Australian Nuclear Association

Nuclear power for space applications

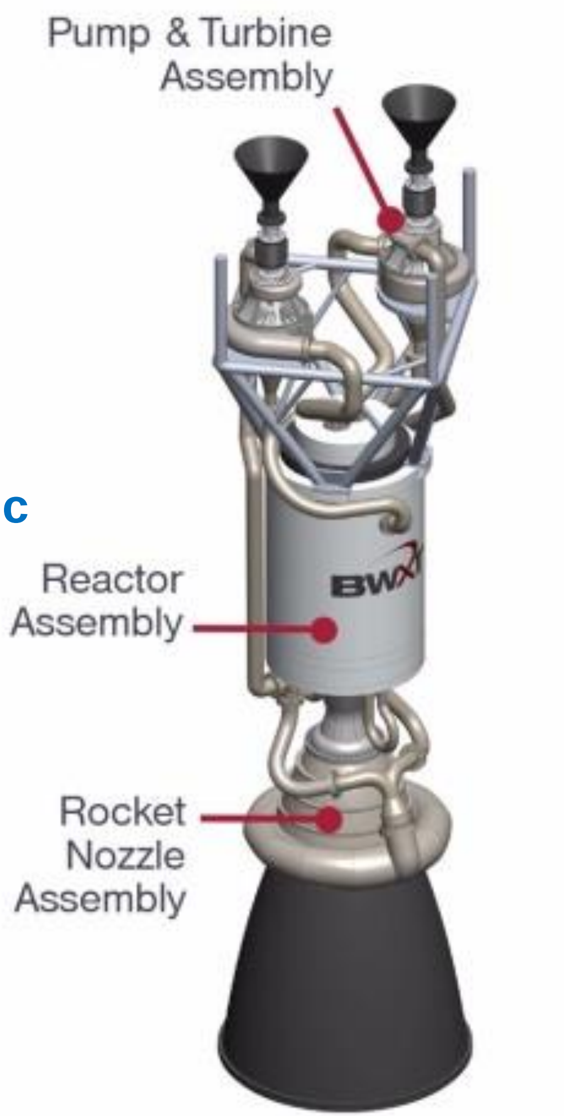
Dr Mark Ho

Outline

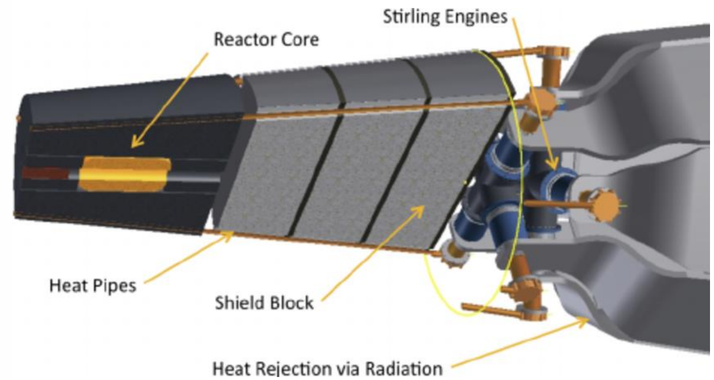
1. **Nuclear Thermal Propulsion**

2. **RTGs**
   Radioisotope Thermoelectric Generators – for electricity.

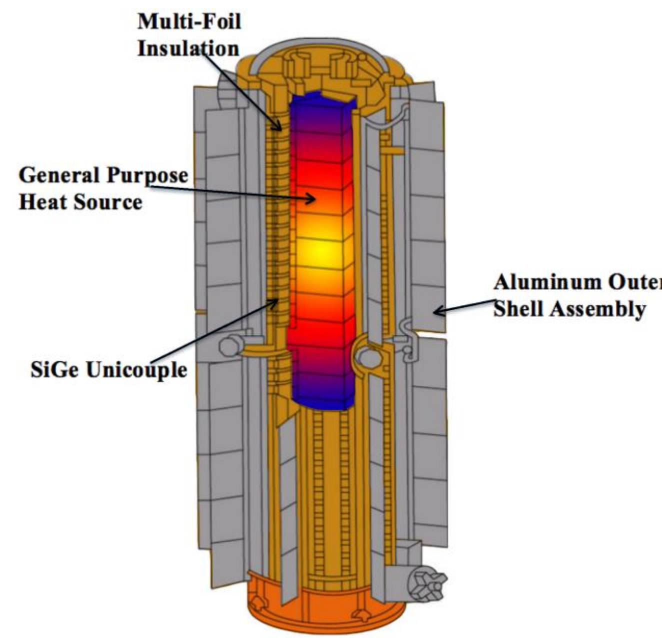
3. **Space Fission Systems** (> 1 kW)



BWXT LEU NTP



Kilopower Reactor



GPHS RTG

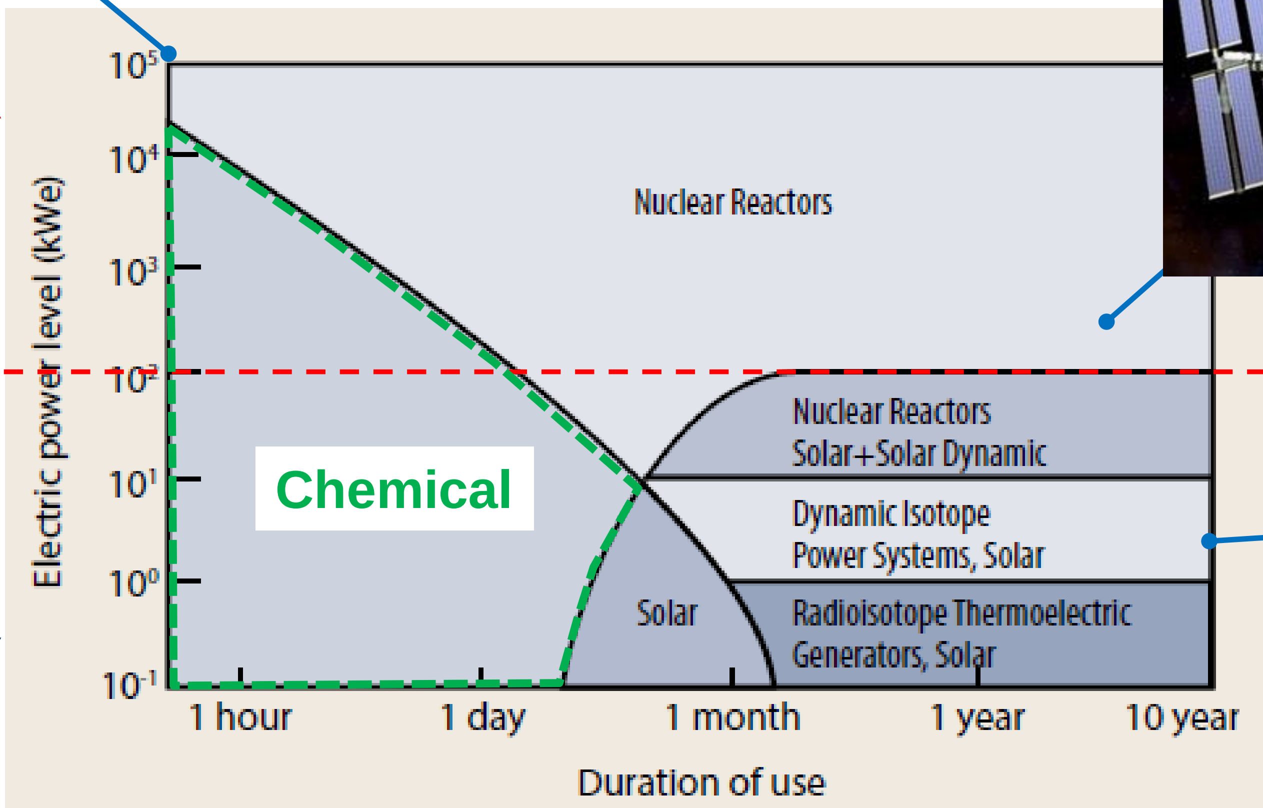
Choices

100 MW NTP @ 10^5 kW$_{th}$

Nuclear

100 kW$_e$

Solar



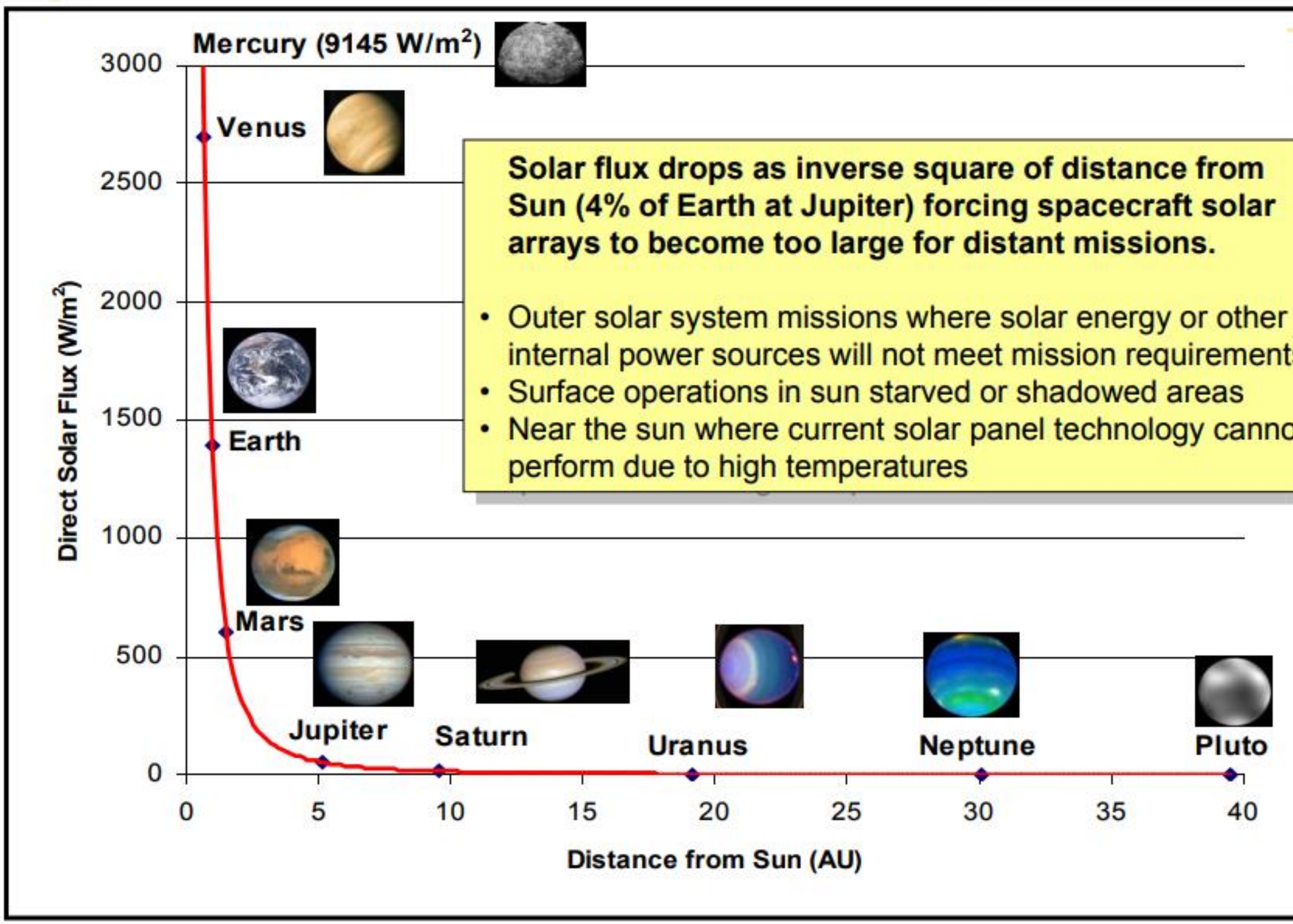
ISS 120 kW$_e$

Rosetta
1500 – 400 W$_e$

Philae (lander)
32 W$_e$
to comet 67P/Churyumov–Gerasimenko

Source: Atomic Power in Space II: A History 2015, Idaho National Lab.

Not much Solar in deep space

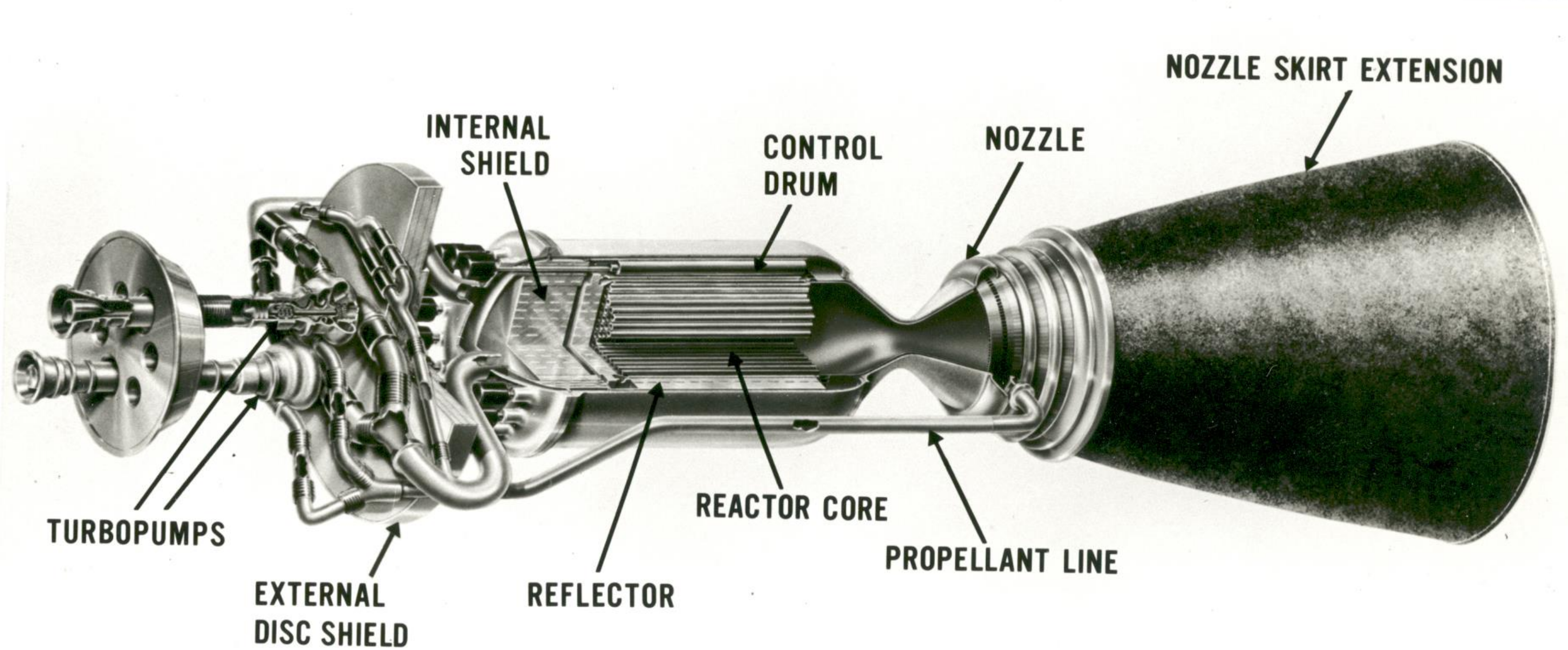


Solar flux drops as inverse square of distance from Sun (4% of Earth at Jupiter) forcing spacecraft solar arrays to become too large for distant missions.

- Outer solar system missions where solar energy or other internal power sources will not meet mission requirements
- Surface operations in sun starved or shadowed areas
- Near the sun where current solar panel technology cannot perform due to high temperatures

Graphics: Miota, DOE (2008).

1. Nuclear Thermal Propulsion



Why Nuclear Thermal Propulsion?

$$\Delta V = v_e \ln \frac{m_0}{m_f}$$

$$\frac{m_0}{m_f} = e^{\left[\frac{\Delta V}{v_e}\right]}$$

Tsiolkovsky's equation

The maximum change in velocity is the equal to the propellant exhaust velocity multiplied by the natural log of the initial mass and final mass ratio

1. *High exhaust velocity is good*
2. *Optimally the initial and final vehicle mass should be as small as possible.*

$$I_{sp} = \frac{v_e}{g_0}$$

Specific Impulse (sec.)

The time it takes for one kilogram of propellant to produce one newton of thrust.

Higher specific impulse, means higher efficiency.

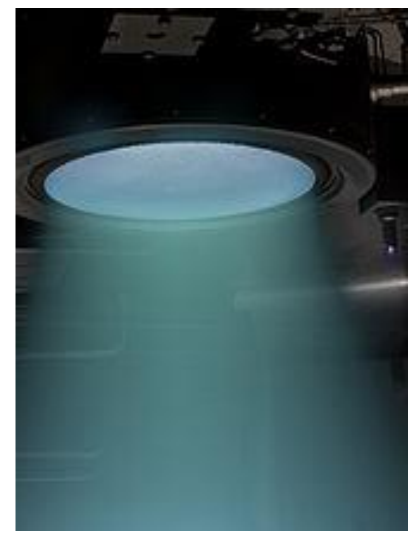
Engine selection depends on the mission

Engine type	*Chemical Rocket*	*Chem. R.*	*NTR*	*Ion drive*
Engine name	*Raptor 1st stage*	*J-2 (SLS)*	Pheobus 2A	NEXT
Propellant	CH_4 / LOX	LH_2 / LOX	LH_2	Xenon
Thrust to Weight Ratio	? >180	55	3.2	v. low
Specific Impulse	330 – 380 s	448 s	925 s	4400 s @6.9kW
Max. Thrust	1,993 kN	1,310 kN	930 kN (tested)	0.236 N

Raptor

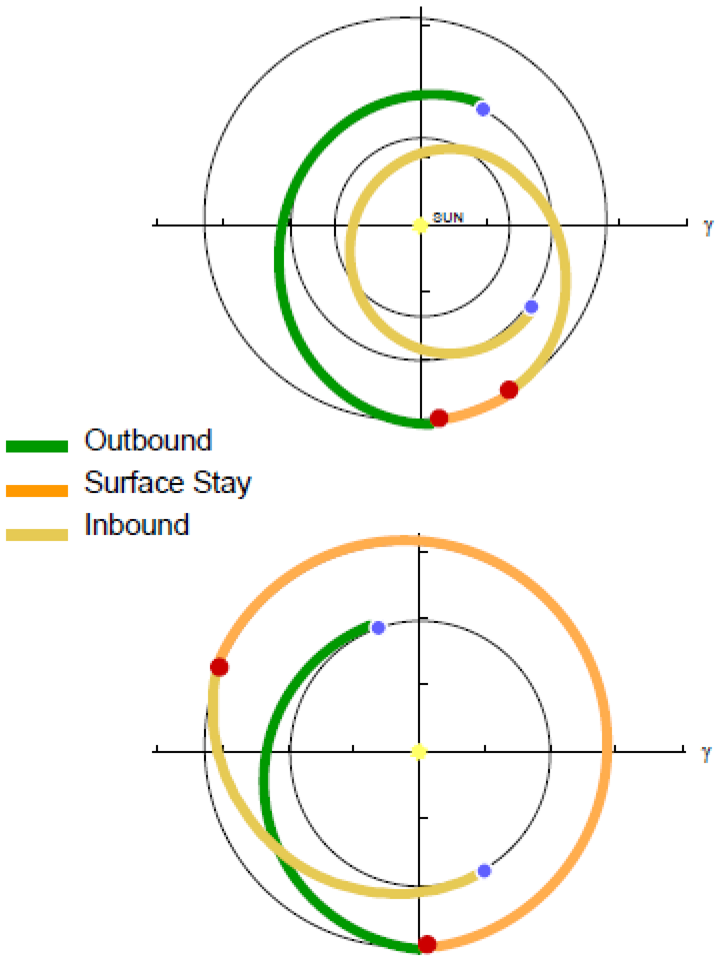
J-2

Pheobus 2A



NEXT

Options other than Hohmann Transfer



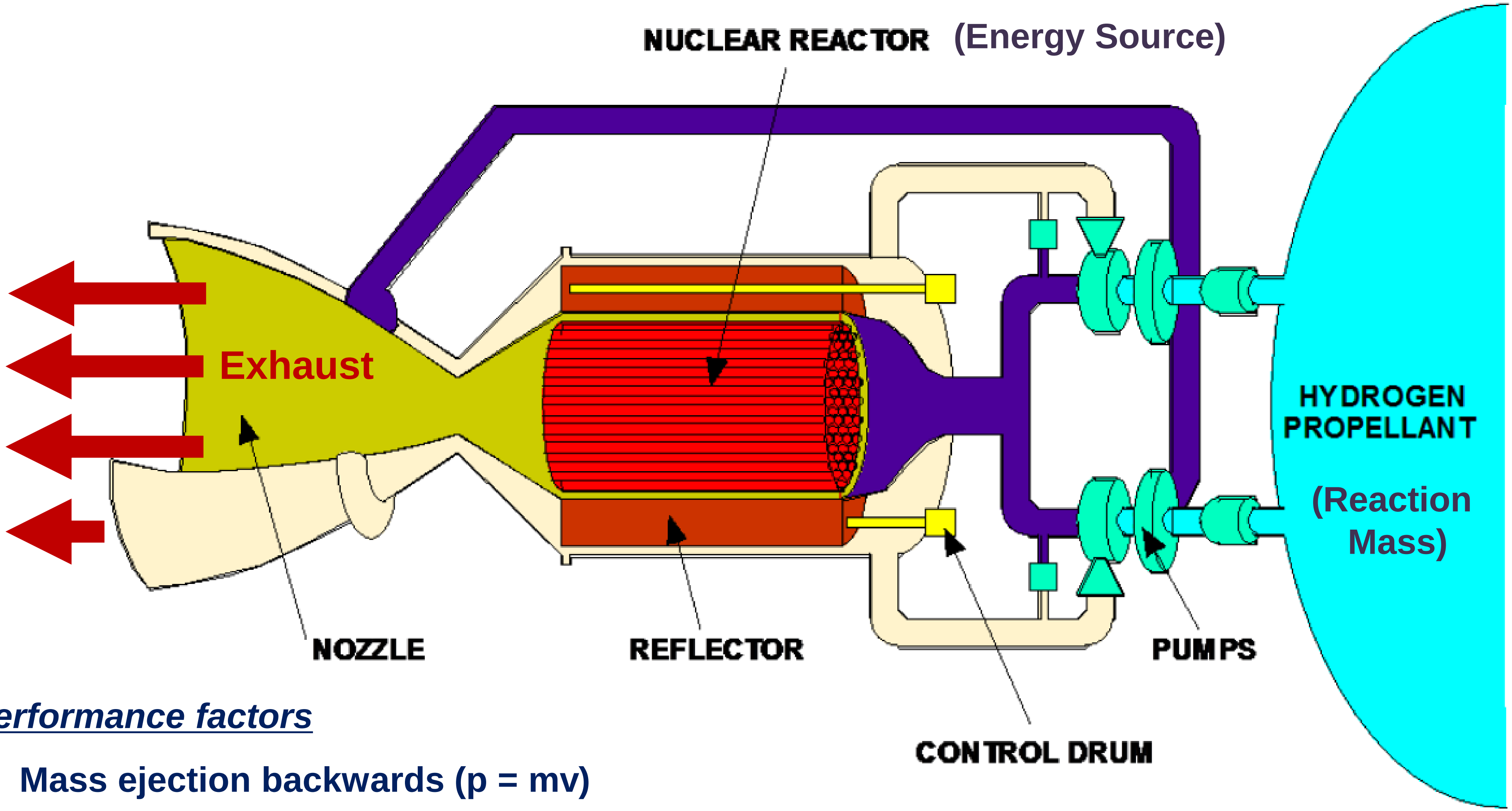
- **Opposition-Class Mission Characteristics (Used in "90-Day" / SEI Mars Studies)**
  - Short Mars stay times (typically 30 - 60 days)
  - Relatively short round-trip times (400 - 650 days)
  - Missions always have one short transit leg (either outbound or inbound) and one long transit leg
  - Long transit legs typically include a Venus swing-by and a closer approach to the Sun (~0.7 AU or less)
  - This class trajectory has higher ΔV requirements

  NOTE: Short orbital stay missions will likely be chosen for initial human missions to Mars and its moons, Phobos and Deimos

- **Fast-Conjunction Class Mission Characteristics (Used in DRM 4.0 and DRA 5.0 Studies)**
  - Long Mars stay times (500 days or more)
  - Long round trip times (~900 days)
  - Short "in-space" transit times (~150 to 210 days each way) ***Question: Can we go faster?***
  - Closest approach to the Sun is 1 AU
  - This class trajectory has more modest ΔV requirements than opposition missions

Source: Glenn Research Centre, NASA Taken from M. Houts and S. Mitchell's presentation
https://ntrs.nasa.gov/search.jsp?R=20160002256

Nuclear Thermal Rocket



Performance factors

- Mass ejection backwards (p = mv)
- Energy to accelerate propellant to ejection velocity. ($E = \frac{1}{2} mv^2$)
- System mass = Energy source + Propulsion device + Propellant

Hydrogen for Max. Exhaust Vel. (v_e)

Root Mean Square of Speed of Particles

$$v_{rms} = \sqrt{\frac{3RT}{M}}$$

$R = Gas\ Constant$
$T = Temperature\ (Kelvin)$
$M = Molar\ Mass$

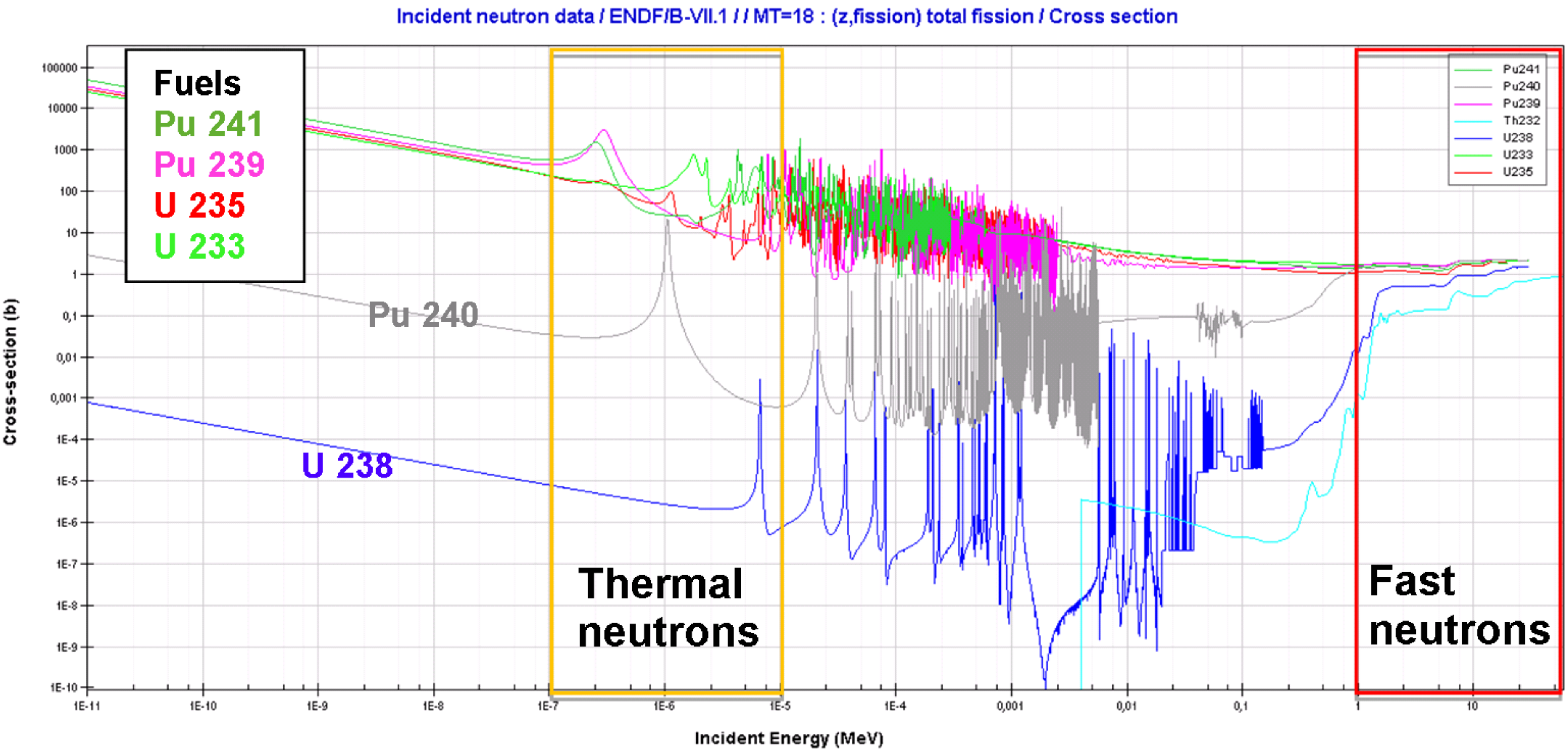
@ 295 K (Room Temperature)		@ 3000 K (Reactor Temperature)	
O_2:	v = 480 m/s	O_2:	v = 1529 m/s
N_2:	v = 512 m/s	N_2:	v = 1634 m/s
CO_2:	v = 409 m/s	CO_2:	v = 1304 m/s
He:	v = 1356 m/s	He:	v = 4324 m/s
H_2:	v = 1918 m/s	H_2:	v = 6092 m/s

Exhaust velocity improves with the square root of the mass ratio of two gases

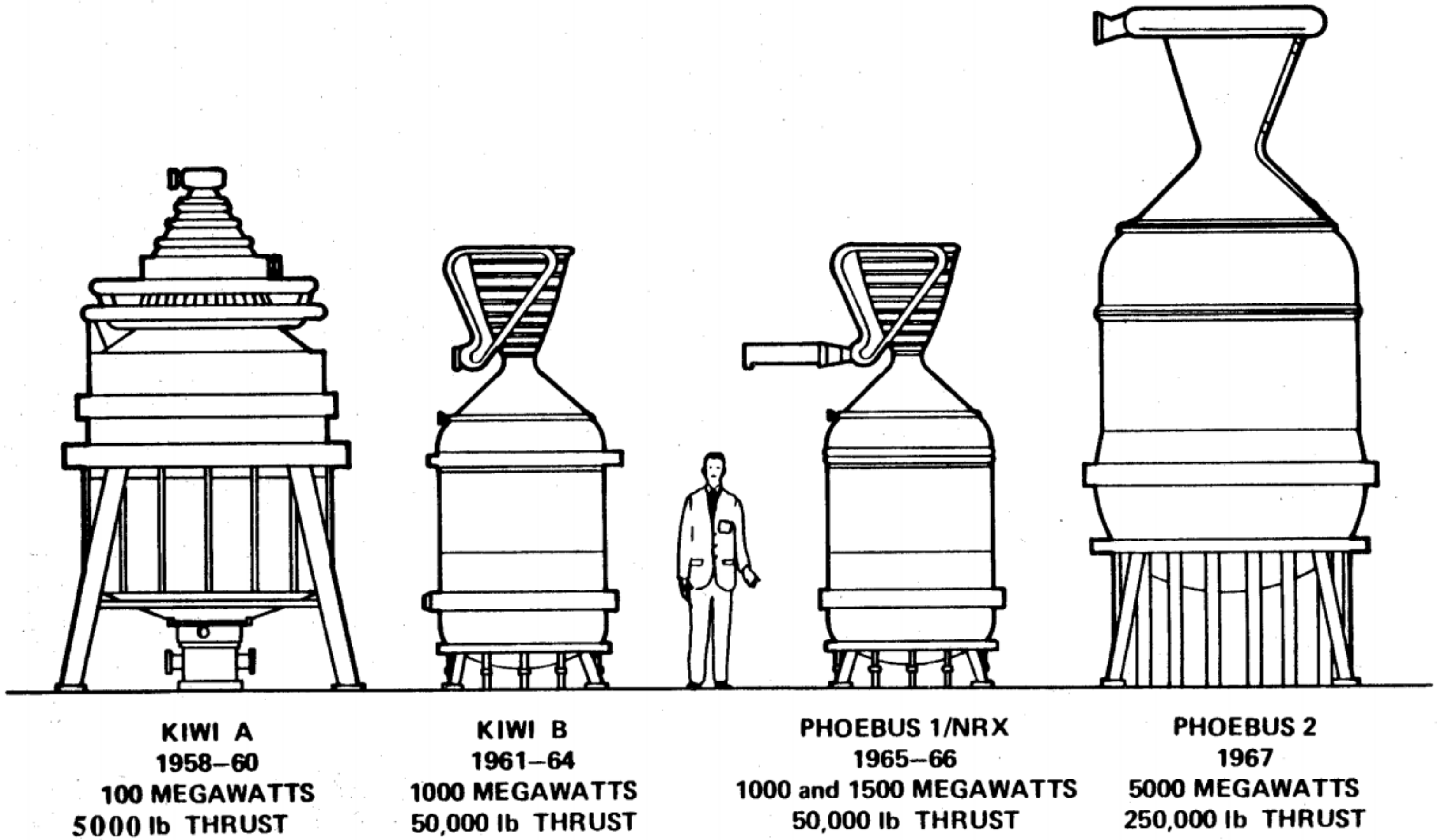
Heat Transfer: H_2 is ~6 times more conductive & about half as viscous than air

Hydrogen is a neutron moderator.

Neutron cross sections



Rover / NERVA



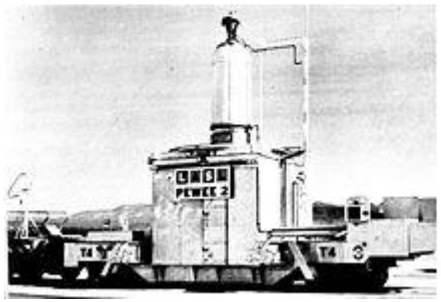
(22 kN) (222 kN) (222 kN) (1,110 kN design)

(930 kN tested)

Source: U. of Wisconsin

Project Rover / NERVA (1959 - 1972)

Various OKBs (1950s - 1989)



NERVA NRX
"Kiwi"

NERVA EX
"Phoebus 1B"

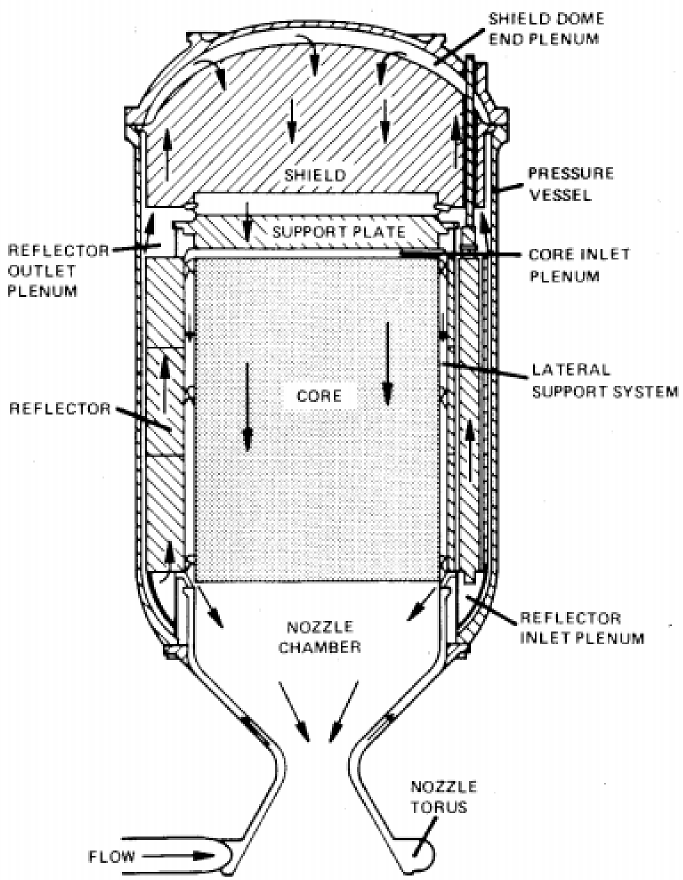
RD-410

Thrust = 333 kN, I_{sp} = 850s

RD-410: Thrust = 69 kN, I_{sp} = 900 s

Source: edX, The Conquest of Space – NTPs, Universidad Carlos III de Madrid

	KIWI-4BE	NRX-A6	Phoebus-2A	Pewee-1
Reactor power (MW)	950	1,167	4,080	507
Flow rate (kg/s)	31.8	32.7	119.2	18.6
Fuel exit average temperature (K)	2,330	2,472	2,283	2,556
Chamber temperature (K)	1,980	2,342	2,256	1,837
Chamber pressure (MPa)	3.49	4.13	3.83	4.28
Core inlet temperature (K)	104	128	137	128
Core inlet pressure (MPa)	4.02	4.96	4.73	5.56
Reflector inlet temperature (K)	72	84	68	79
Reflector inlet pressure (MPa)	4.32	5.19	5.39	5.79
Periphery and structural flow (kg/s)	2.0	0.4	2.3	6.48

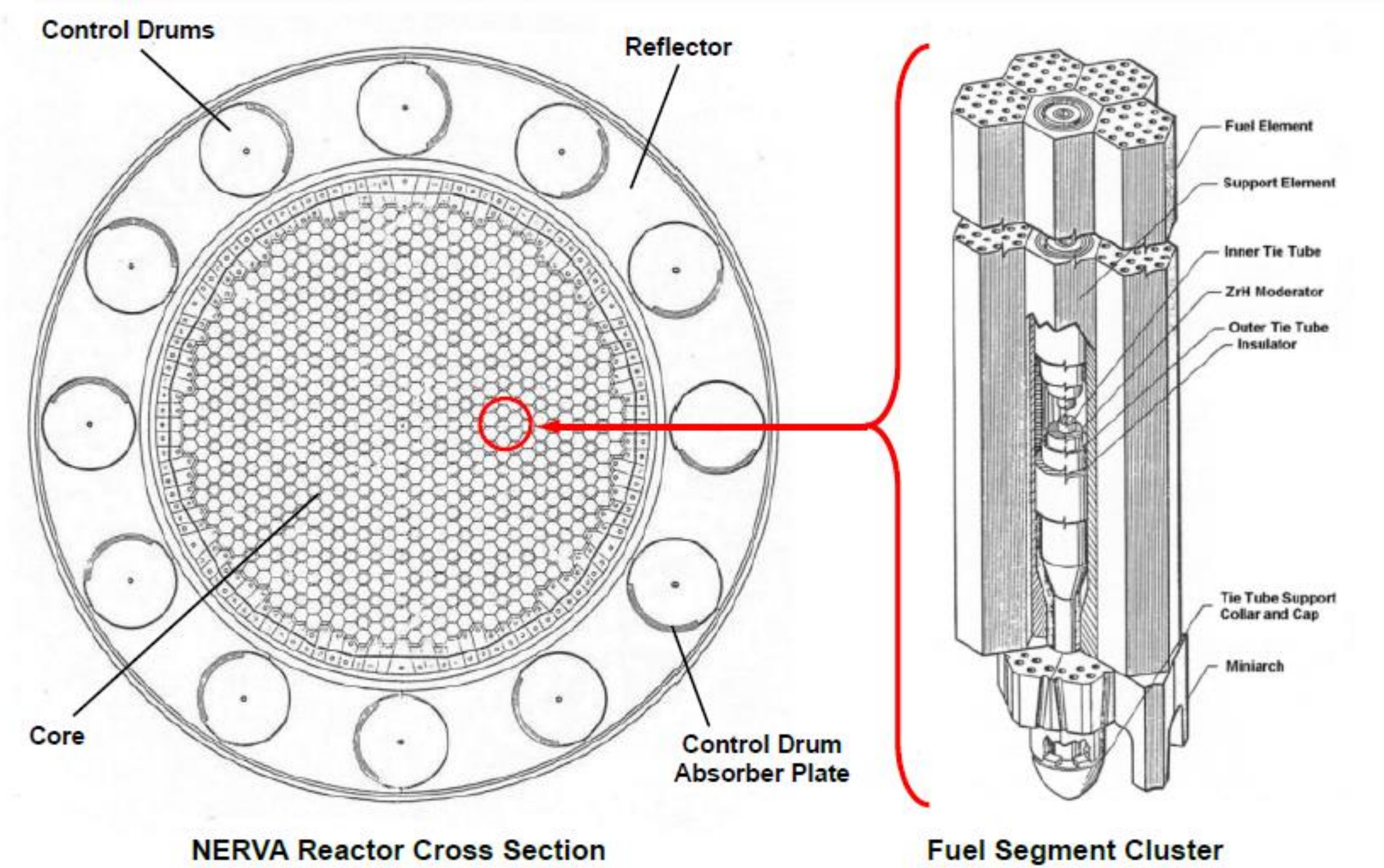


Reactor Features

- 93.15% high enriched uranium
- hydrogen cooled
- graphite moderated
- Epi-thermal neutron spectrum,
- Orifice sizing for flow distribution
- Neutron absorbing drums
- Varied fuel loading for flux flattening

Source: Westinghouse Astronuclear lab.

1st Gen NTP Fuel Element



Source: Houts et al. Presentation: NASA's NTP project (2017)
https://ntrs.nasa.gov/search.jsp?R=20170003378

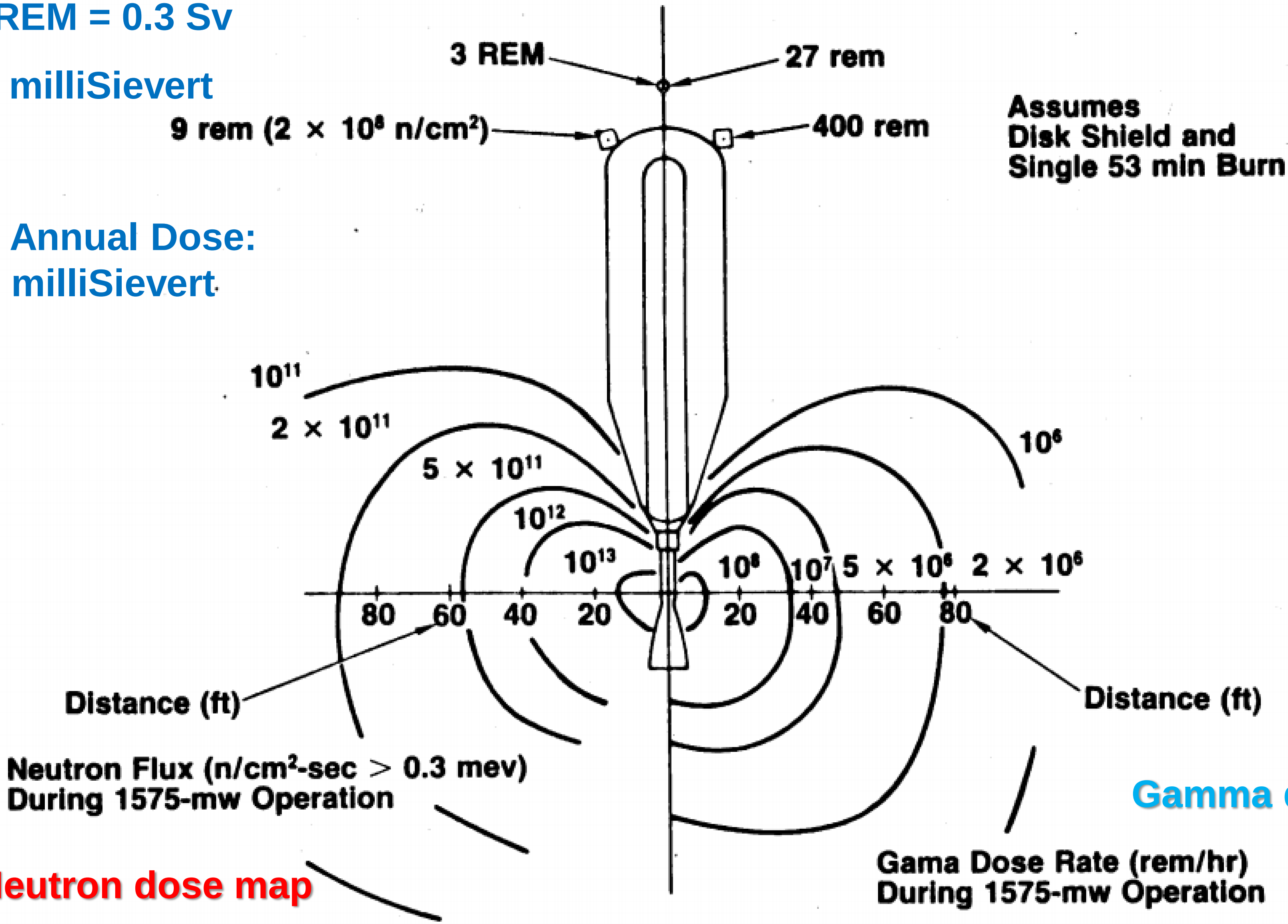
1 Sv = 100 REM

30 REM = 0.3 Sv

300 milliSievert

US Annual Dose:
3.5 milliSievert

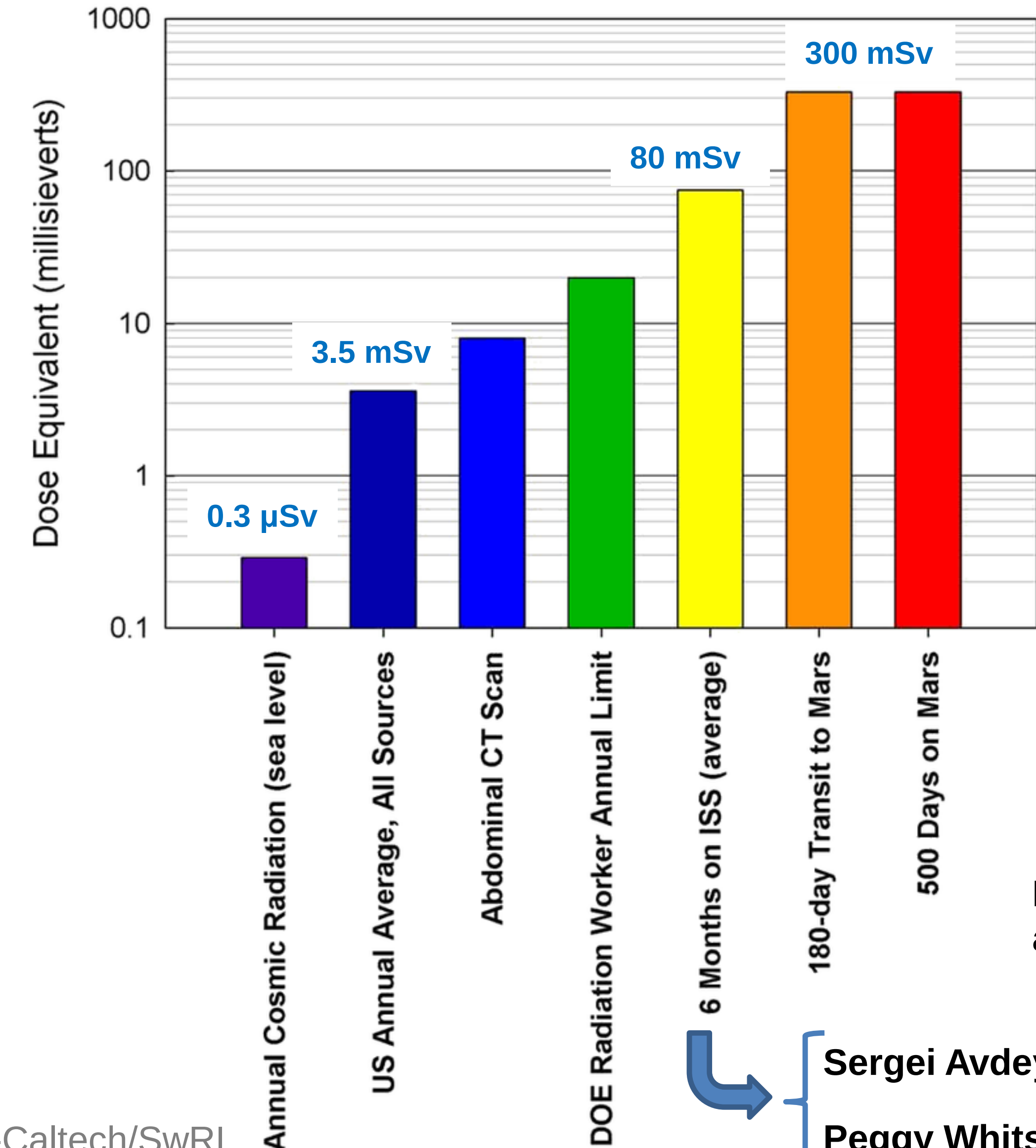
RADIATION MAP



Gamma dose map

Neutron dose map

Ionising Radiation



Both Mir and ISS orbits at an altitude of 300 – 400 km

Sergei Avdeyev – 747 days in space

Peggy Whitson – 534 days in space

Source: NASA/JPL-Caltech/SwRI

NTPs, then and now

Then (Rover/NERVA: 1959 - 72)

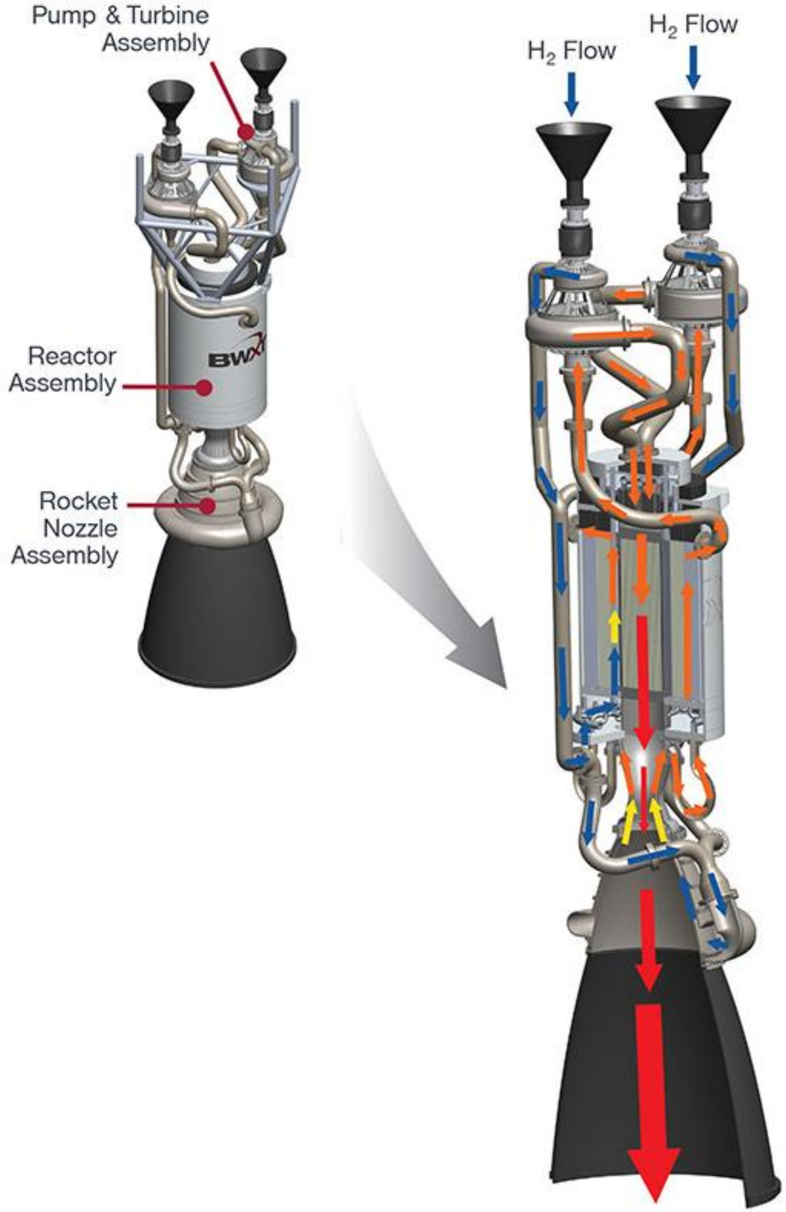
- Engines tested
  - 50,000 to 250,000 pound force (lbf)
  - 222 kN – 1110 kN of thrust
- H_2 exit temperature
  - 2,350 – 2,550 K (Graphite)
- I_{sp} capability
  - 825 – 850 sec (hot bleed cycle)
- Thrust to weight
  - ~3
- “Open Air” testing at Nevada Test Site

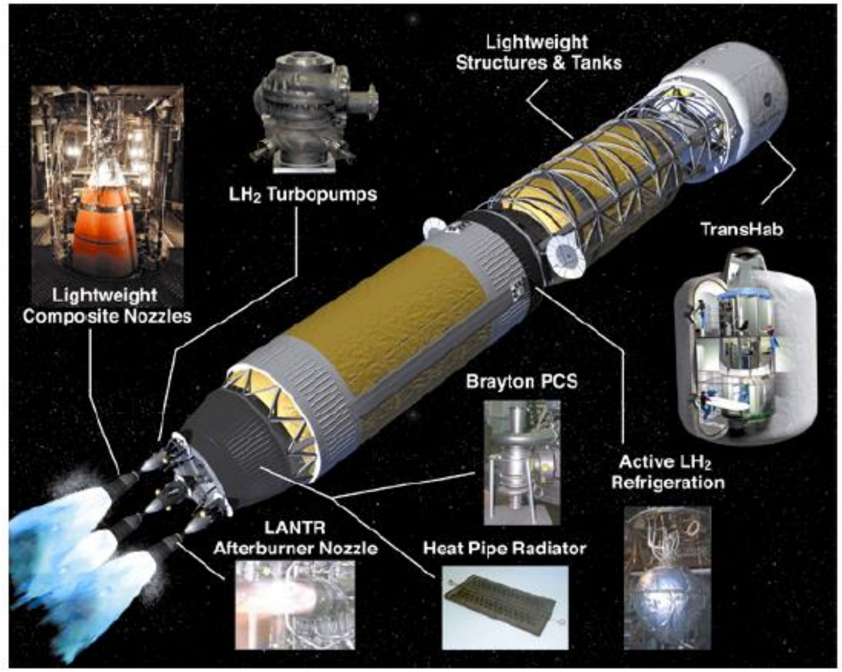
Now

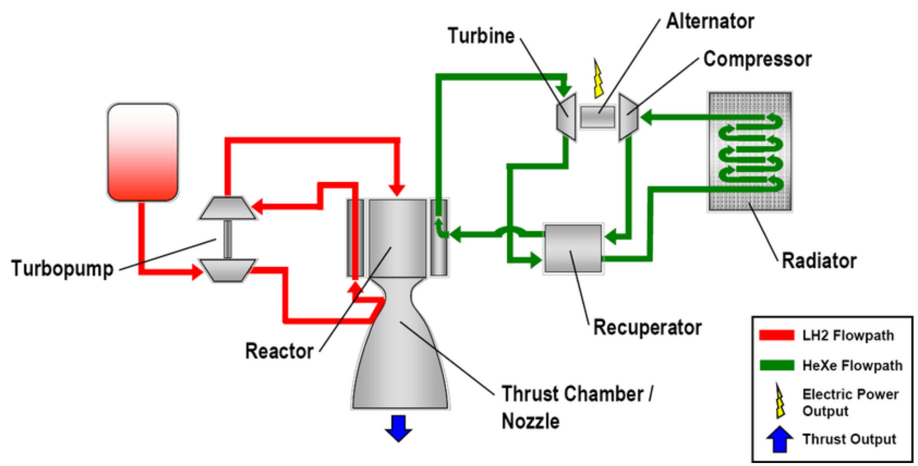
- Focus on small NTRs
  - 5,000 – 15,000 lbf
  - 22 kN – 67 kN
- High Temp. fuel under development
  - 2,700 (Composite)
  - 2,990 K (Cermet - W matrix with UO2)
  - ~3,100 (Ternary Carbides)
- I_{sp} capability
  - 915 – 1005 sec (expander cycle)
- Thrust to weight improvement:
  - reportedly up to 6 for small NTRs
- Contained Test Facility at INL
- $100 million for NTP research (2019)

Source: NASA/CP—2004-212963/VOL1

Design Ref Arch. 5.0







Source: BWXT

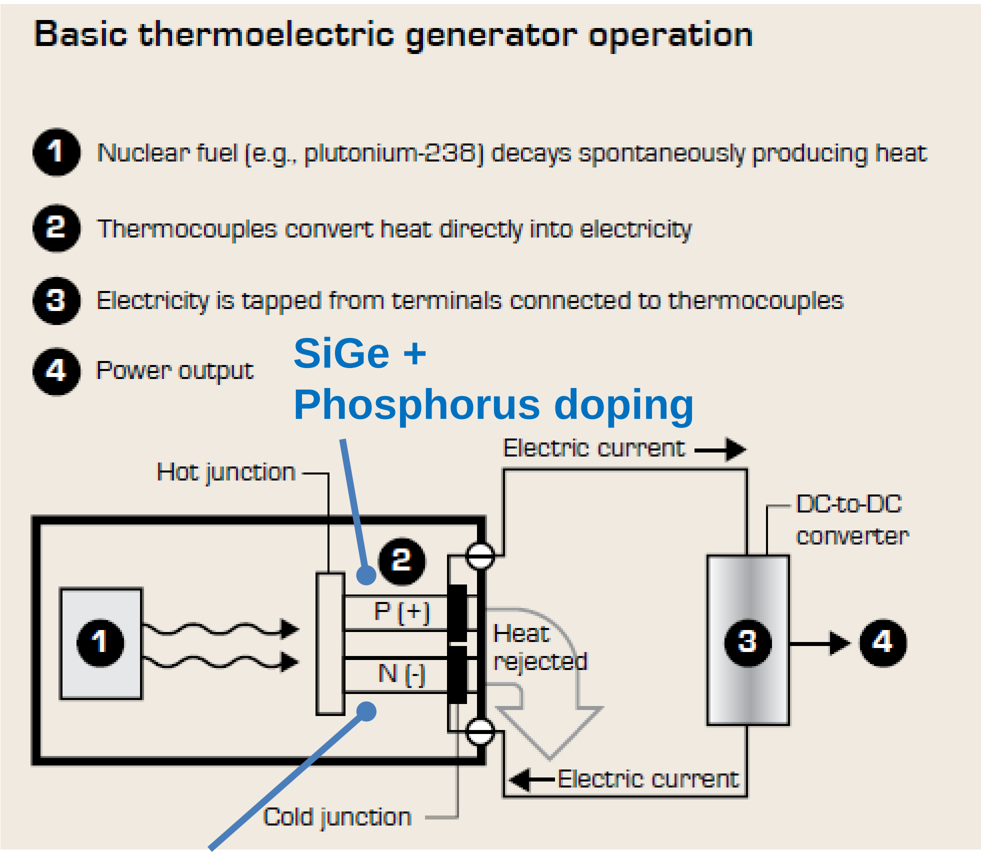
2. Radioisotope Thermoelectric Generators

New Horizons
Mission to Pluto
& Kuiper Belt

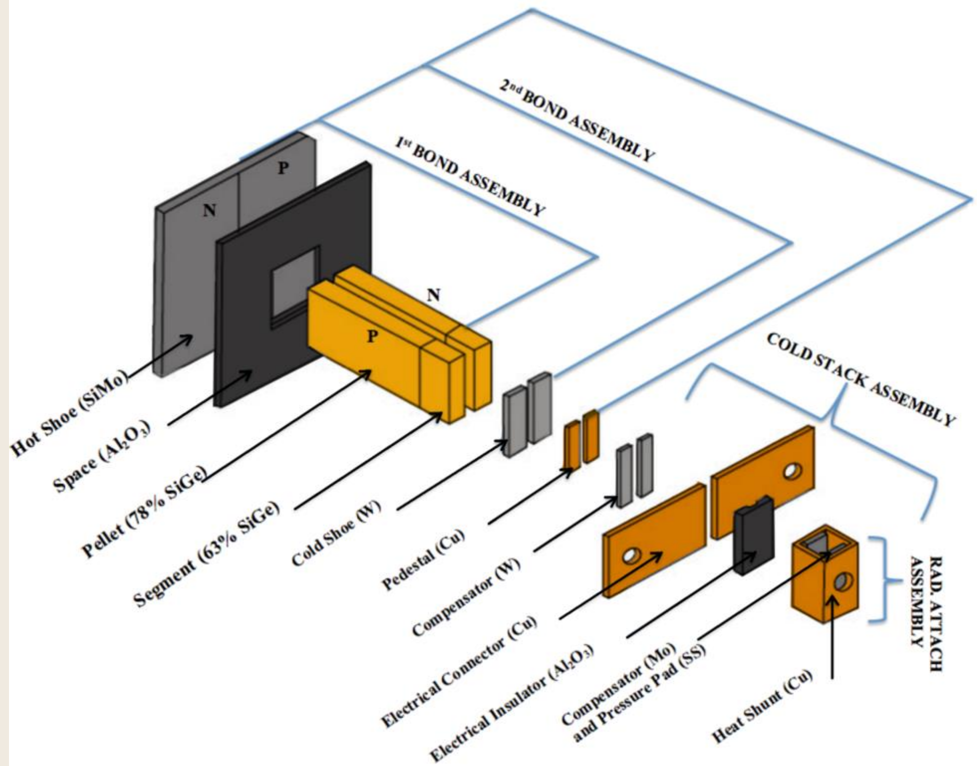
Stats

Probe	**478 kg**
RTG	**57 kg**
PuO_2	**11 kg**
Power (t_0)	**245 W_e**
	~4000 W_{th}
Launched:	**2006**
@ Pluto	**2015**

Thermo-electric Generator



SiGe +
Boron doping

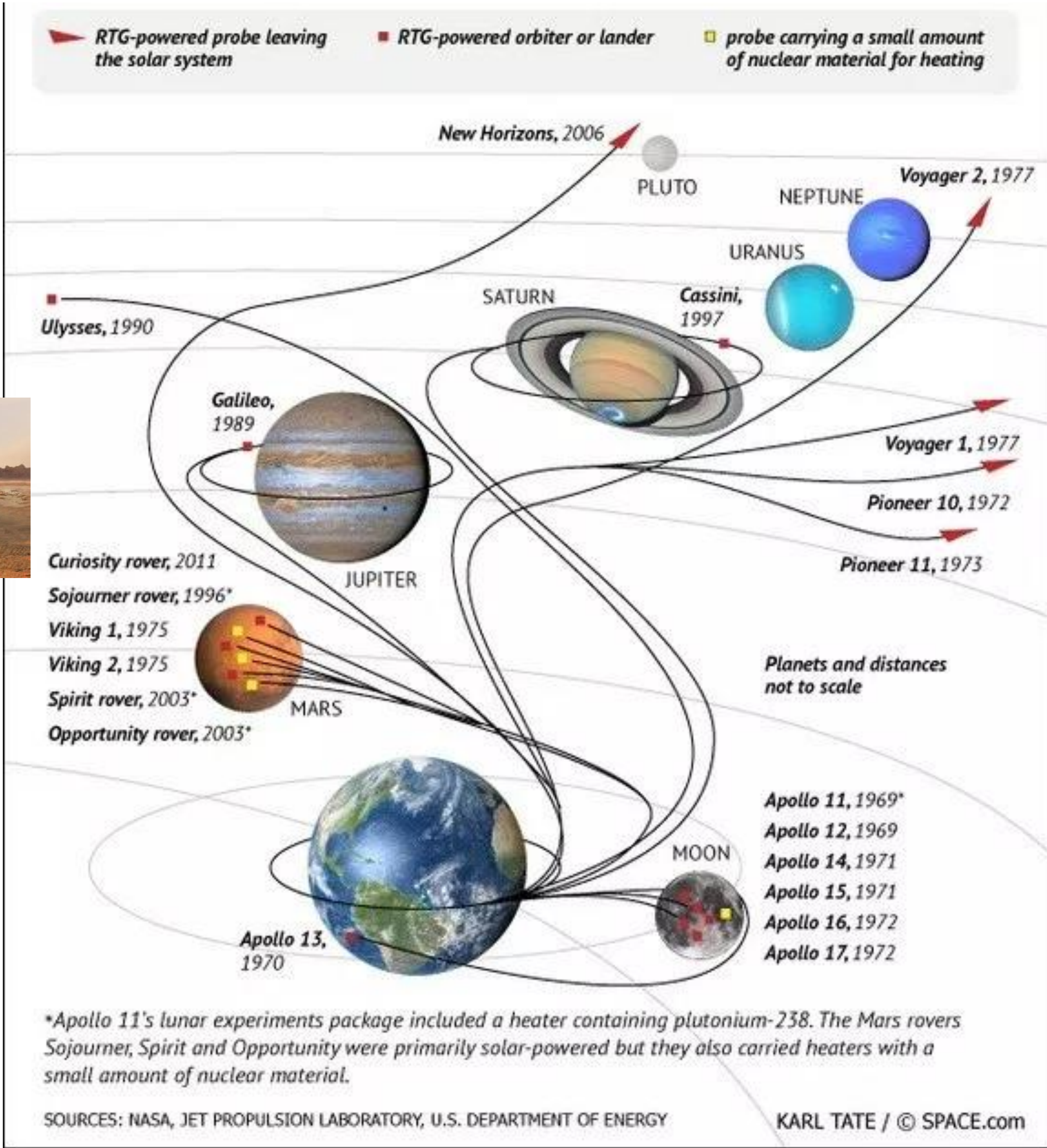


Source: DOE Report, https://www.osti.gov/servlets/purl/1045212

RTG

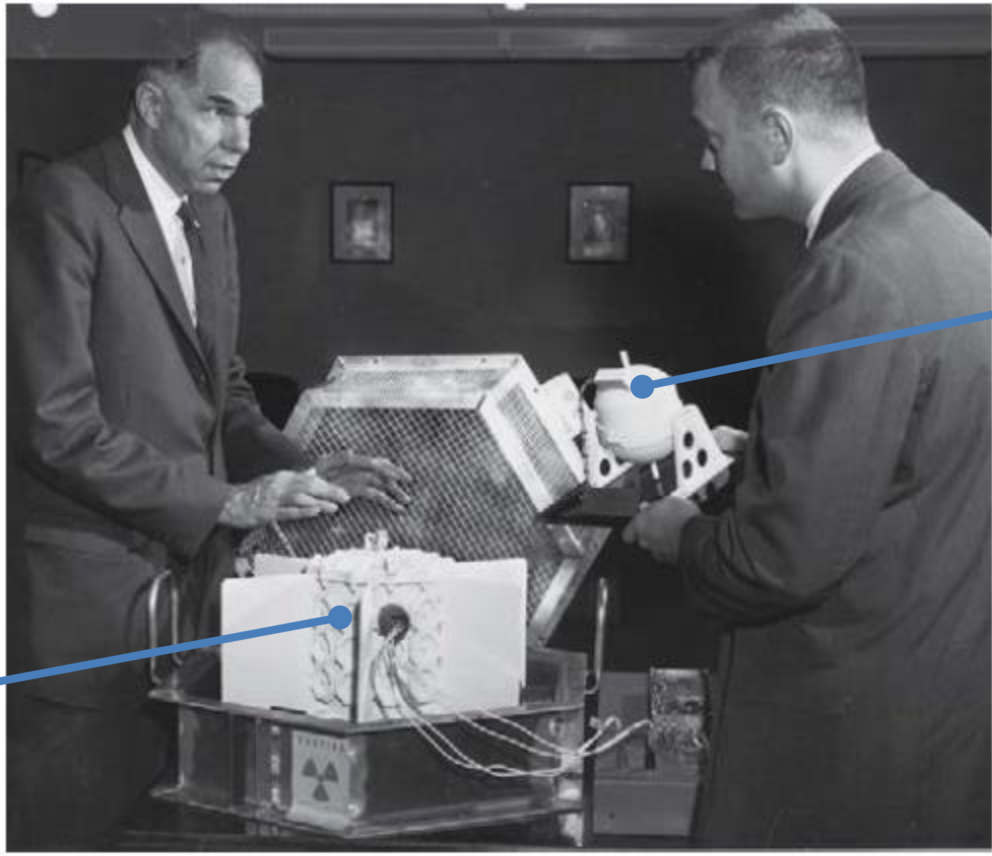
missions

MSL Curiosity Rover



Systems for Nuclear Auxiliary Power

(SNAP)



SNAP-3

polonium-210

λ = 5 months

2.5 W_e

SNAP-9A

plutonium-238

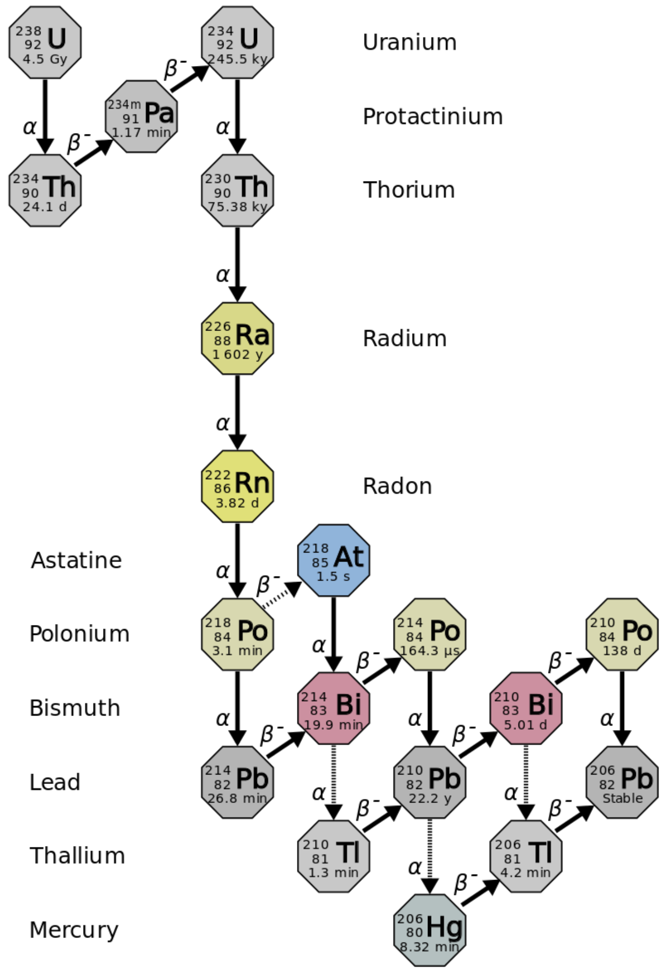
λ = 88 years

$^{238}Pu \rightarrow {}^{234}U + {}^{4}He$

25 W_e

AEC Chairman Glenn T. Seaborg, left, compares a SNAP-9A "atomic battery" (bottom center) with a full-scale model of a SNAP-3B atomic battery held by Major Robert T. Carpenter, AEC-SNAP project engineer. (Photo: 434-N-AEC-63-7042. General Records of the Department of Energy, RG 434, National Archives Still Picture Branch, College Park, Maryland)

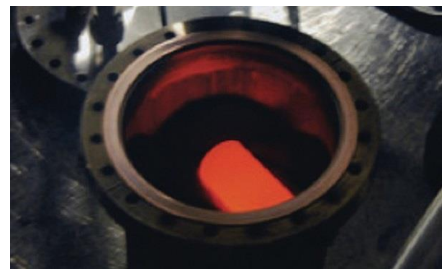
Pu-238



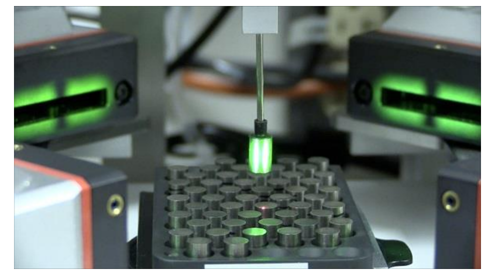
^{238}Pu

- Half-life of 87.7 years
- Decays by 5.593 MeV alpha emission
- 1 gram of ^{238}Pu generates 0.568 W of heat
- Produced by irradiating ^{237}Np in a High Flux reactor

^{237}Np + ^{1}n → ^{238}Np (λ = 2.12 d) → ^{238} Pu + e^-



Pellet production



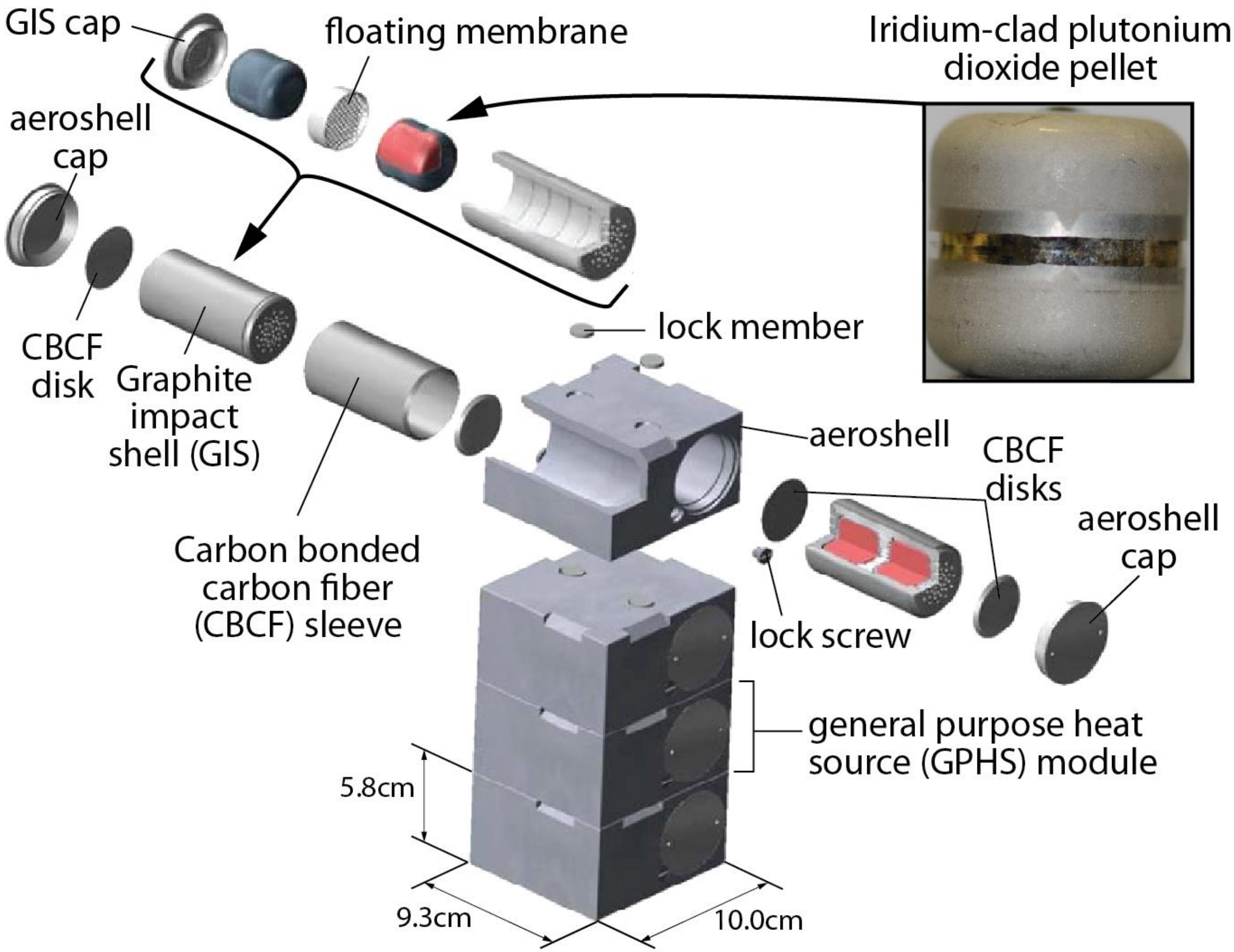
Metrology

$^{238}PuO_2$ pellet

- Ø 2.76 cm, Length 2.76 cm
- Power: 62.5 W_{th}
- Weight: 150g
- MP > 2450° C
- Created by sintering $^{238}PuO_2$ granules
- Iridium alloy clad (0.55 mm)

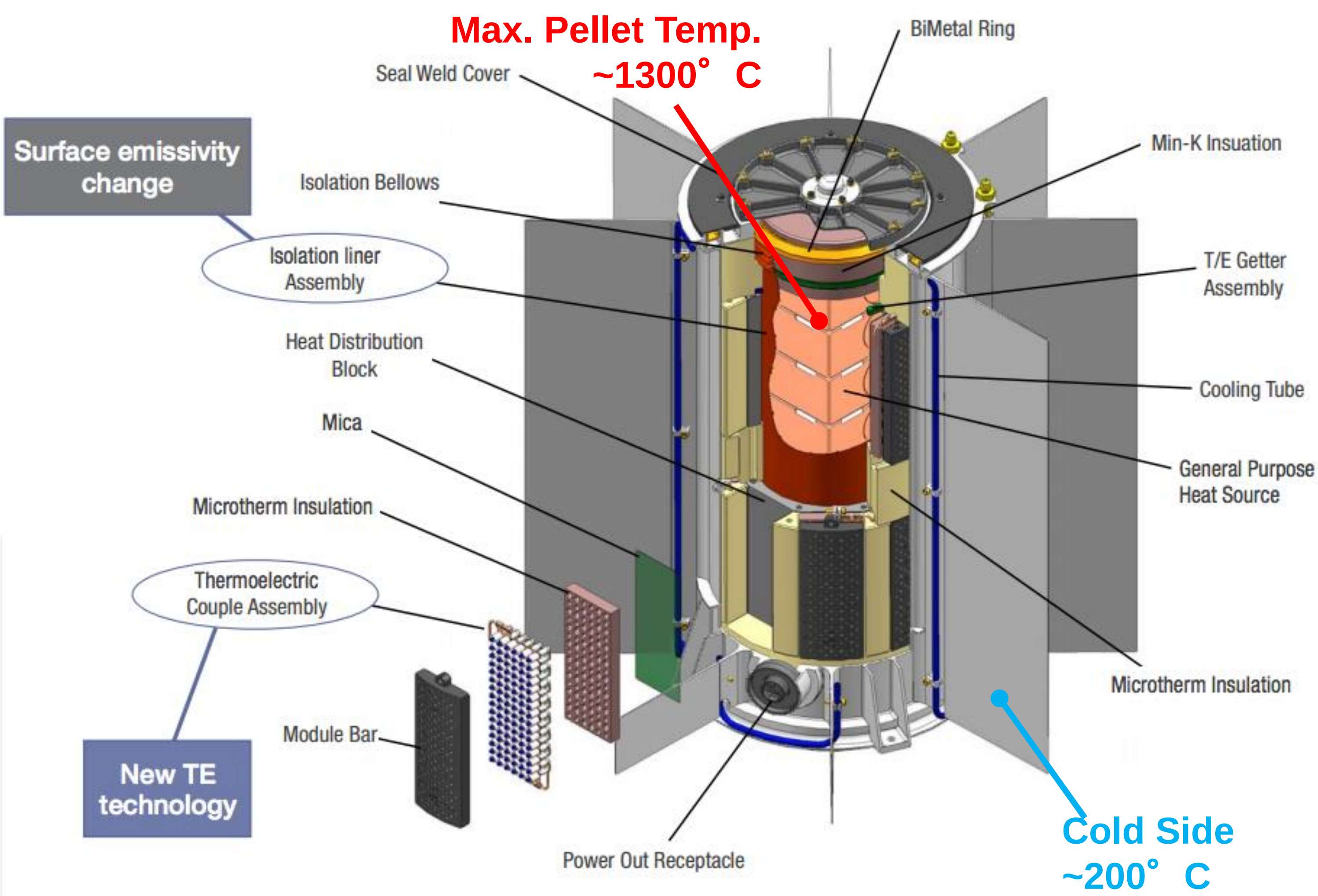
Source: Rankin et al. Production of Pu-238 Oxide for Space Exploration, WSRC-MS-2000-00061

General Purpose Heat Source (GPHS)



Source: NASA

Multi-mission RTG



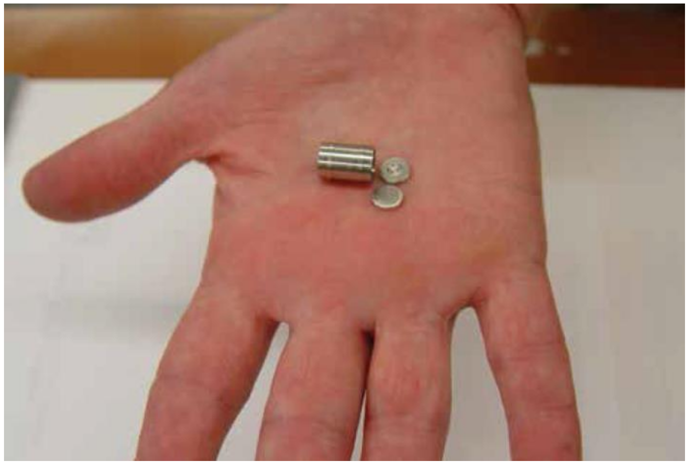
- 8 GPHS stack
- 4.8 kg of Pu-238
- 2 kW thermal power
- 125 W_e initial
- 100 W_e after 14 years
- MMGTR = 45 kg
- Currently NASA has enough Pu-238 for 2 more MMTGRs

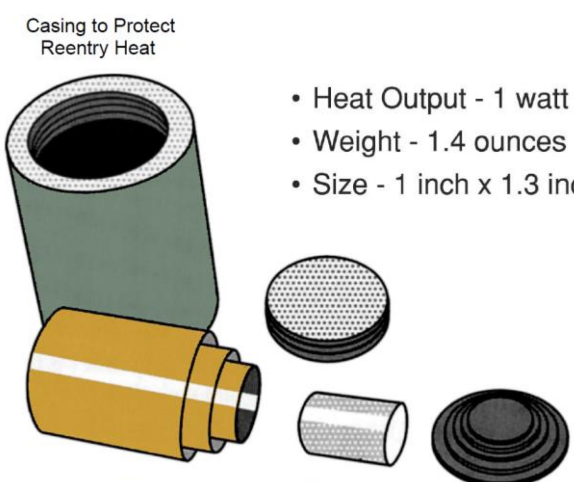
HFIR (ORNL) restarting Pu-238 production

- 400 grams p.a.
- 1.5 kg p.a. by 2025

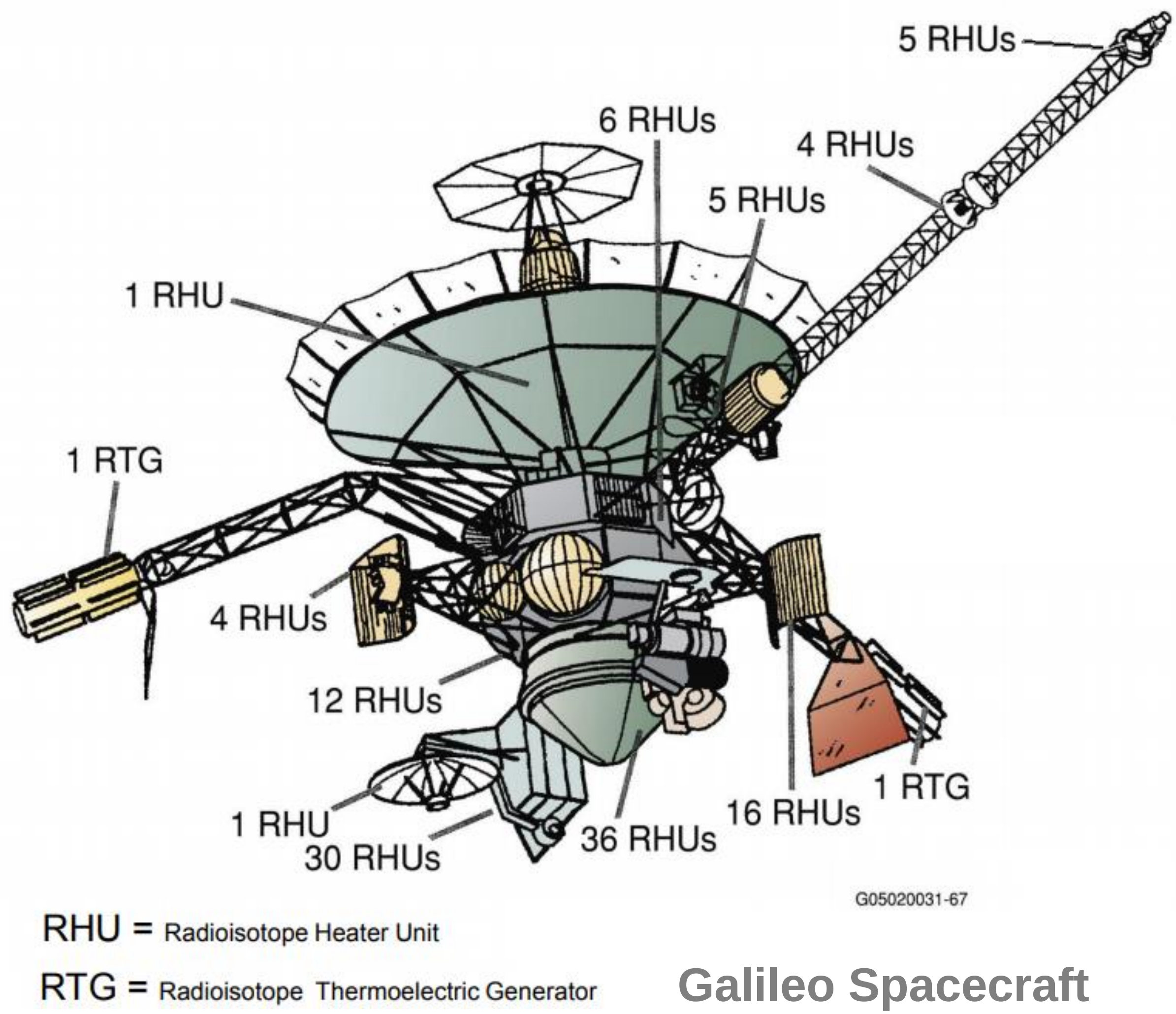
Source: NASA

Radioisotope Heater Units





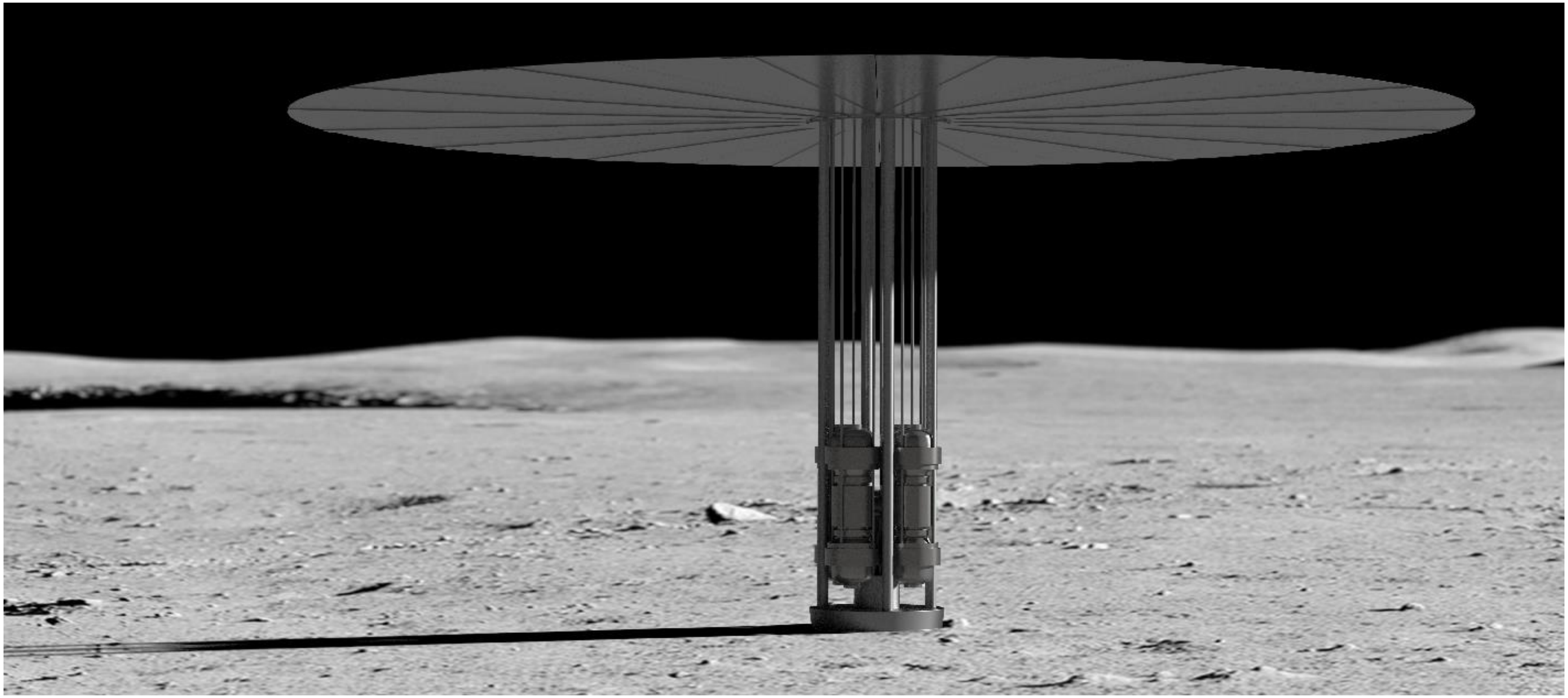
- Heat Output - 1 watt
- Weight - 1.4 ounces
- Size - 1 inch x 1.3 inches



Galileo Spacecraft

Graphic: Dr Alan Walter, (Dir. Ret.) Pacific Northwest National Laboratory

3. Space Fission Systems

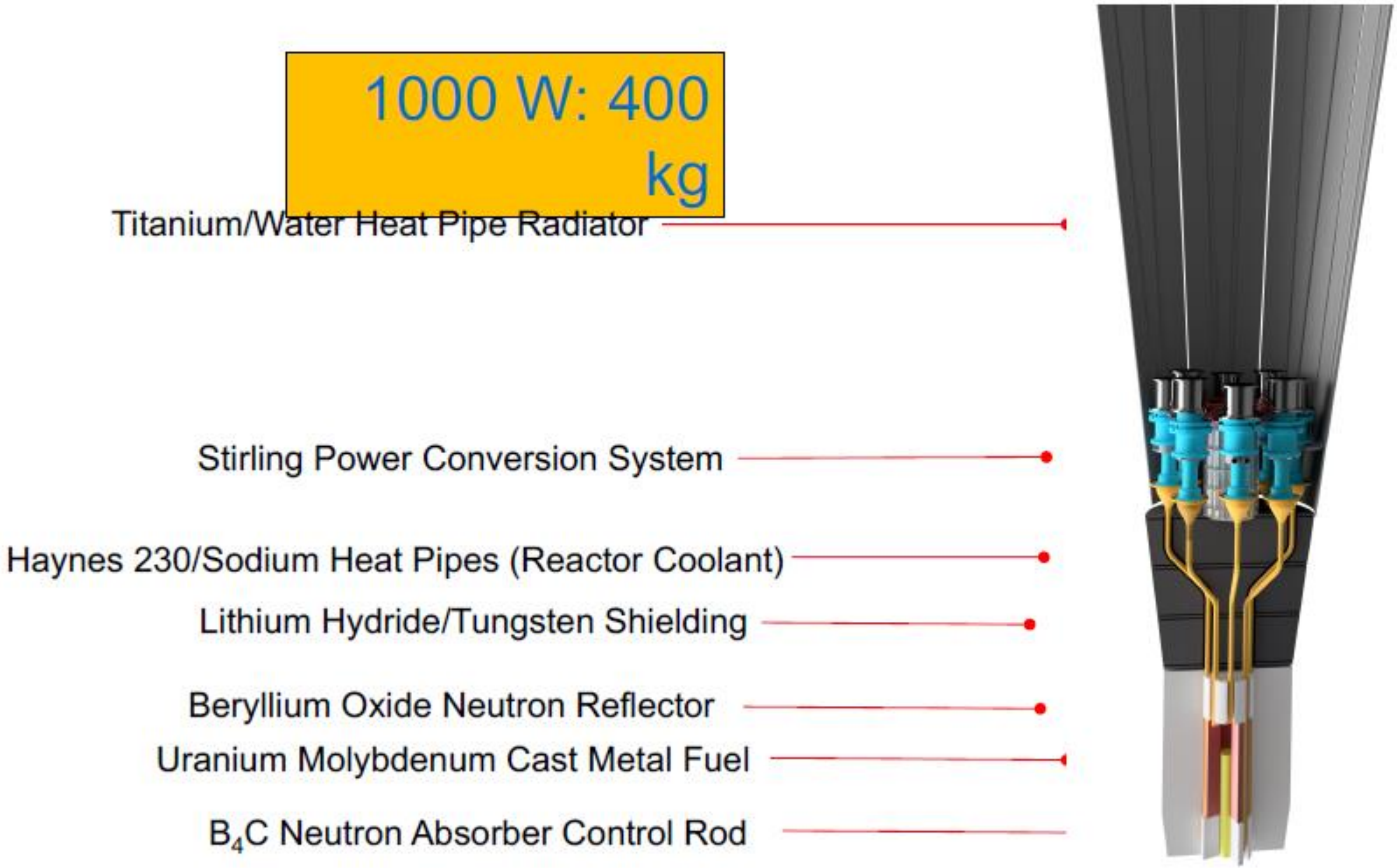


Kilopower Reactor Lunar Deployment Concept

Thanks to NASA for all following material

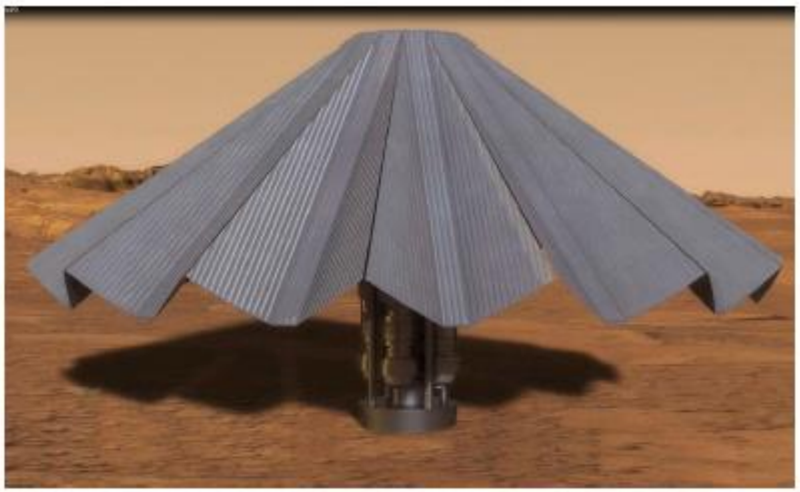
Kilopower Reactor 1-3 kW_e

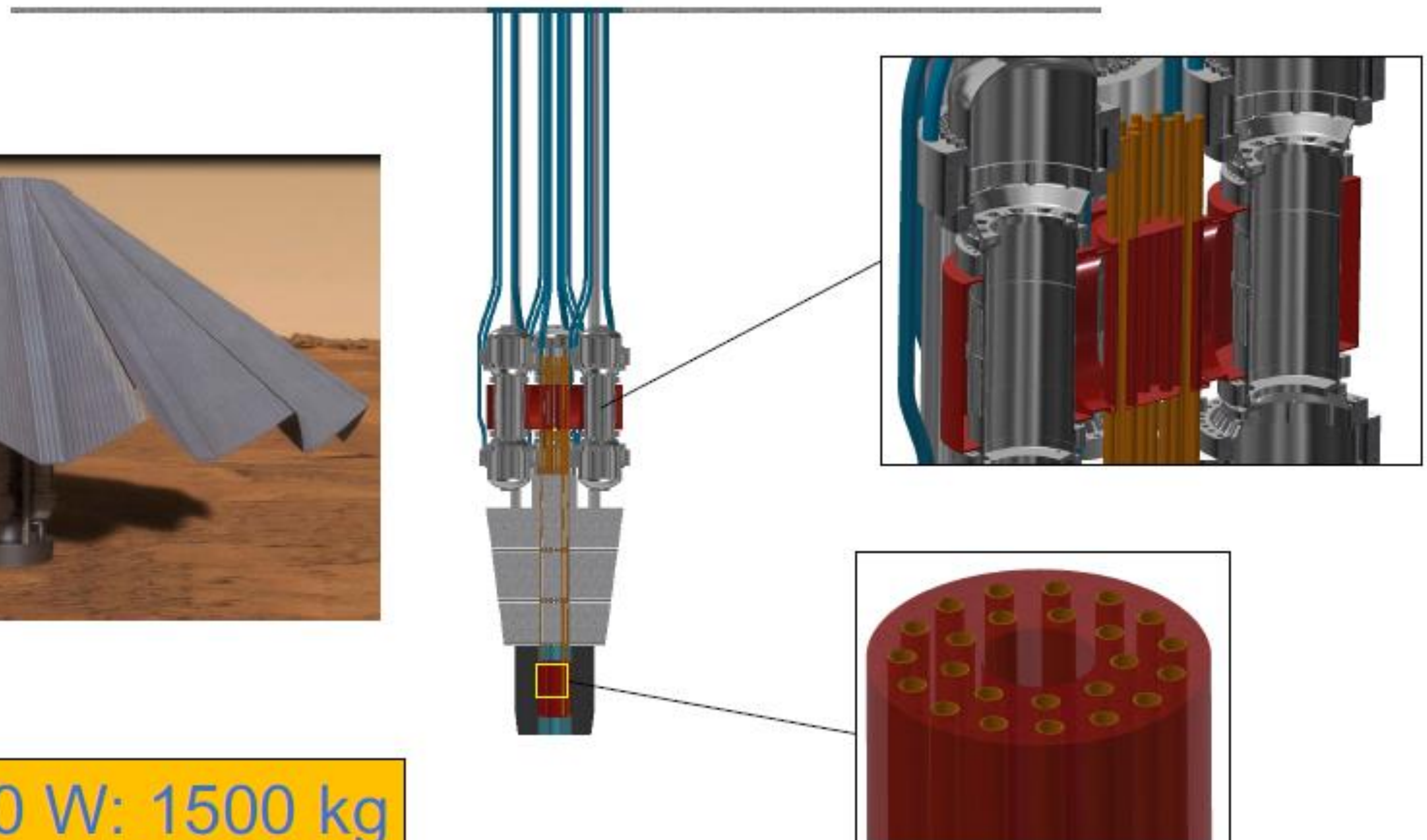
1000 W: 400 kg



Source: NASA

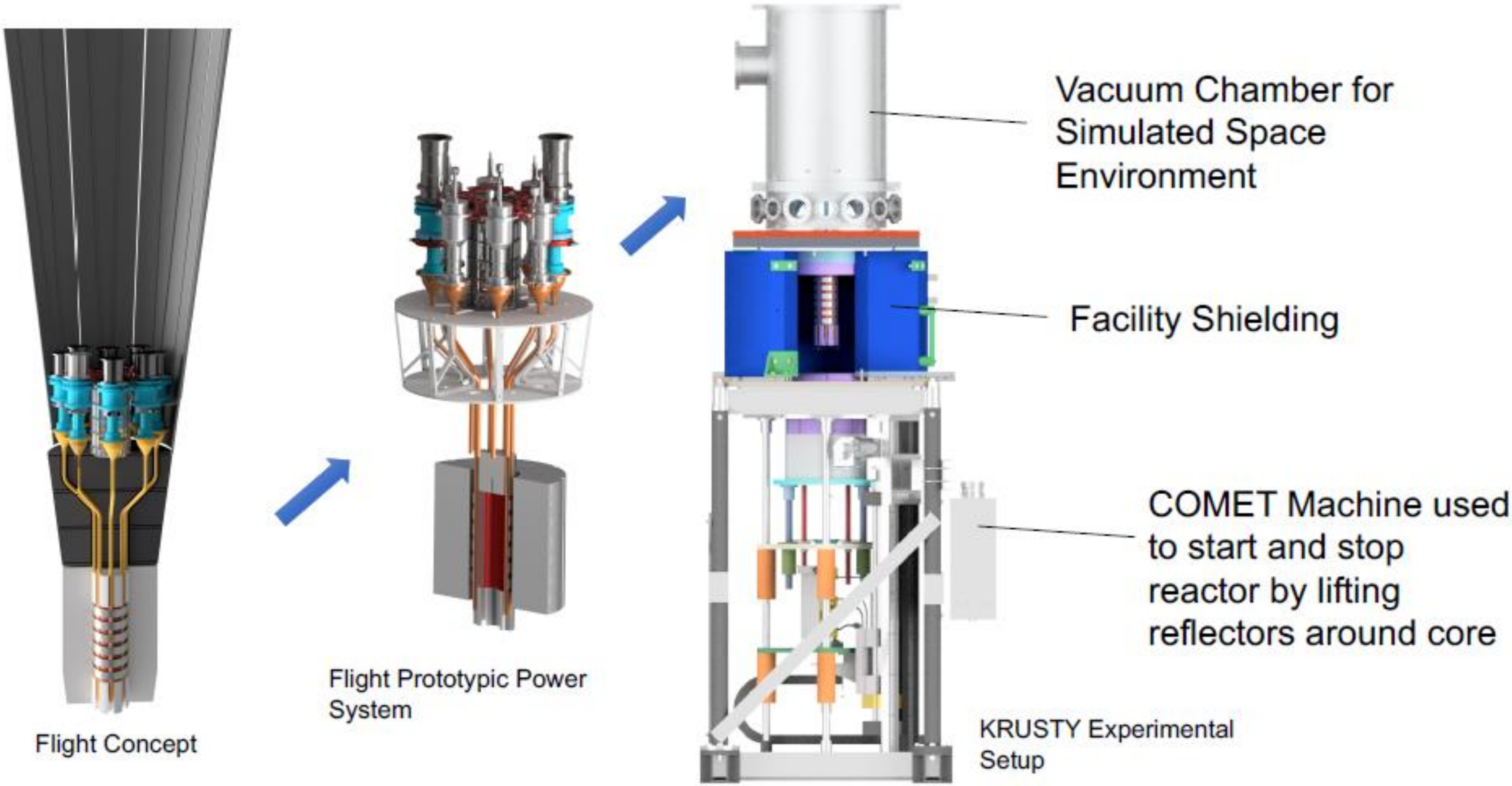
Surface Reactor 3-10 kW_e





10,000 W: 1500 kg

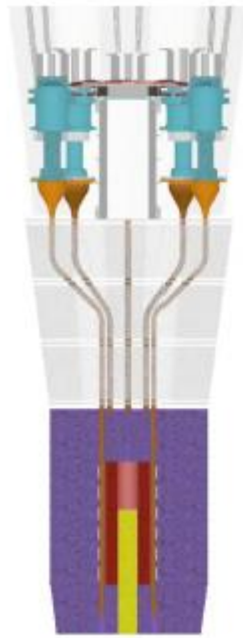
KRUSTY: Kilopower Reactor Using Stirling Technology

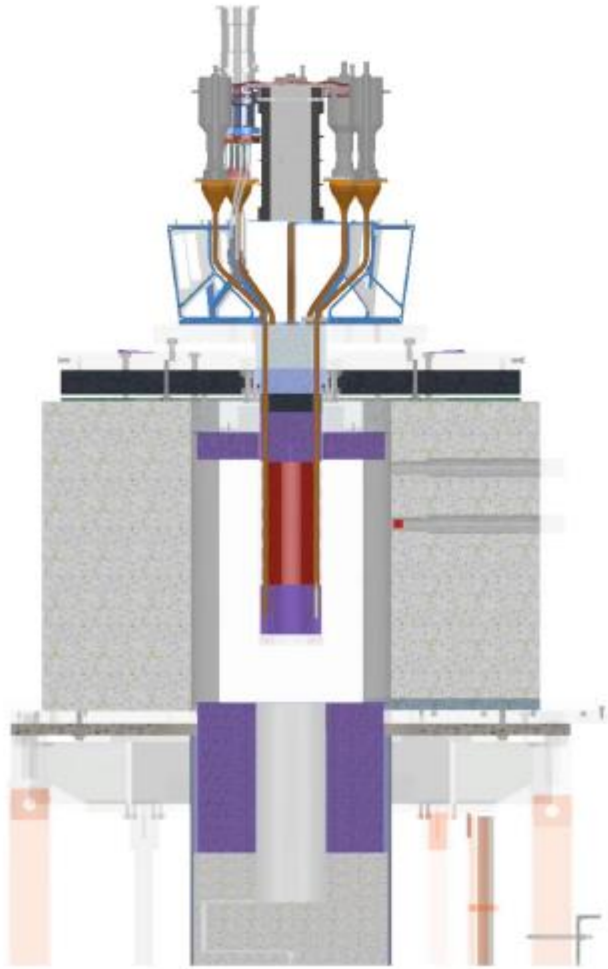


Source: NASA

Flight vs KRUSTY

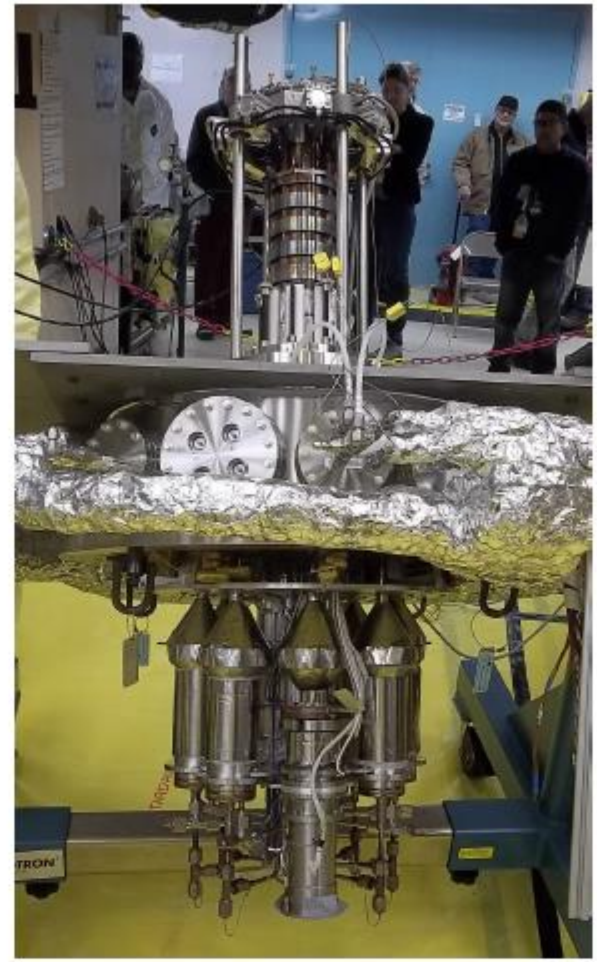
Flight Unit





KRUSTY
Experiment

Reactor Testing

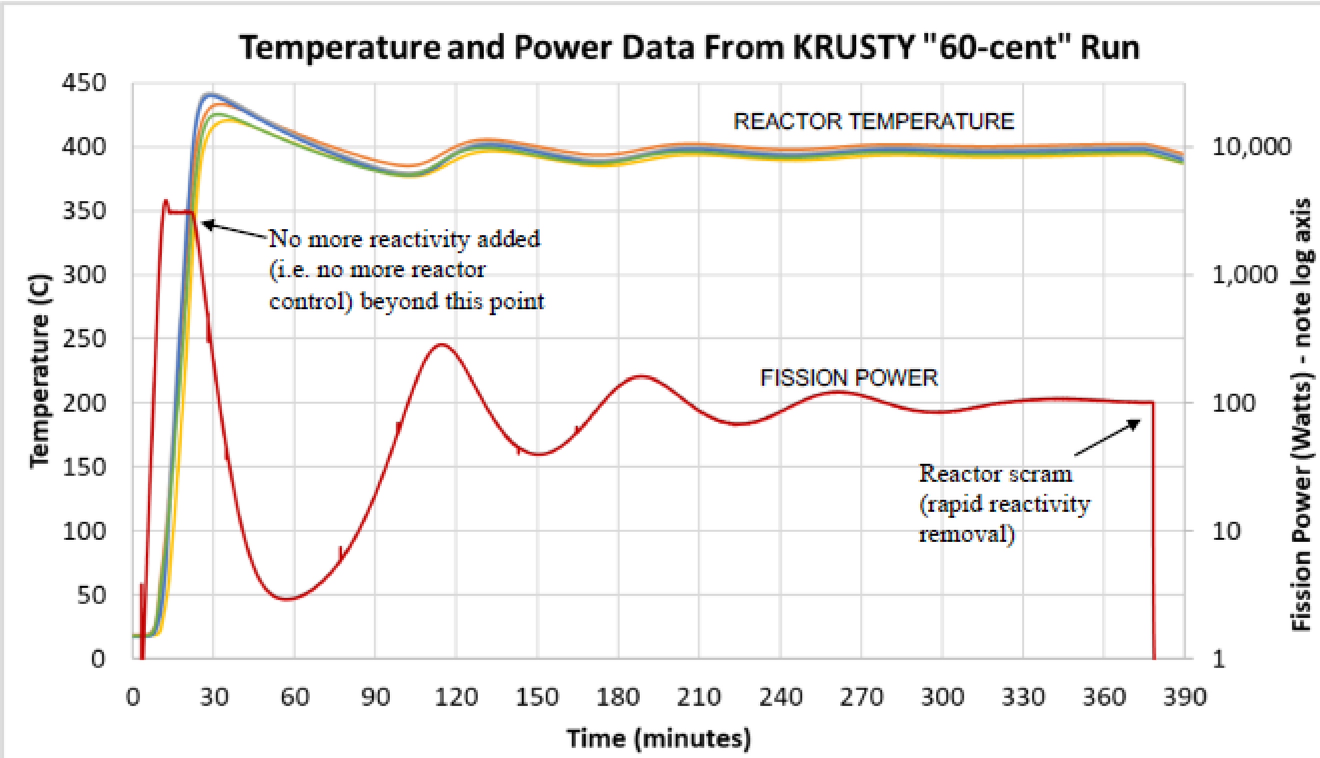


Source: NASA

Passive, Negative Reactivity Control

The warm criticals proved the simple, stable, passive behavior of the KRUSTY reactor.

In the case below, the reactivity was set so the fuel wants to maintain a temperature of 400 C.



Note: the period of oscillation is rather long in this example (75 minutes) because the passive power draw is very low (only 100 Watts) – just as lower gravity would make a pendulum take longer to swing back and forth.

KRUSTY performance

Event Scenario	Performance Metric	KRUSTY Experiment	Performance Status
Reactor Startup	3 hours to 800 deg. C	1.5 hours to 800 deg. C	Exceeds
Steady State Performance	4 kWt at 800 deg. C	> 4 kWt at 800 deg. C	Exceeds
Total Loss of Coolant	< 50 deg. C transient	< 15 deg. C transient	Exceeds
Maximum Coolant	< 50 deg. C transient	< 10 deg. C transient	Exceeds
Convertor Efficiency	> 25 %	> 35 %	Exceeds
Convertor Operation	Start, Stop, Hold, Restart	Start, Stop, Hold, Restart	Meets
System Electric Power Turn Down Ratio	> 2:1 (half power)	> 16:1	Exceeds

Source: NASA

Questions?

Australian Nuclear Association

www.nuclearaustralia.org.au

twitter

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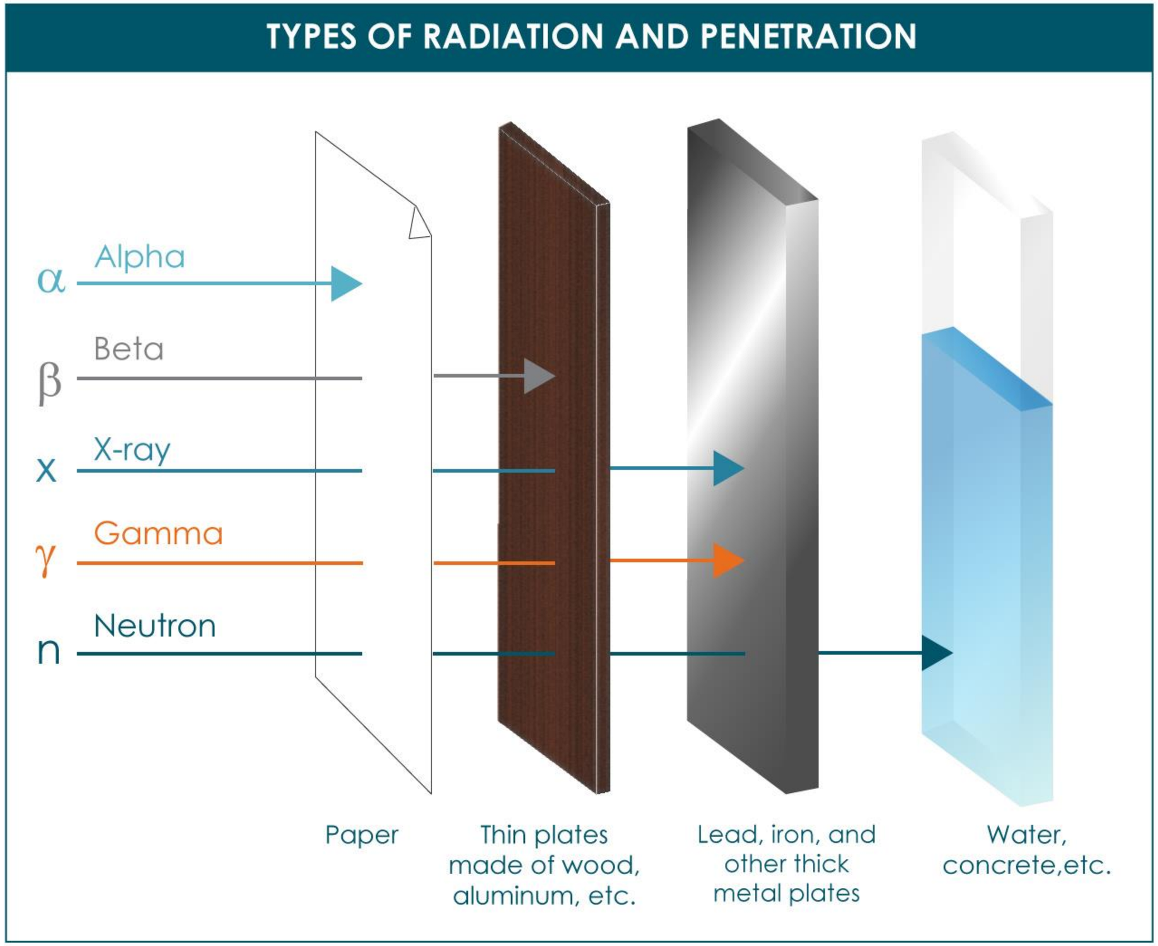
What is Ionising Radiation?

Relative damage

20	**Alpha** (helium nucleus)
1	**Beta** (electrons)
1	**X-ray & gamma** (EM waves)
5-20	**Neutrons**

Combined measure:

Sievert (Sv)



Ionising Radiation Everyday

0.05 µSv Year's dose at nuke-plant

0.09 µSv Year's dose at coal-plant

0.1 µSv Eating a banana

0.4 µSv Background dose / hour

40 µSv 7.5 hour flight

100 µSv 2 weeks inside Fukushima Town-hall

3,500 µSv Australian annual background dose

7,000 µSv CT chest scan

20,000 µSv Australian radiation worker limit (1 year)

50,000 µSv US radiation worker limit (1 year)

100,000 µSv Maximum 1 year dose without risk of developing cancer

4 million µSv Fatal dose