Next-Generation RTGs for NASA

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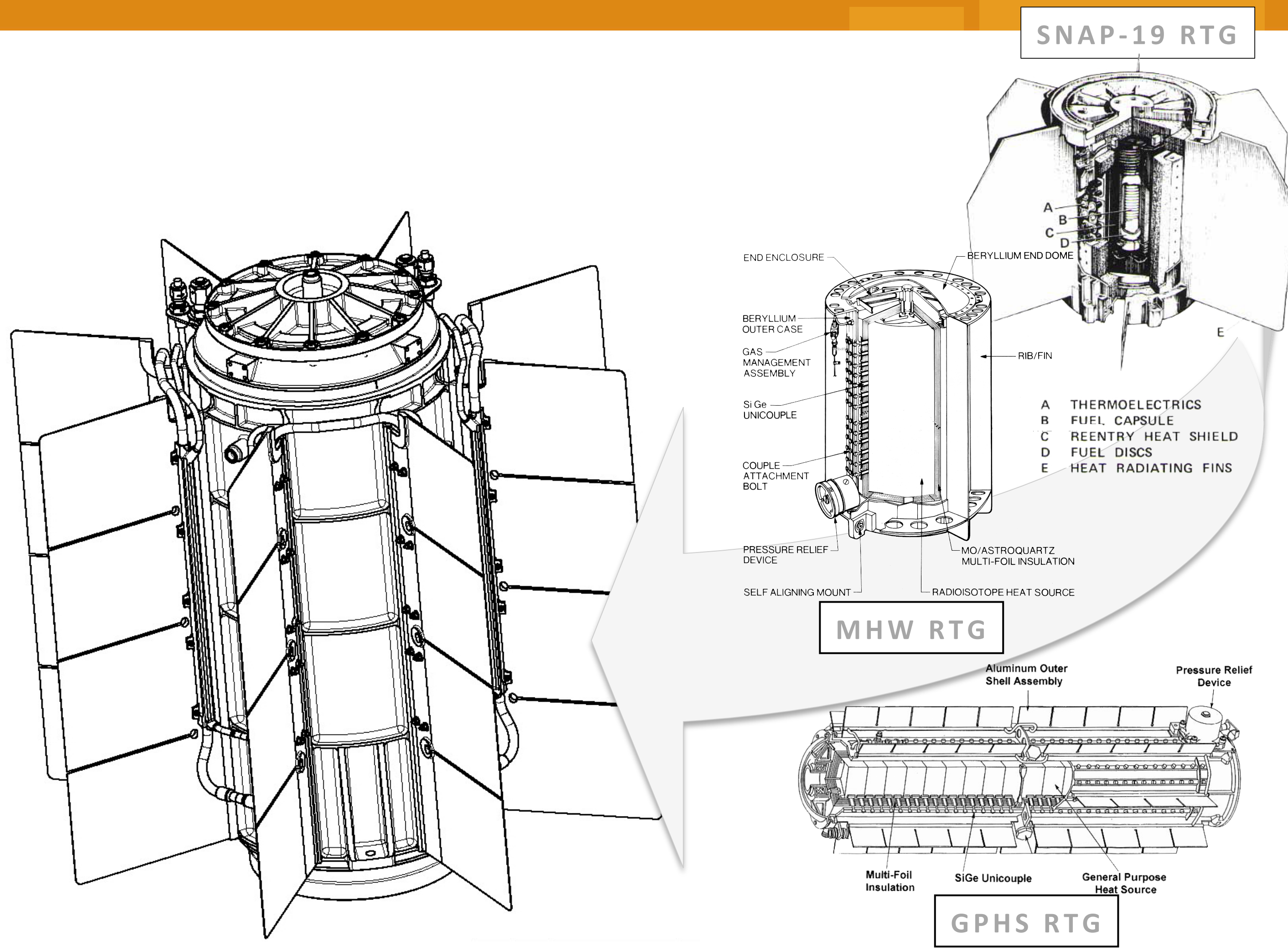
Next-Generation RTGs for NASA – *Topics*

- Introduction
- Mission Analyses
- Thermoelectric Materials and Technologies
- RTG Concepts
- Conclusion

Next-Generation RTGs for NASA – *Introduction*

- The DOE has produced a variety of RTGs that have been flown by NASA over the last 5 decades.
- RTGs convert heat produced from the decay of plutonium into quiet DC power.
- Only the MMRTG can be procured today.
- No moving parts
- An MMRTG weighs approximately 45 kg and produces 110W at launch.



MMRTG

Thermoelectrics in Space: A Success Story

56 Years of RTG-Powered, U.S. Missions

	Mission	RTG type (number)	TE	Destination	Launch Year	Mission Length	Power Level***
	Transit 4A	SNAP-3B7(1)	PbTe	Earth Orbit	1961	15	2.7
	Transit 4B	SNAP-3B8 (1)	PbTe	Earth Orbit	1962	9	2.7
	Nimbus 3	SNAP-19 RTG (2)	PbTe	Earth Orbit	1969	> 2.5	~ 56
	Apollo 12*	SNAP-27 RTG (1)	PbTe	Lunar Surface	1969	8	~ 70
	Pioneer 10	SNAP-19 RTG (4)	PbTe	Outer Planets	1972	34	~ 160
	Triad-01-1X	SNAP-9A (1)	PbTe	Earth Orbit	1972	15	~ 35
	Pioneer 11	SNAP-19 RTG (4)	PbTe	Outer Planets	1973	35	~ 160
	Viking 1	SNAP-19 RTG (2)	PbTe	Mars Surface	1975	> 6	~ 84
	Viking 2	SNAP-19 RTG (2)	PbTe	Mars Surface	1975	> 4	~ 84
	LES 8	MHW-RTG (2)	Si-Ge	Earth Orbit	1976	15	~ 308
	LES 9	MHW-RTG (2)	Si-Ge	Earth Orbit	1976	15	~ 308
√	Voyager 1	MHW-RTG (3)	Si-Ge	Outer Planets	1977	39	~475
√	Voyager 2	MHW-RTG (3)	Si-Ge	Outer Planets	1977	39	~475
√	Galileo	GPHS-RTG (2)	Si-Ge	Outer Planets	1989	14	~ 574
√	Ulysses	GPHS-RTG (1)	Si-Ge	Outer Planets/Sun	1990	18	~ 283
√	Cassini	GPHS-RTG (3)	Si-Ge	Outer Planets	1997	19	~ 885
	New Horizons	GPHS-RTG (1)	Si-Ge	Outer Planets	2006	11 (17)	~ 246
√	MSL	MMRTG (1)	PbTe	Mars Surface	2011	5 (to date)	~ 115
√	*Mars 2020***	*MMRTG (1 baselined)*	*PbTe*	*Mars Surface*	*2020*	*(5)*	*> 110*

*Apollo 12, 14, 15, 16, and 17 **Planned √ JPL/RTG Powered Missions

From a few watts to ~ 900 W; up to 39 years of operation (and counting)

Next-Generation RTGs for NASA – *Introduction*

The Next-Generation RTG Study

- Was motivated by the need for more powerful RTGs than presently available
- Serve NASA for 2-3 decades to come starting in ~2030
- To address the needs of future Decadal Survey missions
  - An RTG that would be useful across the Solar System
  - An RTG that maximizes the types of missions: flyby, orbit, land, rove, boats, submersibles, balloons
  - An RTG that has reasonable development risks and timeline

Next-Generation RTGs for NASA – *Introduction*

The Next-Generation RTG Study Team

- Drew on the talent and experience:
  - at three NASA centers:
    - Goddard Space Flight Center,
    - Glenn Research Center,
    - and the Jet Propulsion Laboratory/California Institute of Technology,
  - as well as the US Department of Energy,
  - the John Hopkins University’s Applied Physics Laboratory,
  - and the University of Dayton Research Institute.

Next-Generation RTGs for NASA – *Introduction*

Status of the Next-Generation RTG Study

- Briefed NASA's Planetary Science Directorate on February 21, 2017
- Final Report issued June 27, 2017 – ITAR Controlled
- Developing version of report for unlimited release; projected release is August 15, 2017

Next-Generation RTGs for NASA – *Mission Analyses*

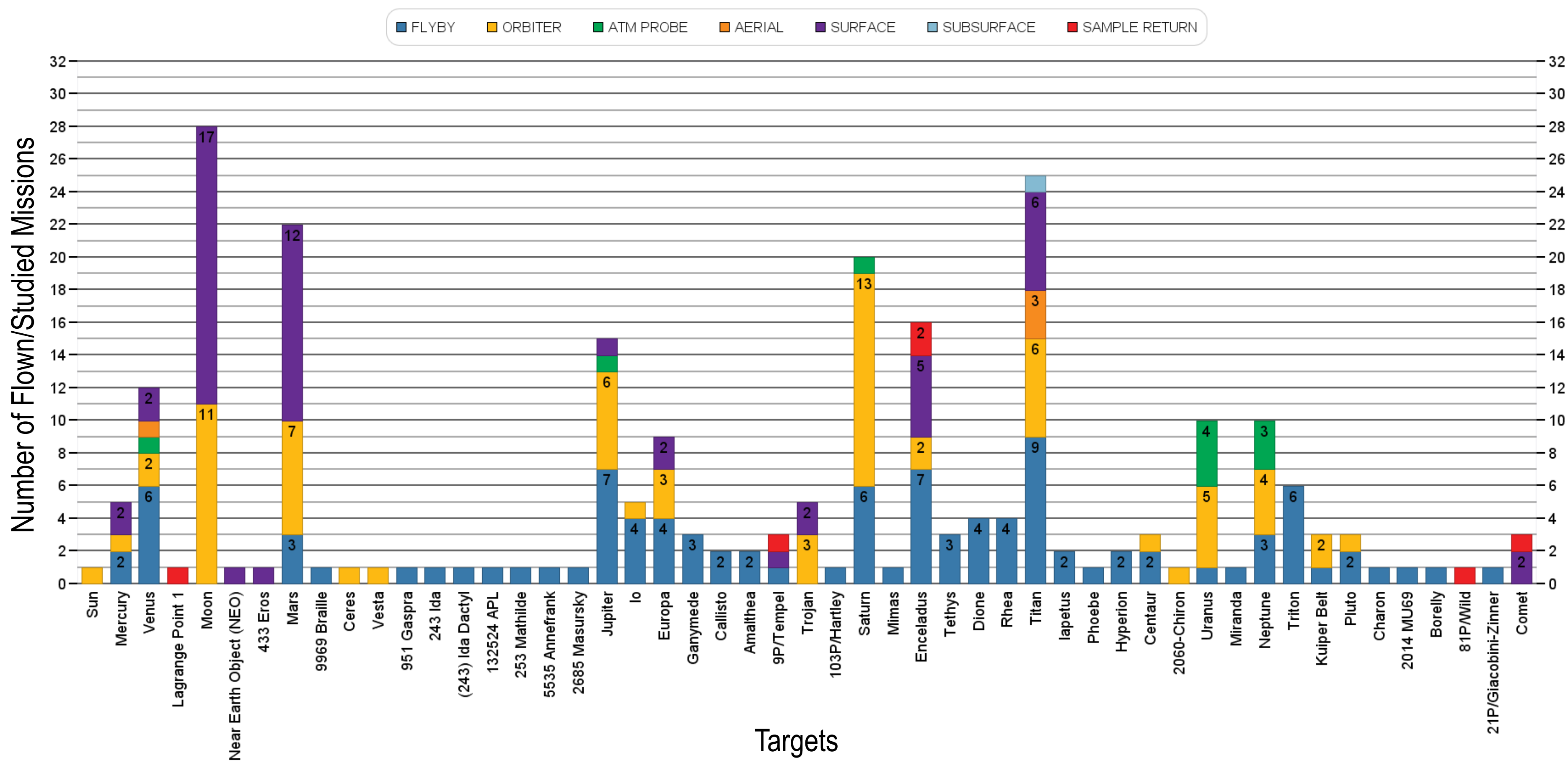
Identify Requirements for Next-Generation RTG Concepts (Top-Down)

- Review and Analyze prioritized missions recommended in Planetary Science Decadal Surveys
  - These are roadmaps used by NASA
- Review and Analyze other mission studies performed within the Agency and without.
- Include destinations within the Solar System not yet studied

An RTG that would be useful across the Solar System

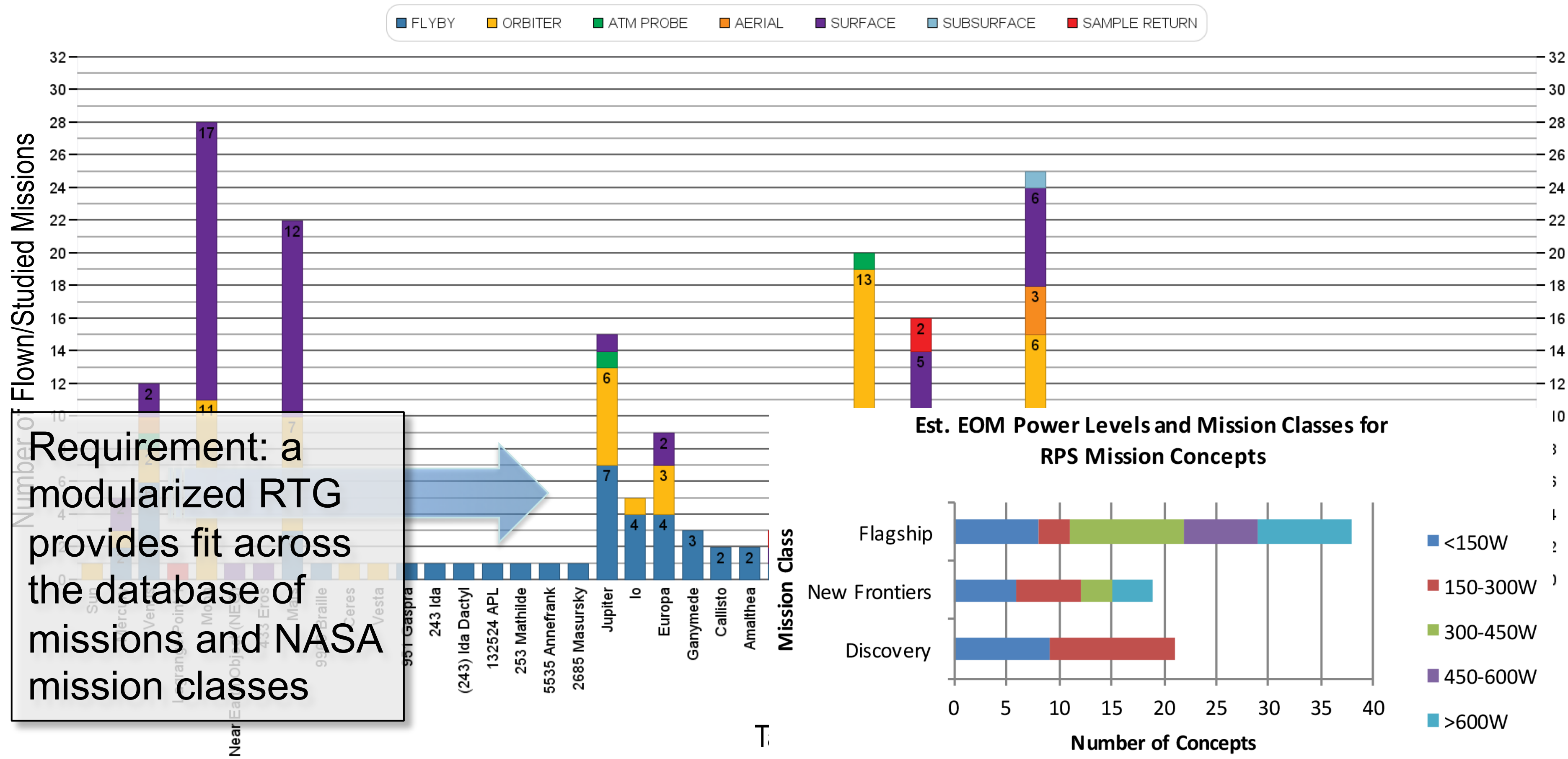
Next-Generation RTGs for NASA – *Mission Analyses*

249 Mission Studies in database



Next-Generation RTGs for NASA – *Mission Analyses (MA)*

Example of a requirement derived from Mission Analyses



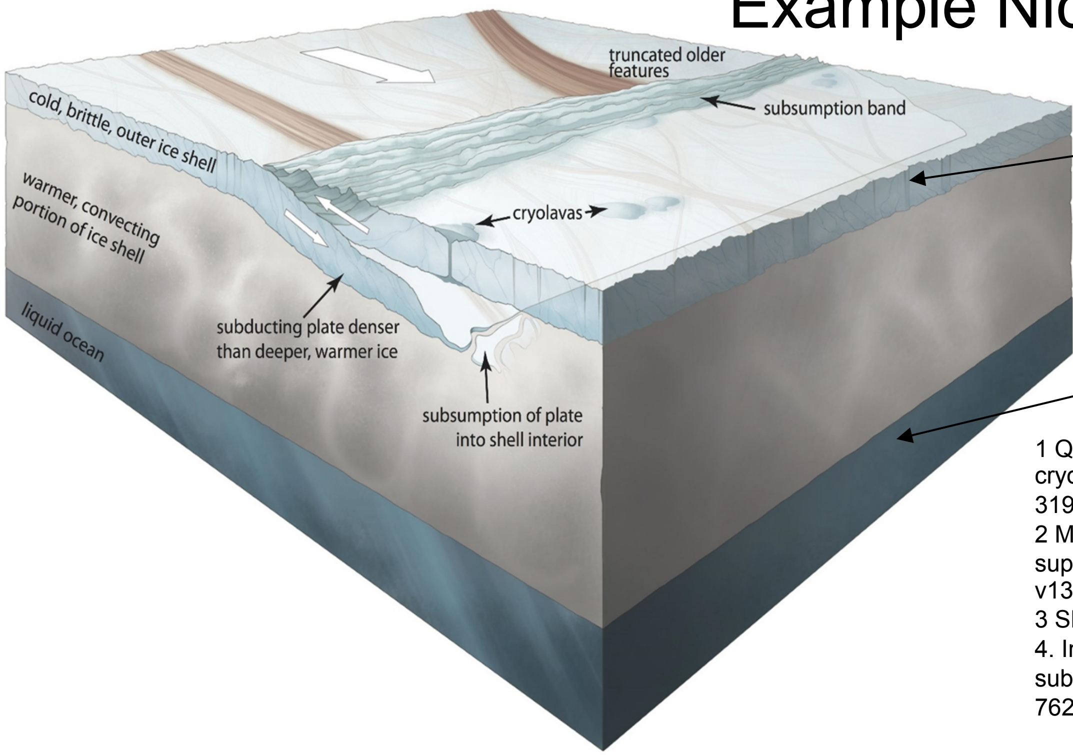
Requirement: a modularized RTG provides fit across the database of missions and NASA mission classes

Next-Generation RTGs for NASA – *Mission Analyses (MA)*

A few additional requirements flowing from the missions flown and studied

- Mission Length
- Radiation
- Descent and Landing
- Micrometeoroids
- Atmospheric pressure and atmospheric constituents
- Environmental temperatures

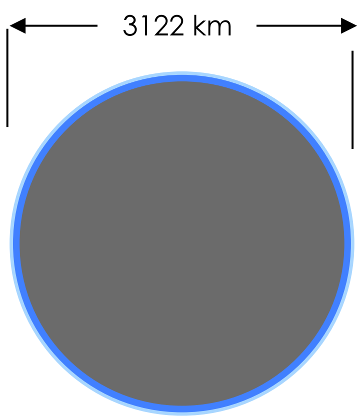
Example Niche Requirements

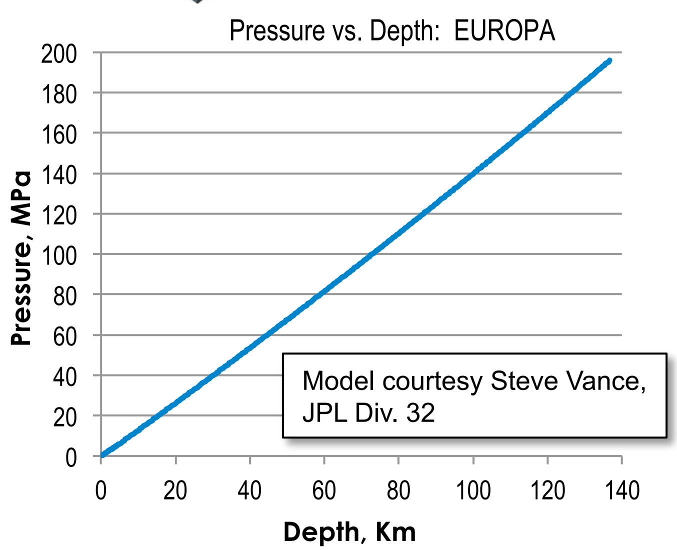


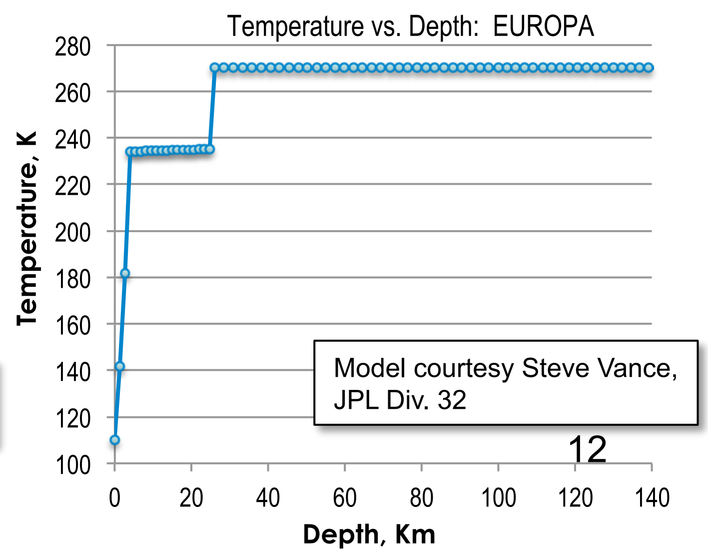
Cold (~100K), sublimation regim
- no liquid phase near surface
- no gaseous pressure

~0ºC solid/liquid, high P

1 Quick, L.C. and Marsh, B.D., 2016. Heat transfer of ascending cryomagma on Europa. Journal of Volcanology and Geothermal Research, 319, pp.66-77.
2 Murphy, D. & T. Koop, 2005, Review of the vapour pressures of ice and supercooled water for atmospheric applications, Q. J. R. Meteorol. Soc., v131, pp. 1539–1565
3 Slack, G., 1980, Thermal conductivity of ice, Phys. Rev. B, v22, No. 6.
4. Image ref: (Kattenhorn, S.A. and Prockter, L.M., 2014. Evidence for subduction in the ice shell of Europa. *Nature Geoscience*, *7*(10), pp. 762-767.)







Next-Generation RTGs for NASA – *Mission Analyses*

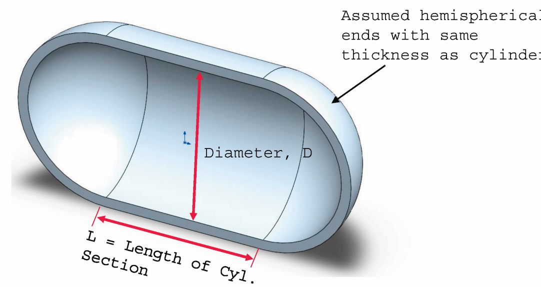
- RTG housings enhanced to be pressure vessels could be designed for high-pressure environments:
  - deep in ice,
  - oceans,
  - and on the surface of Venus.
- They are classified as specialized because of this niche requirement. The niche however is not small; the number of potential destinations/missions is significant.

Simplified Pressure Vessel for Ocean Worlds

- External Pressure
- Buckling Failure
- No additional rib structure

$$P_{cr} = \frac{2E}{(1-\nu^2)}\left(\frac{t}{d}\right)^3$$

ν = Poisson's Ratio
E = Elastic Modulus
t = shell thickness
d = shell outer diameter
P_{cr} = Buckling Pressure



S. Chattopadhyay, *Pressure Vessels, Design and Practice,* CRC Press 2004, Chapter 5

A first order look at pressure vessel concepts.

Next-Generation RTGs for NASA – *Mission Analyses*

- The waste heat of an RTG would provide advantage to a melt probe
- This capability remains a niche requirement due to the burden it would impose on users not destined for high-pressure environments

Preliminary Analysis

	composition	g (m/s2)	h max (km)	fluid density (kg/m3)	P max (atm)	shell thick Al (cm)	shell mass Al (kg)
Earth	H2O	9.8	11	1000	1064	4.31	202
Ganymede	H2O	1.43	144	1000	2032	5.64	275
Callisto	H2O	1.24	150	1000	1836	5.40	261
Europa	H2O	1.31	30	1000	388	2.90	130
Mimas*	H2O	0.064	100	1000	63	1.49	64
Enceladus	H2O	0.133	40	1000	53	1.39	59
Titan - Lakes	C2H6	1.352	0.3	650	3	0.49	20
Titan - Subsurface Ocean	H2O	1.352	20	1000	267	2.52	111
Triton	H2O/NH3	0.779	200	1000	1538	5.02	240
Ceres*	H2O/NH3	0.28	?	?		0.00	0
Pluto	H2O/NH3	0.62	260	1000	1591	5.09	244

The numbers will change with further study.

Next-Generation RTGs for NASA – *Mission Analyses*

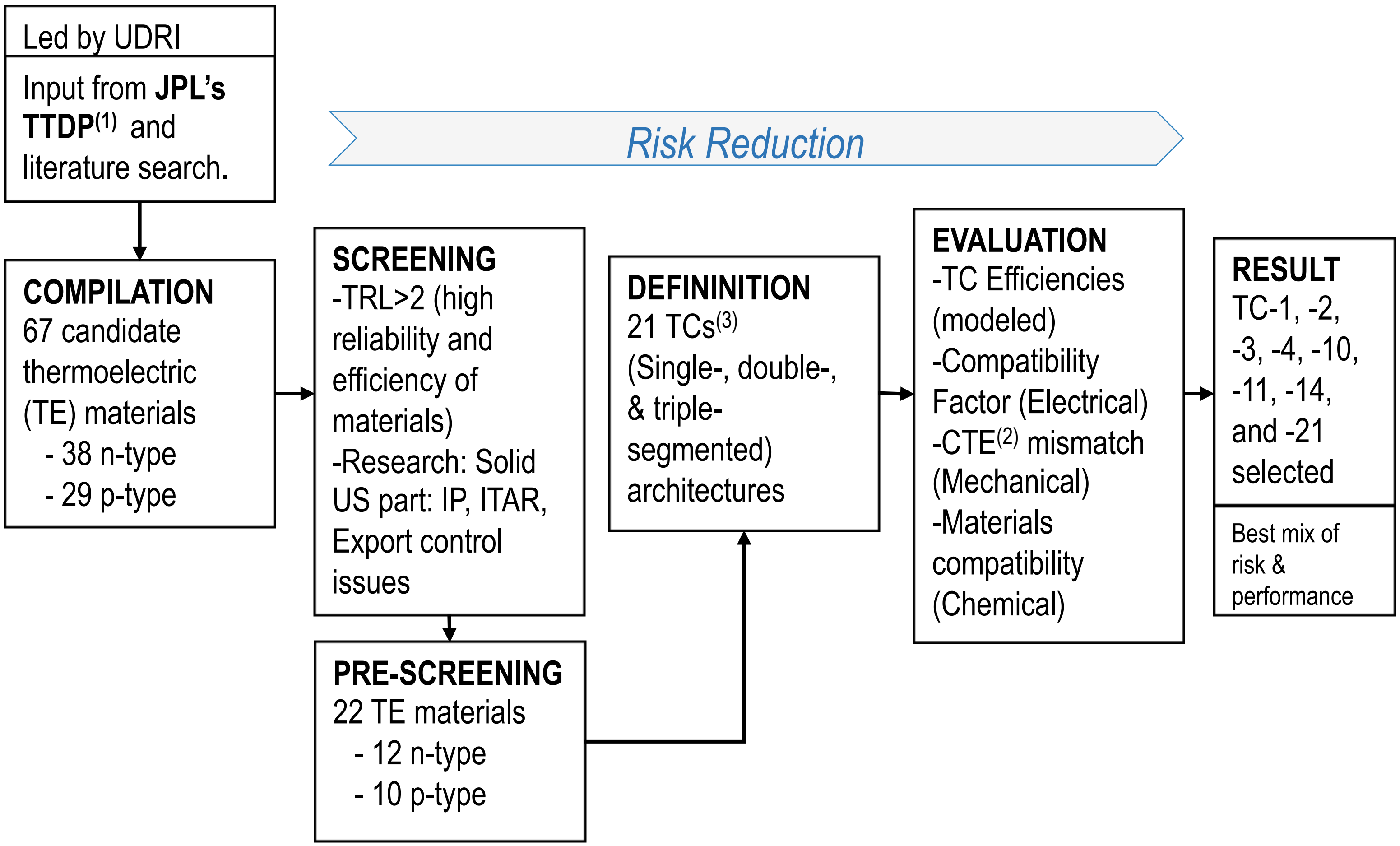
- Lastly, where mission analyses did not suffice, requirements came from reference RTGs: GPHS RTG, MMRTG, and eMMRTG
- Requirements were captured for:
  - Launch Vehicle Environments (Random vibe, shock)
  - Maximum dimensions (Height, diameter)
  - Neutron emissions
  - Ground processing-related requirements
  - Fuel thermal inventory
  - Fueled storage life
  - Allowable Flight Temperatures and Voltages
  - Qualification requirements

Next-Generation RTGs for NASA – *TE Materials & Tech*

- A wide net was cast to survey literature and laboratory results to identify TE materials potentially suitable for spaceflight
- Those materials were screened and top candidates emerged from down-selection
- Candidate materials were configured into 21 possible thermoelectric couples and risk rated
  - 8 couples survived this process

TE – Thermoelectric

Thermoelectric Technologies: Screening, Evaluation, and Selection



[(1)] TTDP: Thermoelectric Technology Development Program, managed under the NASA's Radioisotope Power System (RPS) Program. The TTDP routinely evaluates potential thermoelectric candidate technologies

[(2)] CTE: Coefficient of Thermal Expansion

[(3)] TC: Thermoelectric couple

Next-Generation RTGs for NASA – *TE Materials & Tech*

- Evaluated 3-Segment, 2-Segment and 1-Segment Configurations
  - Risks increase as number of segments increases
  - Efficiency increases (model predicted) as number of segments increases
  - System degradation rate of 1.9% assumed for all configurations

- 8 different TE configurations modeled in generator concepts

TE – Thermoelectric

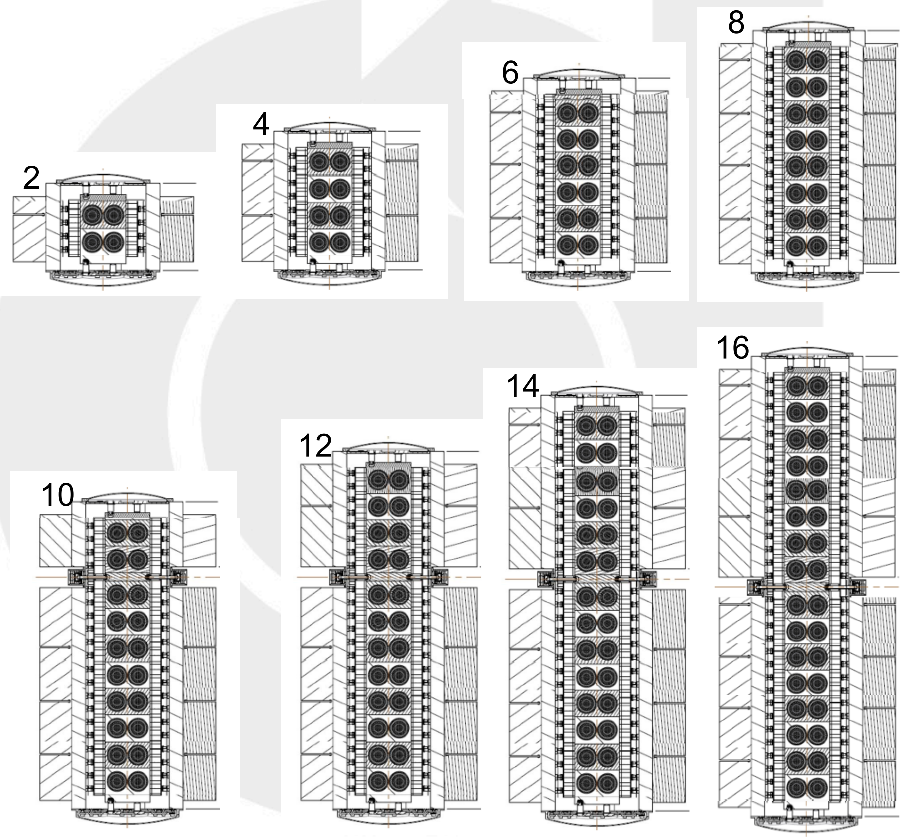
Results – TE Maturity

Configuration	# Segments	~Couple Efficiency (%) at Tcj 450K	TRL Materials n|p		TRL of Configuration	~ SMRTG Concept Efficiency (16 GPHSs)
0	SKD Only	9.8	4	4	3	9.6
1	3 Element	17	9/2/2	9/2.5/3.5	1	14.8
2	3 Element	15	9/2/3.5	9/2.5/3.5	1	13.6
3*	3 Element	16	9/4/2	9/4/3.5	2	13.9
4*	3 Element	14	9/4/3.5	9/4/3.5	2.5	12.7
10	1 Element	14	2	3.5	2	12.1
11	1 Element	11	3.5	3.5	3.5	10
14	2 Element	14	9/2	9/3.5	2.5	12.6
21	2 Element	12	9/3.5	9/3.5	2.5	10.6

* Contains SKD

Next-Generation RTGs for NASA – *Concepts*

- Types of *new* General-Purpose RTG Concepts:
  - Vacuum Only
    - Segmented (TECs)
    - Cold Segmented
    - Segmented-Modular
    - Cold Segmented-Modular
  - Vacuum and Atmosphere
    - Hybrid Segmented-Modular
    - Cold Hybrid Segmented-Modular
- Variants: 2, 4, 6, 8, 10, 12, 14, and 16 GPHS
- Specialized RTGs:
  - Pressure Vessel RTGs



Vacuum-only operations
Vacuum and atmosphere operations

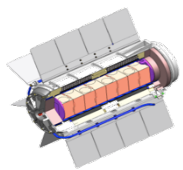
Next-Generation RTGs for NASA – *Concepts*

- Vacuum
  - Can reliably fulfill need for Flyby/Orbit and can be used to for Ocean World exploration
- Cold
  - Requires 3 segment TEC
  - Higher risk to develop
  - Conceived to benefit colder environments but is of little benefit and is NOT necessary
- Hybrid
  - Requires hermetically sealed TEC compartment
  - Complexity in design which is more complex with modularity
  - Additional risks and costs. With investment in proposed eMMRTG, not necessary.
- Modular
  - Unique housing size for each variant
  - Allows for mission flexibility without significant risk

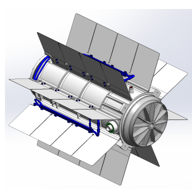
Next-Generation RTGs for NASA – *Concepts*

Types of Reference RTGs

GPHS-RTG
General Purpose Heat Source - RTG



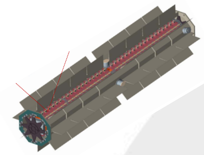
MMRTG
Multi Mission RTG



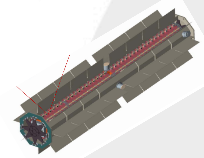
Proposed eMMRTG
enhanced Multi Mission RTG

Vacuum-only operations
Vacuum and atmosphere operations

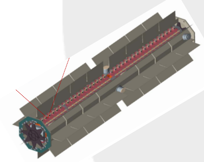
Types of Next-Generation RTGs



SRTG and CSRTG
(Cold (T_{fr}= 50 -150 C) or not T_{fr}= 50 -200C) Segmented (TEC) RTG

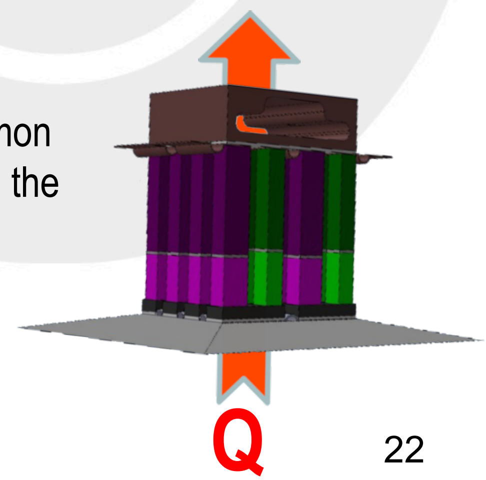


SMRTG and CSMRTG
(Cold or not) Segmented (TEC) Modular RTG

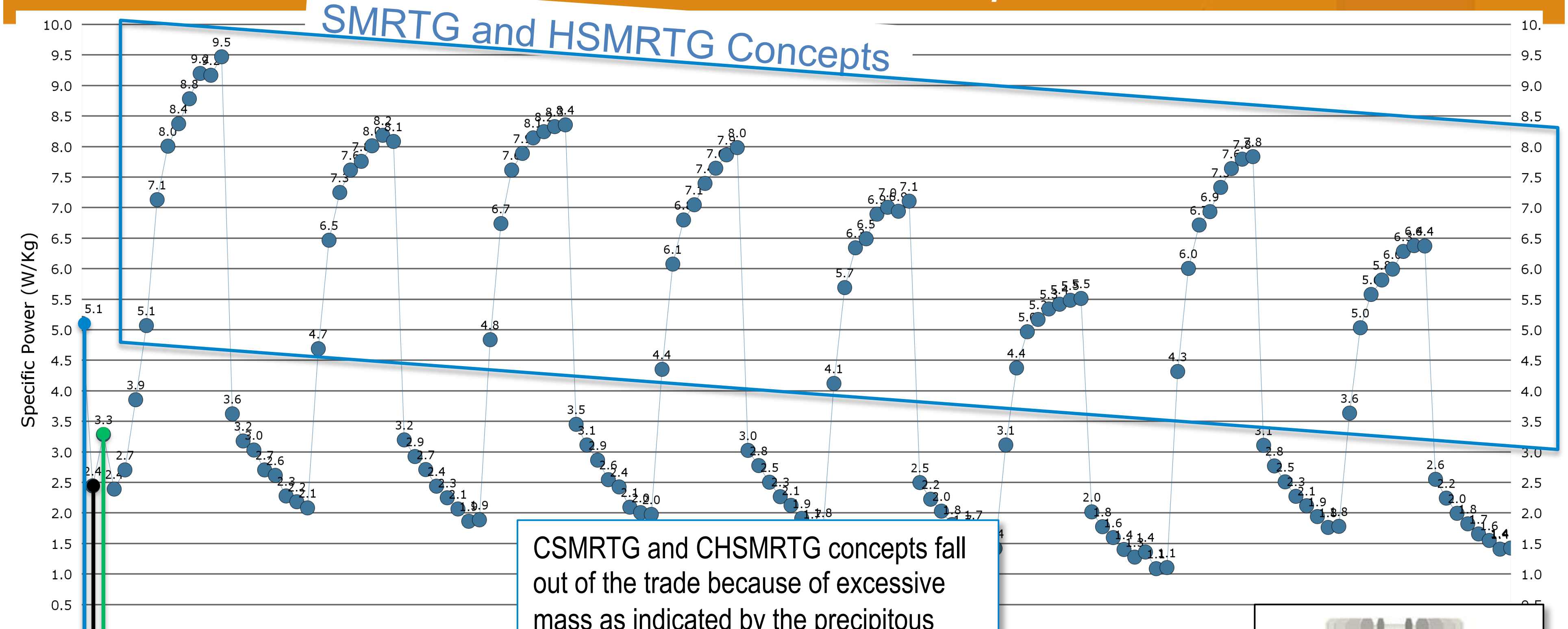


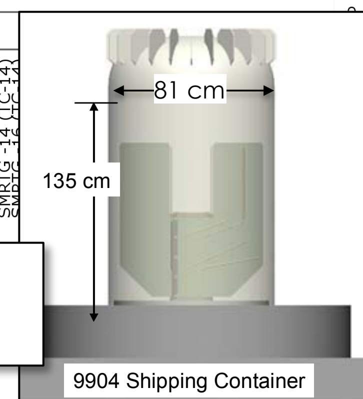
HSMRTG and CHSMRTG
(Cold or not) Hybrid Segmented (TEC) Modular RTG

Notional common building block: the multicouple. 8 couples per multicouple



Next-Generation RTGs for NASA – *Specific Power*

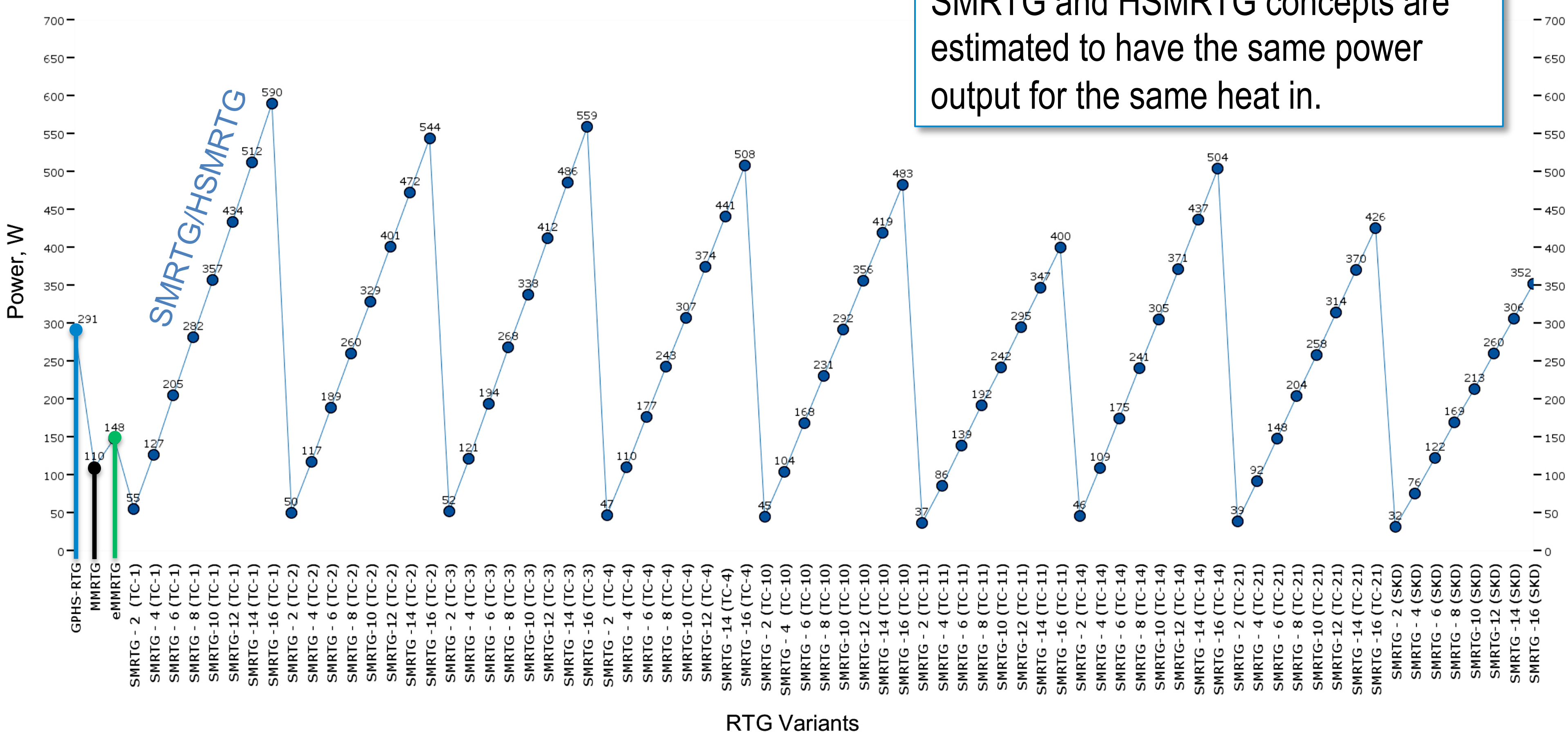




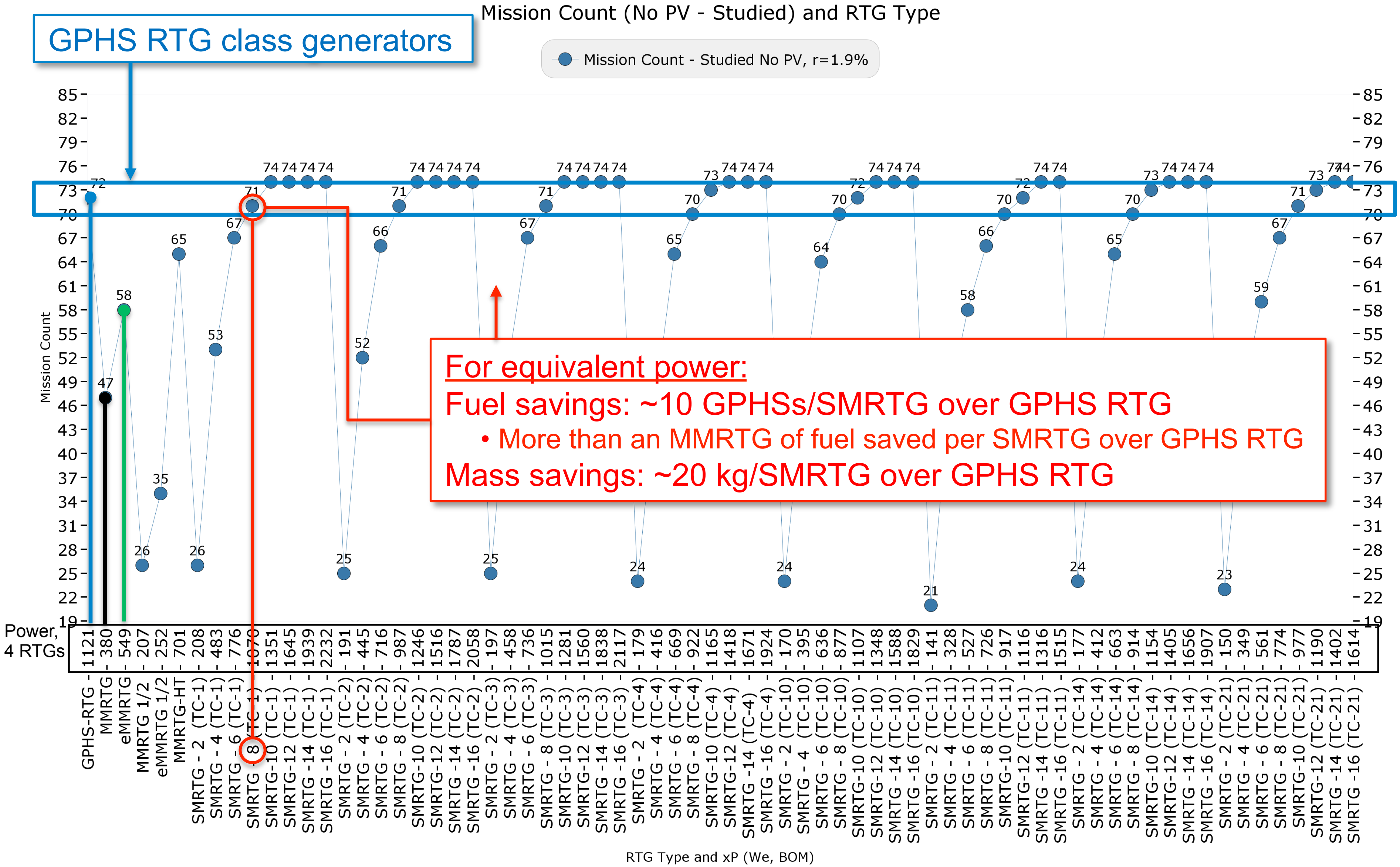
"Cold" concepts all suffer from extreme masses due to fin size to achieve "cold" temperatures. RTGs using 8 or more GPHSs do not fit in the shipping container.

Next-Generation RTGs for NASA – *Power*

SMRTG and HSMRTG concepts are estimated to have the same power output for the same heat in.

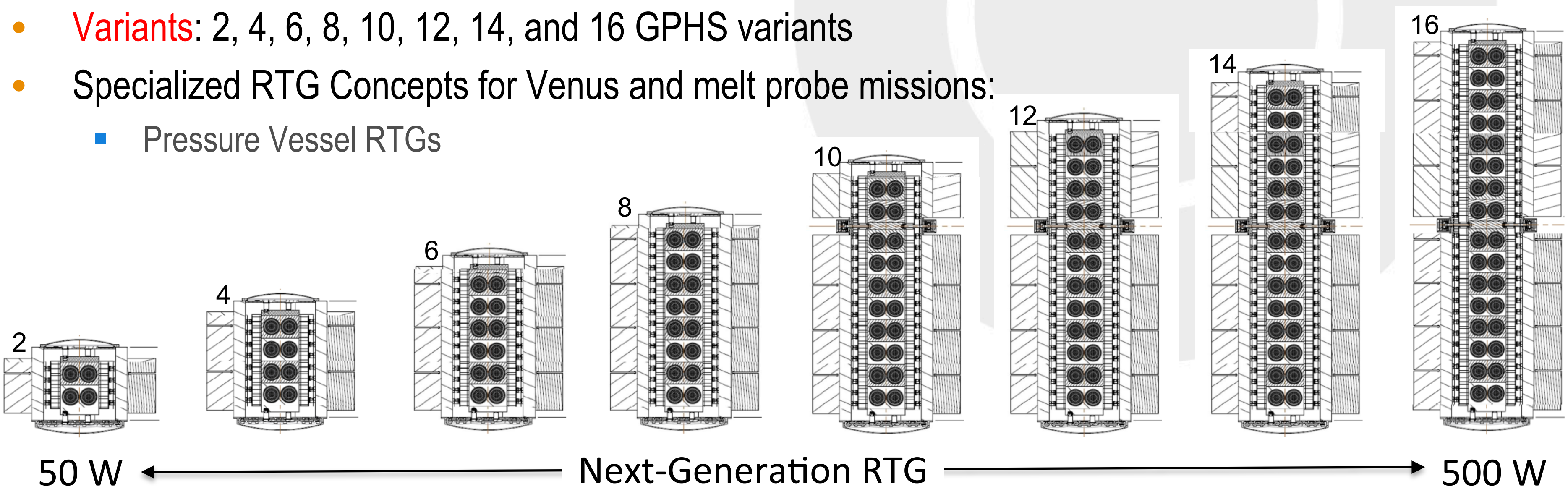


Mission Concepts "Fit" – Power Only



Next-Generation RTGs for NASA – *Concepts*

- Three surviving Types of *new, General-Purpose* RTG Concepts:
  - Vacuum Only
    - Single-point design
    - Modular
  - Vacuum and Atmosphere
    - Hybrid
- Variants: 2, 4, 6, 8, 10, 12, 14, and 16 GPHS variants
- Specialized RTG Concepts for Venus and melt probe missions:
  - Pressure Vessel RTGs

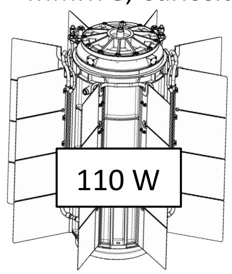


Next-Generation RTGs for NASA – *Concepts*

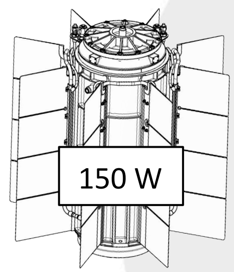
- Complete proposed eMMRTG
  - Continue with skutterudite thermoelectric couple
  - Carry development to eMMRTG Qualification Unit

- Initiate Next-Generation RTG System
  - Vacuum-only
  - Modular
  - 16 GPHSs (largest variant)
  - P_{BOM} = 400-500 We (largest variant)
  - Mass goal of < 60 kg
  - Degradation rate < 1.9 %

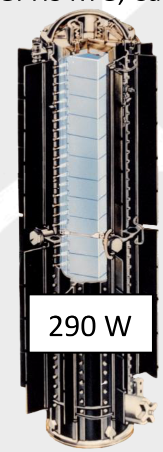
Next-Generation RTGs for NASA – *Concepts*



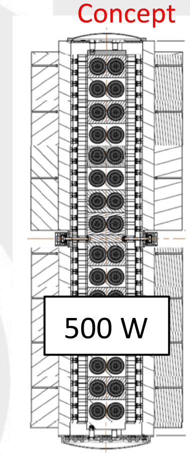
MMRTG, Curiosity



Proposed eMMRTG



GPHS RTG, Cassini



Next-Generation RTG Concept

Power, launch, W	**110**	**150**	**290 (880)**	**500**
Power, end of life, W	55	91	213 (640)	362
Degradation rate, av	4.8%	2.5%	1.9%	1.9%
# GPHSs	8	8	18	16
Length, m	0.69	0.69	1.14	1.04
Mass, kg	45	44	57	62

Next-Generation RTGs for NASA – *Study Team*

JPL	Bairstow	Brian		GSFC	Mason	Paul		GRC	Oleson	Steve
JPL	Berisford	Dan		GSFC	Beltran	Porfy		GRC	Lorenz	Ralph (APL)
JPL	Bhandari	Pradeep		GSFC	Godfrey	John		GRC	Woytach	Jeff
JPL	Borden	Chester		GSFC	Smith	Terry		GRC	Michael	Paul (ARL)
JPL	Chanakain	Sevan		GSFC	Lorenz	Blake		GRC	McCarty	Steve
JPL	Drymiotis	Fivos		GSFC	Burke	Jacob		GRC	Martini	Mike
JPL	Didion	Alan		GSFC	Beaman	Bob		GRC	Walsh	Justin (ARL)
JPL	Elliot	John		GSFC	Robinson	David		GRC	Fittje	James
JPL	Fleurial	Jean-Pierre		GSFC	Palace	Dave		GRC	Gyekenyesi	John
JPL	Hendricks	Terry		GSFC	Ramspacher	Daniel		GRC	Colozza	Tony
JPL	Jun	Insoo		GSFC	Batchelor	David		GRC	Roelke	Evan (GT)
JPL	Landau	Damon		GSFC	Garrison	Matthew		GRC	Schmitz	Paul
JPL	Lee	Young		GSFC	Kirchman	Frank		GRC	Bogner	Amee
JPL	Nayar	Hari		GSFC	Brown	Kim		GRC	Jones	Robert
JPL	Neff	David		GSFC	Knittel	Jeremy		GRC	Packard	Tom
JPL	Nitin	Arora		GSFC	Hughes	Kyle		GRC	Parkey	Tom
JPL	Oxnevad	Knut		GSFC	Englander	Jacob		GRC	Turnbull	Elizabeth
JPL	Ratliff	Martin		GSFC	Sturm	James				
JPL	Shirey	Timothy								
JPL	Woerner	David		Consultants	DOE INL	Johnson	Steve			
JPL	Yu	Kevin		Consultants	DOE	Cairns-Gallin	Dirk			
GRC	Zakrajsek	June		Consultants	JPL	Reh	Kim			
GSFC	Nicoletti	Anthony		Consultants	GSFC	Nicoletti	Anthony			
APL	Paul	Ostdiek		Consultants	GSFC	Amato	Mike			
APL	Hibbard	Ken		Consultants	APL	Reed	Cheryl			
UDRI	Barklay	Chadwick		Consultants	APL	Procktor	Louise			
				Consultants	Independent	Spilker	Tom			