new US Pu^{238} production (FY09 appropriation)
    - First output would be in 2014, with full production by 2016 *(Only 1/2 assumed to NASA)*
- **Plutonium needs must be balanced between Science & Exploration**

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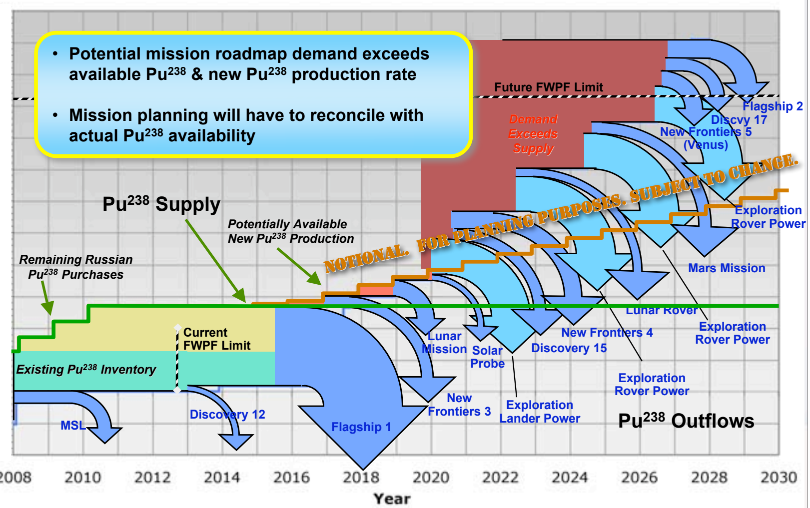
Plutonium Supply vs Potential NASA Demand
Magnitude of the Potential Shortage



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RPS Availability Study Results

- **SMD has allocated money to purchase all remaining Russian ^{238}Pu, and support DoE efforts to negotiate a new contract**
- **SMD has allocated money to extend current last-production run of FWPF to meet mission needs for the foreseeable future**
- **SMD & ESMD endorse DoE efforts to restart domestic production of ^{238}Pu**
- **The 2015 Outer Planet Flagship mission will use MMRTGs**
  - Missions encouraged to reduce power requirements
  - Decision based on risk of large OPF mission with new technology (including ASRG)
- **ASRG will be readied for flight as quickly as practical, and SMD will look for a mission opportunity to flight validate the new power system**
  - Competed missions (Discovery & New Frontiers) avoid new technology risk (like ASRG)
  - Imperative for Discovery & Scout Mission Capability Expansion Program

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Discovery & Scout Mission Capability Expansion
Program Summary

- **Program Purpose**
  - Create opportunity for new science on Discovery and Scout budgets
  - Foster exploration of Discovery & Scout class missions enabled by nuclear power in the planetary science community
    - Encourage the formation of mission design teams to begin the discussion of necessary engineering trades
  - Inform NASA of the breadth of missions possible with the addition of the ASRG technology to the Discovery and/or Mars Scout programs
- **Program Plan**
  - Solicit mission concept proposals for small planetary missions that require a nuclear power source (such as the ASRG)
  - Award funding for 6 to 8 six-month detailed mission concept studies.
  - Evaluate these mission concepts to inform decision to expand the mission capabilities of the Discovery and Mars Scout programs to include radioisotope power systems.
- **Groundrules**
  - Studies are expected to be led by a scientist serving as Principal Investigator (PI) with a small science team
  - Mission design is a critical part of these studies to make trades, explore feasibility, & refine the mission concept
    - Mission design expertise will be offered from JPL's Team-X and GSFC IDC
  - Short proposals (7 pages) are solicited that clearly summarize :
    - The mission concept,
    - Science target(s) and objectives,
    - Relevance to NASA objectives and Decadal Survey science objectives,
    - Nature of the science advancement expected from the mission.
    - Justification of the need to use the ASRG
  - Missions must fit within Discovery or Scout Mission Class

Discovery & Scout Mission Capability Expansion
Mission Study Selections

No	Target	Title	Principle Inv	Institutions
34	Moon Mobile Lander	ExoMoon: ASRG-Powered Lunar Polar Exploration	Dr Richard Elphic	**LANL**, Ball Aerospace, Honeybee Robotics, UC, GSFC, ARC, CUA, UHi
6	Moon Rover/Comsat	JEDI: A Lunar Polar Volatile Explorer	Dr Bradley Jolliff	**Washington U**, SWRI, LANL, LM, Obv. Midi-Pyrenees, U of Guelph
19	Titan Boat	Titan Mare Explorer (TiME)	Dr Ellen Stofan	**Proxemy Research**, UofAz, CITech, Lockheed Martin, USGS, JHU/APL
3	Io Fly-Bys	Io Volcano Observer (IVO)	Dr Alfred McEwen	**U of Arizona**, USGS, SWRI, Physikalisches Institut
11	Trojan Lander	ASRG-Enabled Trojan Asteroid Mission (Ilion)	Dr Andrew Rivkin	**JHU/APL**, GRC, SETI Institute
21	Comet Lander	Comet Hopper (CHopper)	Dr Jessica Sunshine	**U of Maryland**, Cornell, Smithsonian Inst, UWa-Seatle, UTx-Austin, LM
2	Comet Sample Return	Comet Coma Sample Return Mission	Dr Scott Sandford	**ARC**, U of Central FL, U of Md, Lockheed Martin
32	Mars Lander Drill	Kuklos: A tour through martian history	Dr Michael Hecht	**JPL**, UC-Berk, LM, CITech, ARC, Geological Survey of Canada
5	Venus Balloons (2)	Polar VALOR: Venus Balloon	Dr Kevin Baines	**JPL**, UMi, UWi-Madison

ASRG Status 2nd Quarter FY 2008

- **Advanced Stirling Radioisotope Generator Engineering Unit assembly completed**
  - Three ASC-E convertors were delivered to LMSSC in October 2007, on-time and exceeding power specification!
  - Two convertors have been integrated into the ASRG-EU
  - Generator processing completed January 28, 2008
  - Generator testing has begun at LMSSC
  - Generator will be delivered to NASA GRC in June 2008 for life testing

ASC-E Convertor

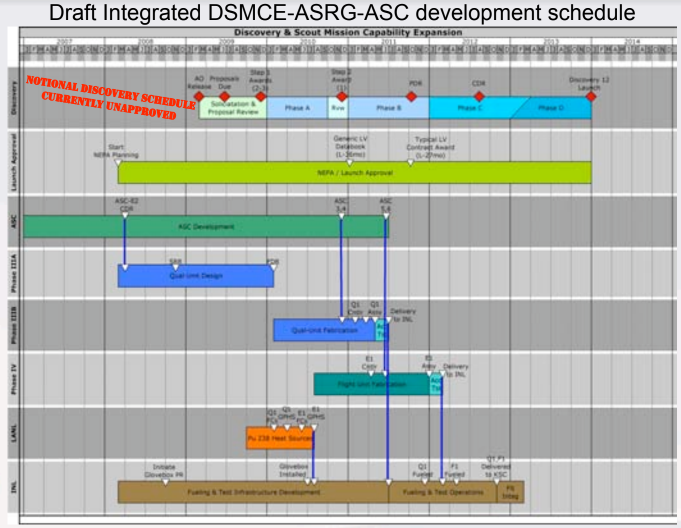
Pair of ASC-E Convertors during Integration

Completed ASRG Engineering Unit

SUNPOWER GRC LOCKHEED MARTIN

ASRG Development Plan

Draft Integrated DSMCE-ASRG-ASC development schedule



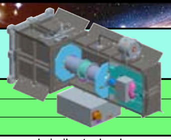
Discovery ASRG Expectations

- Up to 2 ASRGs will be offered to the mission PI as GFE (no-cost to proposal)
- AO will be open to RPS/ASRG and Non-RPS proposals
- TMCO assessed risk for proposing ASRG will be discounted by selecting official
- If a non-RPS mission is selected, ASRGs will be completed and available for flight on another mission

Backup Information

RPS Comparisons from a Mission Perspective

Major Advantage
Minor Advantage



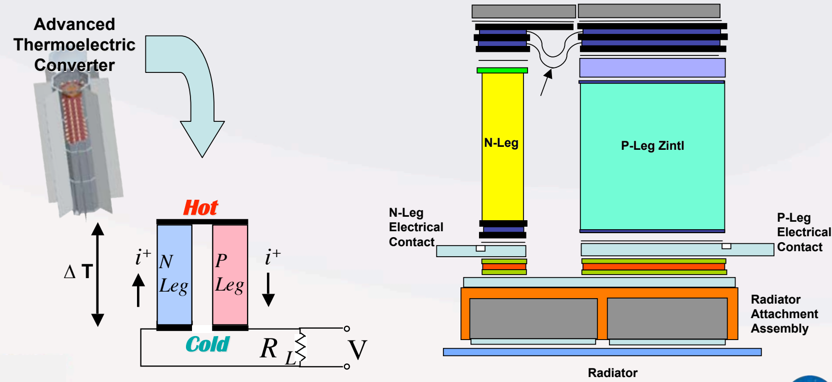
	MMRTG	ASRG
Char-acteristic:	123 W BOL	140 W BOL
	44 kg	22 kg
	Requires 8 GPHS modules.	Requires 2 GPHS modules.
Flight Heritage:	PbTe-TAGS elements were used on RPS missions 1972 to 1975	Cryocoolers have flown with same and similar technology.
	New generator design first flight in 2009 on MSL.	Gas mgmt and some structure components have RTG heritage
	Experienced in mission implementation and S/C integration.	Ground testing continues on engines/alternators. 10+ yr demo.
Lifetime:	Design requirement for 14 year mission after 3 year storage.	Design requirement for 14 years after 3 year storage
	0.7%/yr loss of power (+0.8%/yr from Pu decay)	Negligible from ASC (0.8%/yr from Pu decay)
	Predicted power loss 22% over 14 year life	Extended ASC ground tests continue. System life test starts 4/08
Reliability:	Passive failure modes with series/parallel/cross-strapping of every TE element w/100s of elements in each RTG.	Same tech terrestrial Stirling coolers have MTBF >500,000hr, >4000 w/44M cum hrs. 50% power if one converter fails.
		Controller fault tolerant. To be proven in EU in Q1 FY08
Risk Mitigation:	EU tests nearing completion	EU assembled and tested by Q2 FY08.
	Extended operation testing will begin in Q3 FY07.	Extended operation to begin in Q3 FY08.
Thermal:	Waste heat available from 8 GPHS modules at 210 ºC skin	Waste heat available from 2 GPHS modules at 80 ºC skin
	More waste heat may require added cooling for aeroshells.	Less heat at lower temperature is desirable for aeroshells.
Cost:	$94 M development ($11 M remains for QU)	$115 M development ($15M remains for EU, $36 M for QU)
	$36M recurring cost for fueled units.	$20M recurring cost for fueled units.
Radiation hardness:	Materials selected for radiation environments	All controller components rated between 500 kRad and 5 Mrad.
	No shielding required to increase radiation tolerance.	Standard shielding for higher radiation environments.
Electro-magnetics:	DC only	AC & DC
	EMI needs to be addressed at the spacecraft level. Requirement below 25 nT at 1 meter.	EMI needs to be addressed at the spacecraft level. Requirement below 25 nT at 1 meter. Shielding possible for lower levels.
Vibration:	No moving mechanical components.	Meets requirement of < 35 N at 102 Hz with large margin
MMOD:	Shell pen. results in loss of TE cover gas & rapid power degr.	Shell acts as bumper shield for Stirling converter
Shock:	Meets 0.2 g^2/Hz launch vibration requirement.	Meets 0.2 g^2/Hz requirement. 0.3 g^2/Hz goal.

Backup Reference Slides: 9A, 9B,9C

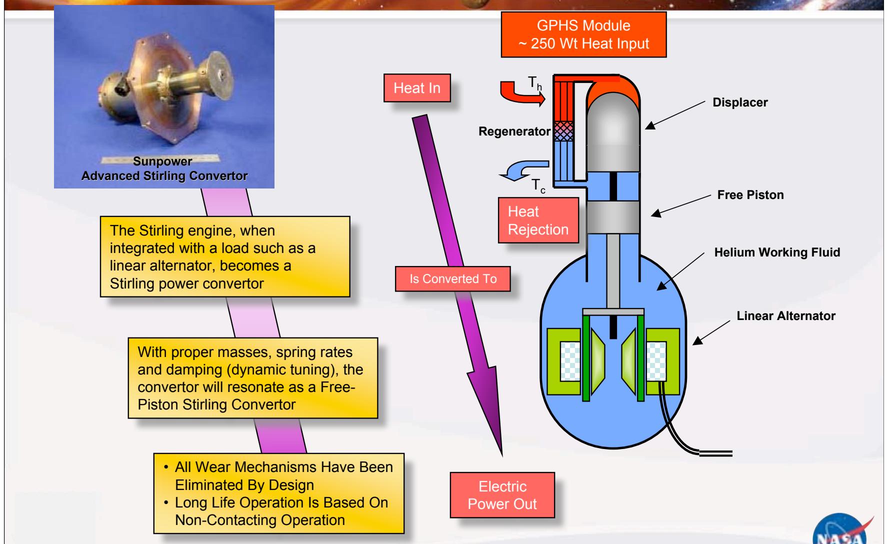
Thermal Electric Principles of Operation

Generic Thermoelectric Couple Principle of Operation

ATEC Couple Concept



Stirling Convertor Principle of Operation



DSMCE Program Overview

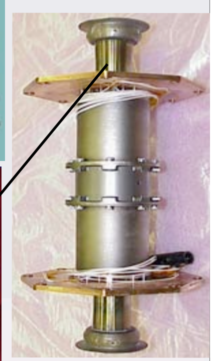
- Program solicited mission concept proposals for small planetary missions that require the ASRG power source
  - Two Stirling Engines with ~140 Watts each (as GFE)
- Intended to foster science exploration in planetary science by missions enabled by ASRG
- Mission design assistance for these 6 month mission concept studies will be offered by NASA
- Selected 9 proposals
  - 40 proposals submitted with average budget of $271K
  - NRA directed proposers to budget $200,000-$300,000

Advanced Stirling Radioisotope Generator Engineering Unit

- Operation in space and on surface of atmosphere-bearing planets and moons
- Characteristics:
  - ≥14 year lifetime
  - Nominal power : 140 We
  - Mass ~ 20 kg
  - System efficiency: ~ 30 %
  - 2 GPHS ("Pu^{238} Bricks") modules
  - Uses 0.8 kg Pu^{238}
- Final wiring and connections for ASRG engineering unit underway
- Reliability to be demonstrated by the end of 2009

Lockheed Martin/Sunpower

Outboard Housing and Paired ASC-Es



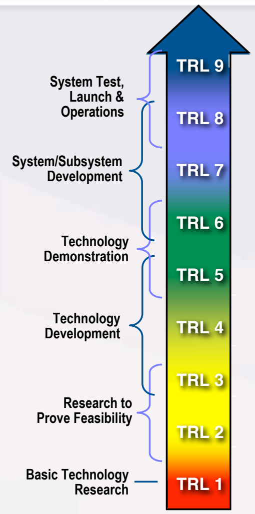
Paired converters with interconnect sleeve assembly

Just Released NRC NOSSE Report

- "*Opening New Frontiers in Space: Choices for the Next New Frontiers AO*" - NASA should:
  - R1: Emphasize science objectives
  - R2: Expand the list of candidate missions
  - R3: Limit to the list below unless compelling science
- Recommended target list in alphabetic order:
  - *Asteroid Rover/Sample Return** — Possibly RPS Enabled
  - Comet Surface Sample Return — Possibly RPS Enabled
  - *Ganymede Observer** — Likely RPS Enabled
  - *Io Observer** — Likely RPS Enabled
  - Jupiter Polar Orbiter with Probes
  - Kuiper Belt/Pluto — RPS Enabled
  - Lunar South Pole Aitken Basin Sample Return
  - *Mars Network Science** — Possibly RPS Enabled
  - *Trojan/Centaur Reconnaissance** — Likely RPS Enabled
  - Venus In-Situ Explorer
- Report located at : http://www.nap.edu/catalog/12175.html

* Additions

NASA Technology Readiness Levels



TRL 9: Actual system "mission proven" through successful mission operations
Thoroughly debugged software readily repeatable. Fully integrated with operational hardware/software systems. All documentation completed. Successful operational experience. Sustaining software engineering support in place. Actual system fully demonstrated.

TRL 8: Actual system completed and "mission qualified" through test and demonstration in an operational environment
Thoroughly debugged software. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. V&V completed.

TRL 7: Initial system demonstration in high-fidelity environment
Most functionality available for demonstration and test. Well integrated with operational hardware/software systems. Most software bugs removed. Limited documentation available.

TRL 6: System/subsystem prototype validated in a relevant end-to-end environment
Prototype implementations on full scale realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.

TRL 5: Module and/or subsystem qualified in relevant environment
Prototype implementations conform to target environment / interfaces. Experiments with realistic problems. Simulated interfaces to existing systems.

TRL 4: Module and/or subsystem qualified in laboratory environment
Standalone prototype implementations. Experiments with full scale problems or data sets.

TRL 3: Analytical & experimental critical function / characteristic proof-of-concept
Limited functionality implementations. Experiments with small representative data sets. Scientific feasibility fully demonstrated.

TRL 2: Technology concept and/or application formulated
Basic principles coded. Experiments with synthetic data. Mostly applied research.

TRL 1: Basic principles observed and reported
Basic properties of algorithms, representations & concepts. Mathematical formulations. Mix of basic and applied research.

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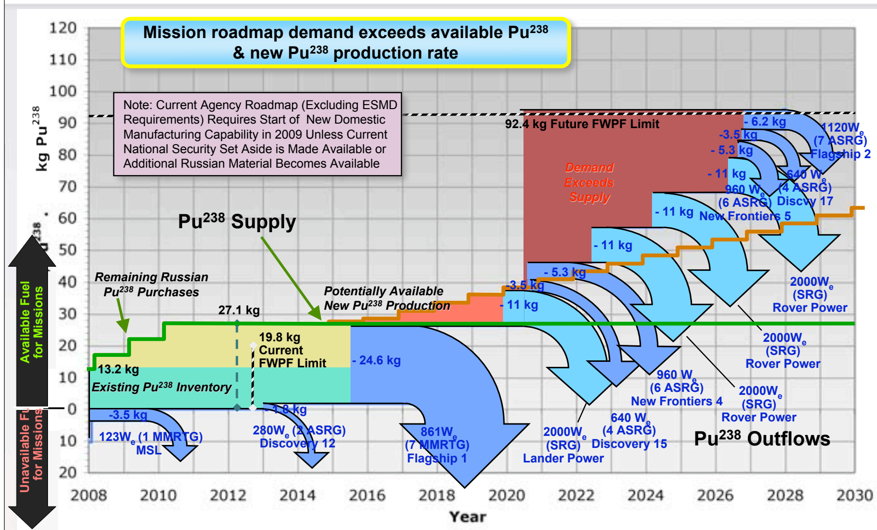
Plutonium Supply vs Potential NASA Demand
Baseline



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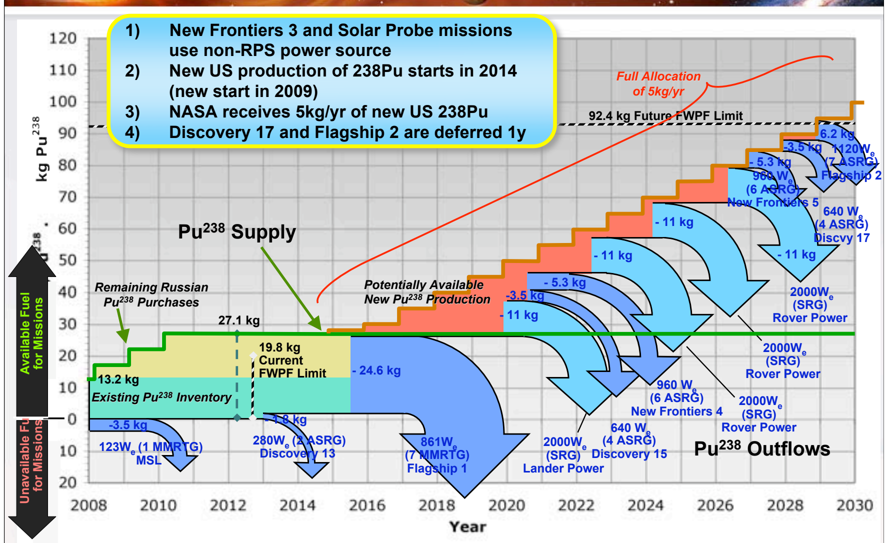
Plutonium Supply vs Potential NASA Demand
Closing Scenario



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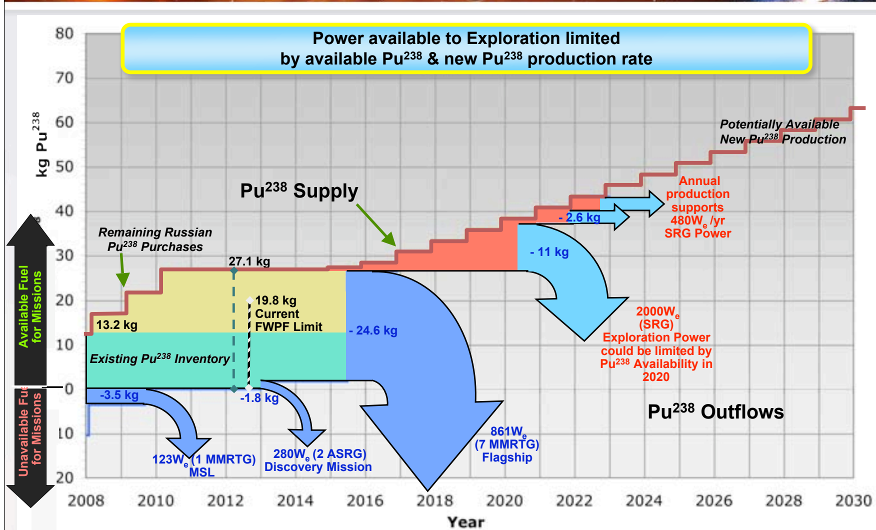
Plutonium Supply vs Potential NASA Demand
Supply Constrained Scenario



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