Power Systems Design

- Lecture #19 – October 31, 2023
- Definitions of energy and power
- Power generation systems
- Energy storage systems
- Integrated systems analysis

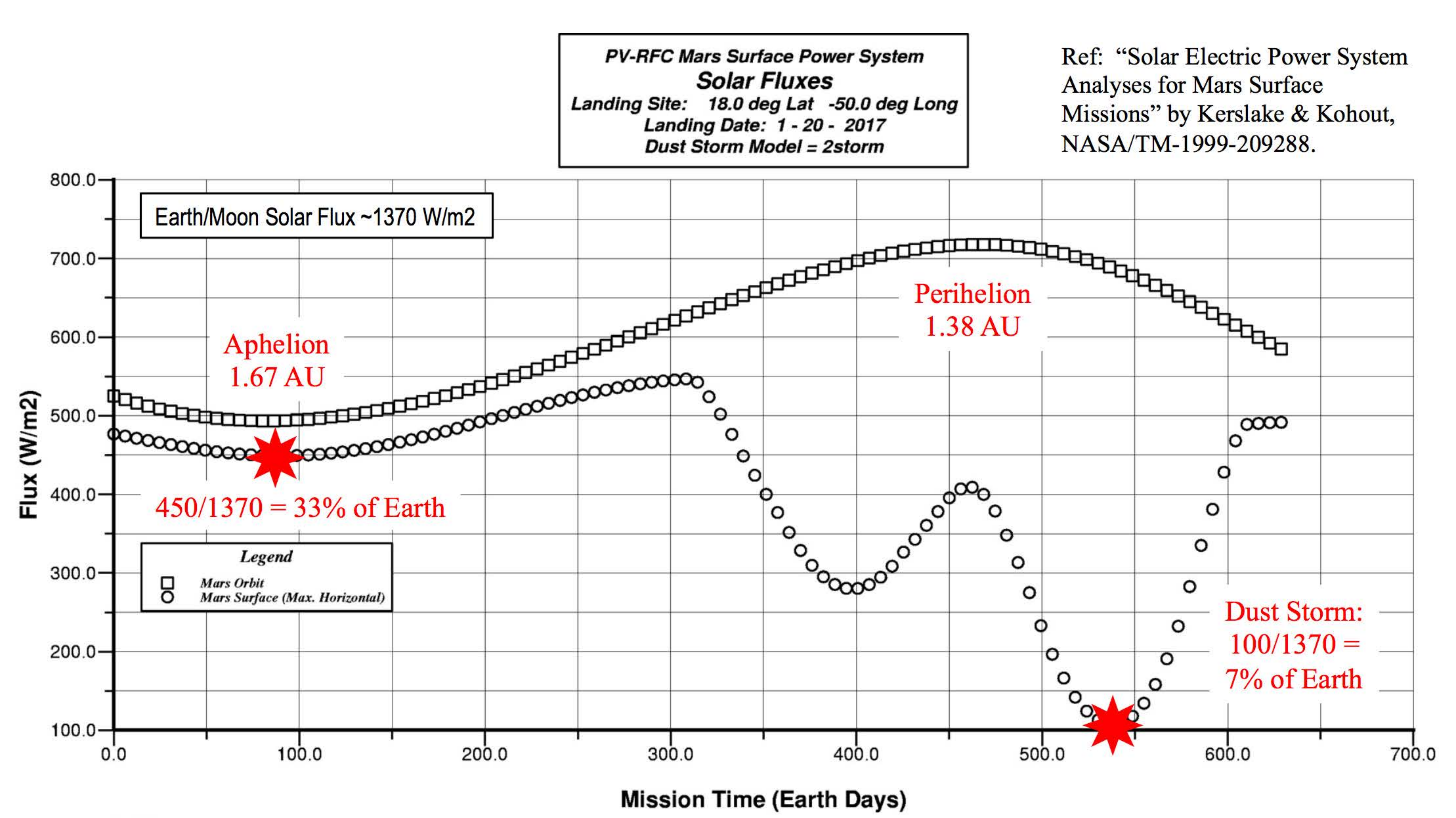
Energy and Power - *Not the Same!!!*

- Energy - the capacity of a physical system to do work (J, N-m, kWhr)
- Power - time rate of change of energy (W, N-m/sec, J/sec)
- We are interested in generating *power*; we store and use *energy* at a given *power* level.

Solar Power

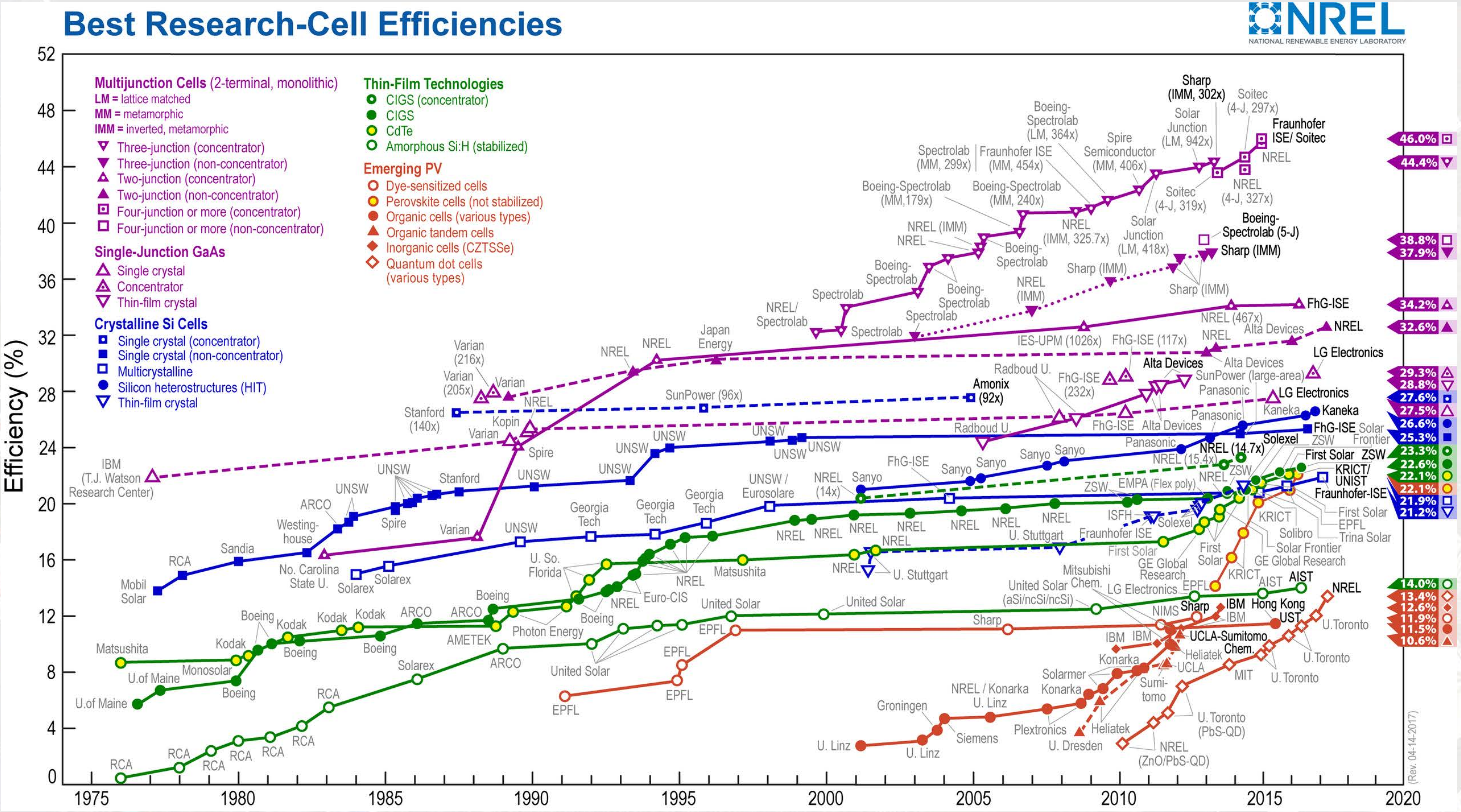
- Insolation constant = 1394 W/m^2 at 1 AU
- Varies with inverse square of distance
- Power conversion technologies
  - Photovoltaic
  - Thermodynamic cycle

Solar Flux at Mars

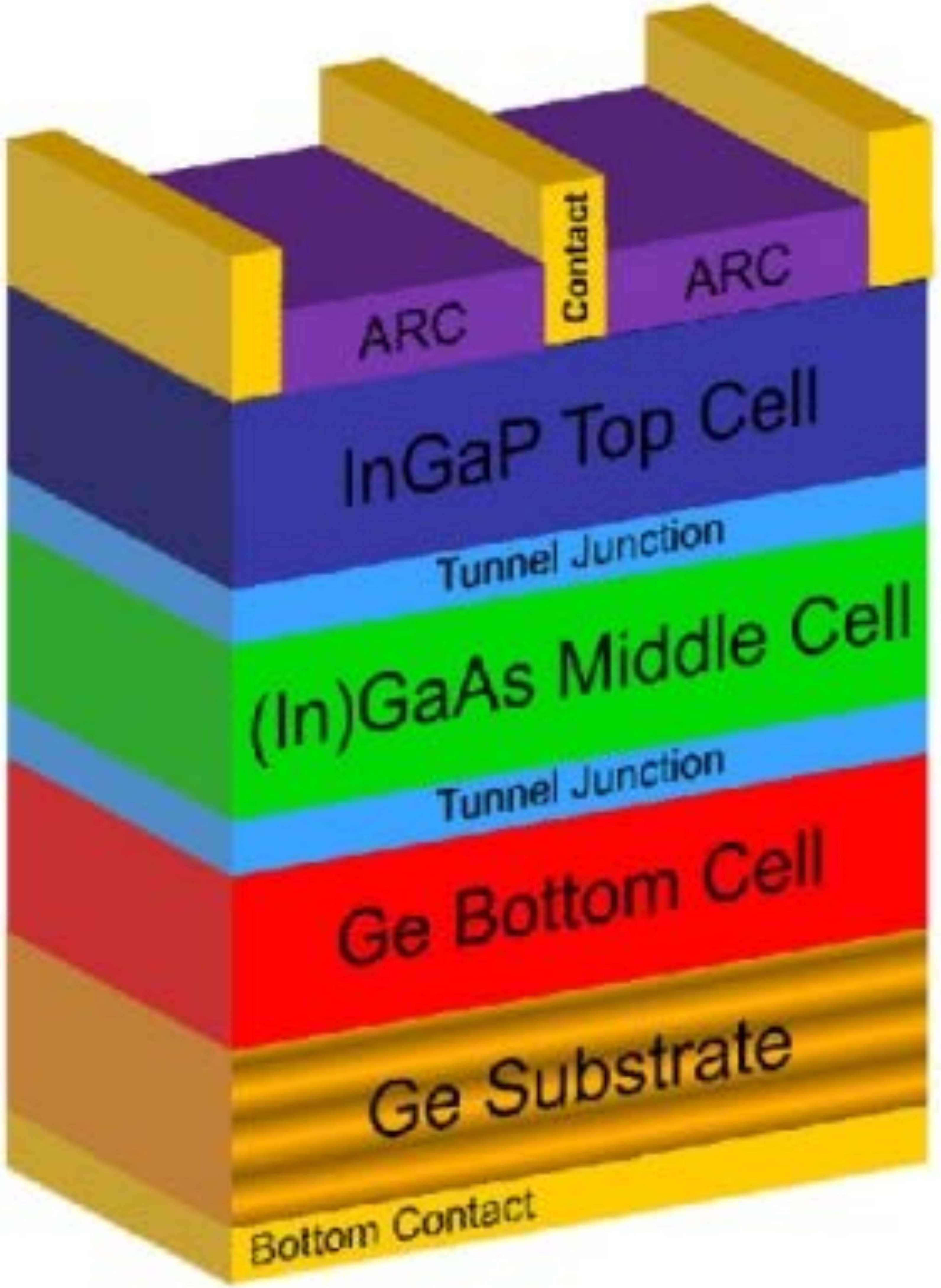


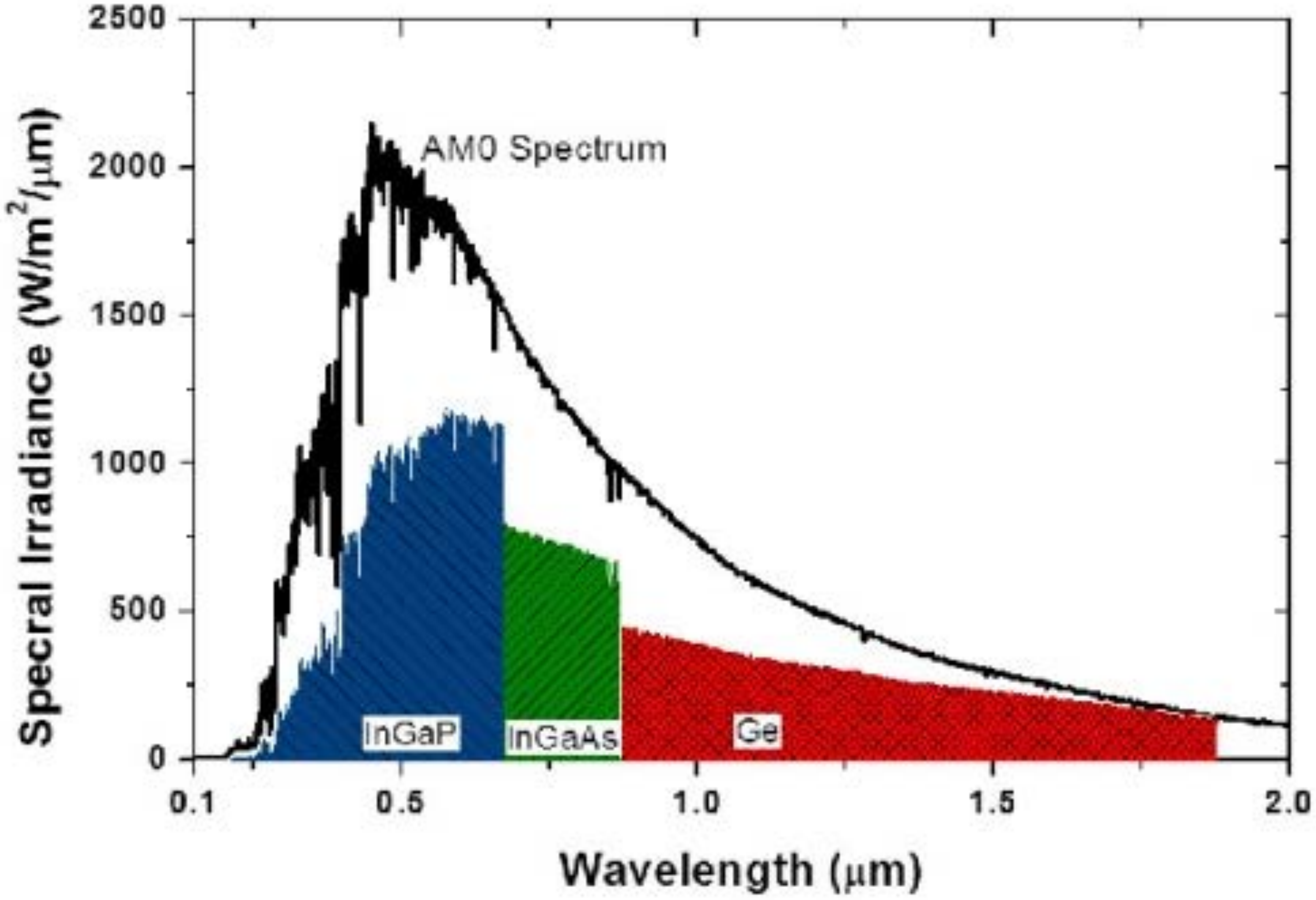
From Mason, *Kilopower: Small Fission Power Systems for Mars and Beyond* NASA FISO Working Group, Feb. 1, 2017

Photovoltaic Cell Efficiency



Triple-Junction Photovoltaic Cell



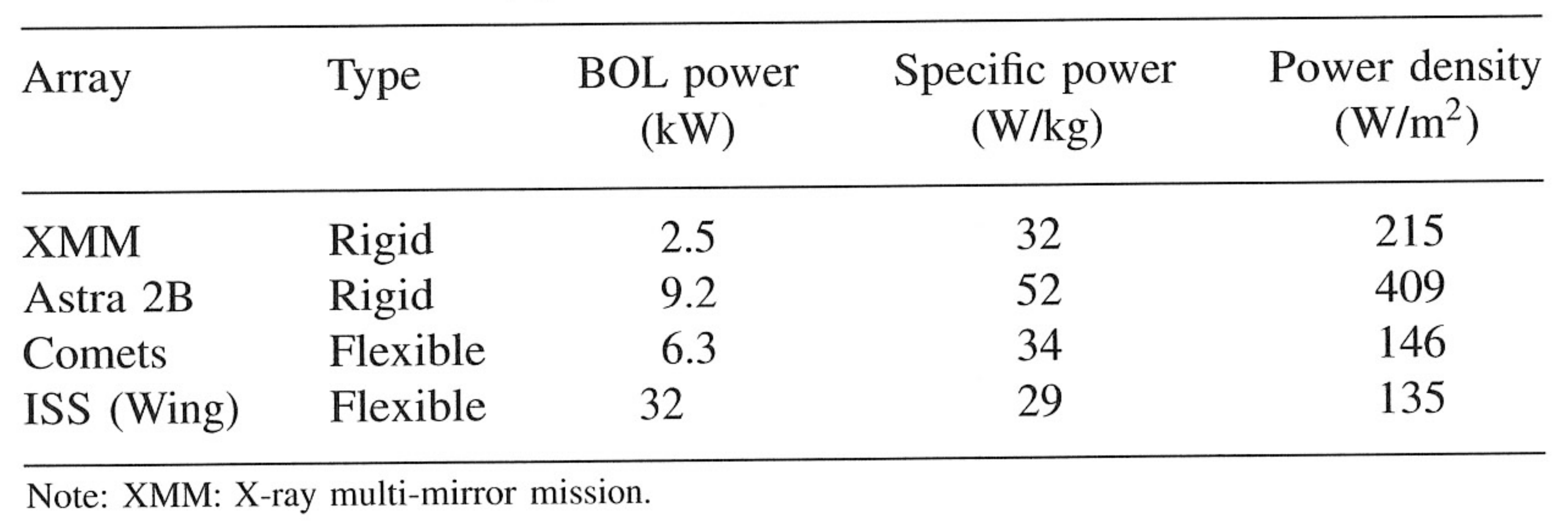


Individual Cell Efficiencies

Cell Type	Silicon	Thin Film Amorphous Si	Gallium Arsenide	Indium Phosphide	Triple Junction GaAs
Planar Cell Theoretical Efficiency	29%	12.0%	23.5%	22.8%	40+%
Achieved Efficiency: *Production* *Best Laboratory*	 22% 24.7%	 8.0% 11%	 18.5% 21.8%	 18% 19.9%	 30.0% 33.8%
Equivalent Time in Geosynchronous Orbit for 15% Degradation *– 1 MeV electrons* *– 10 MeV protons*	 10 yr 4 yr	 10 yr 4 yr	 33 yr 6 yr	 155 yr 89 yr	 33 yr 6 yr

From Wertz, Everett, and Puschell, *Space Mission Engineering: The New SMAD* Microcosm Press, 2011

Photovoltaic Array Examples



Array	Type	BOL power (kW)	Specific power (W/kg)	Power density (W/m^2)
XMM	Rigid	2.5	32	215
Astra 2B	Rigid	9.2	52	409
Comets	Flexible	6.3	34	146
ISS (Wing)	Flexible	32	29	135

Note: XMM: X-ray multi-mirror mission.

From Fortescue, Swinerd, and Stark, *Spacecraft Systems Engineering, 4th ed.* John Wiley and Sons, 2011

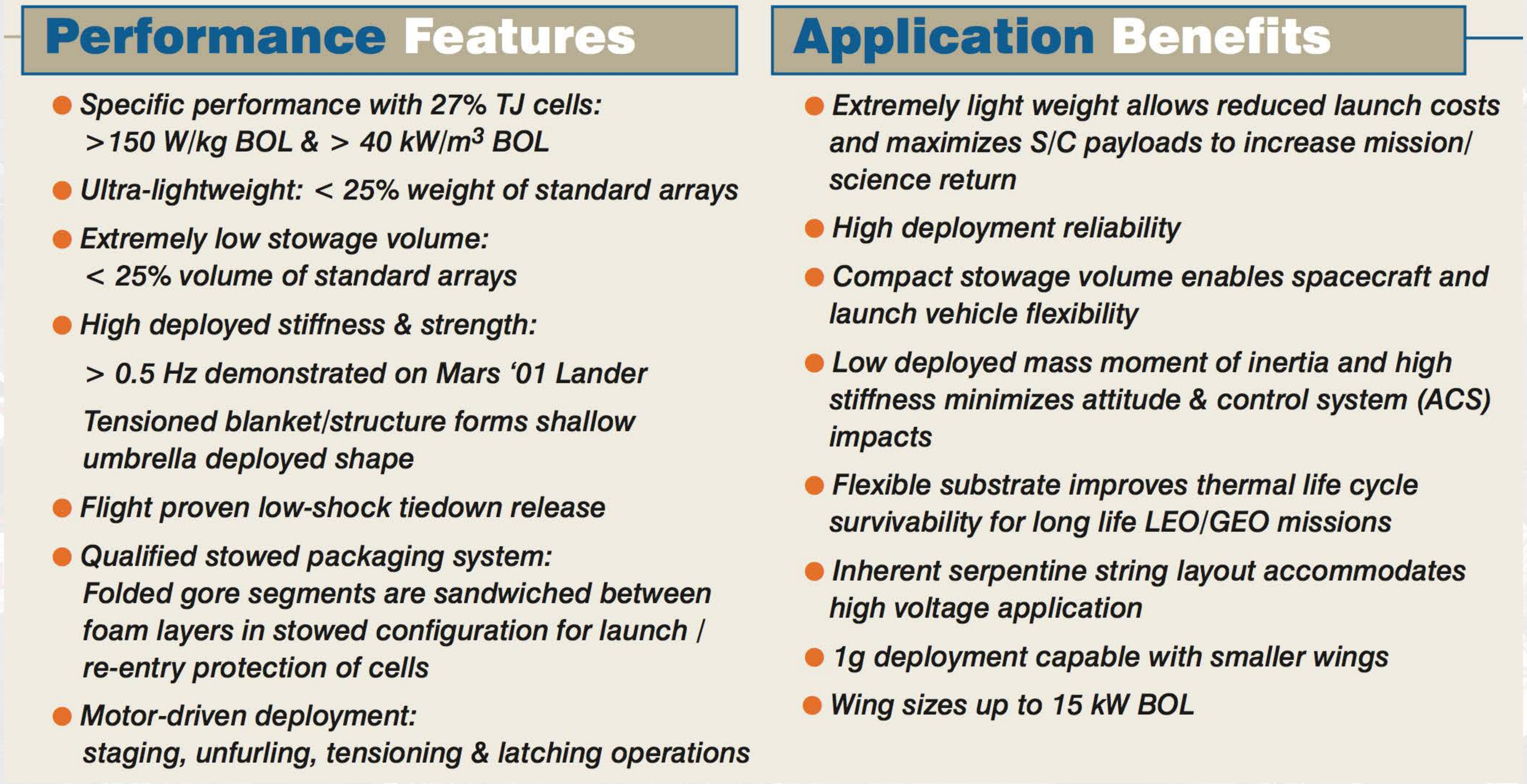
Current Trends in Photovoltaics

- Multi-Band Gap Concentrator Arrays
  - – High efficiency (35%)
  - – Low mass (2-300 W/kg)
  - – Low area (500 W/m^2)
- Ultra-lightweight arrays
  - – Reasonable efficiencies (15-20%)
  - – Very low mass (500-1000 W/kg)
  - – Larger area (200 W/m2)

Ultra-lightweight Photovoltaic Arrays

- Solely optimized for minimum areal mass
- Tends to use simpler (lower efficiency cells)
- AEC-Able Ultraflex
  - 115 W/kg (Si 17%)
  - 140 W/kg (GaAs 23%)

UltraFlex Characteristics



Performance Features

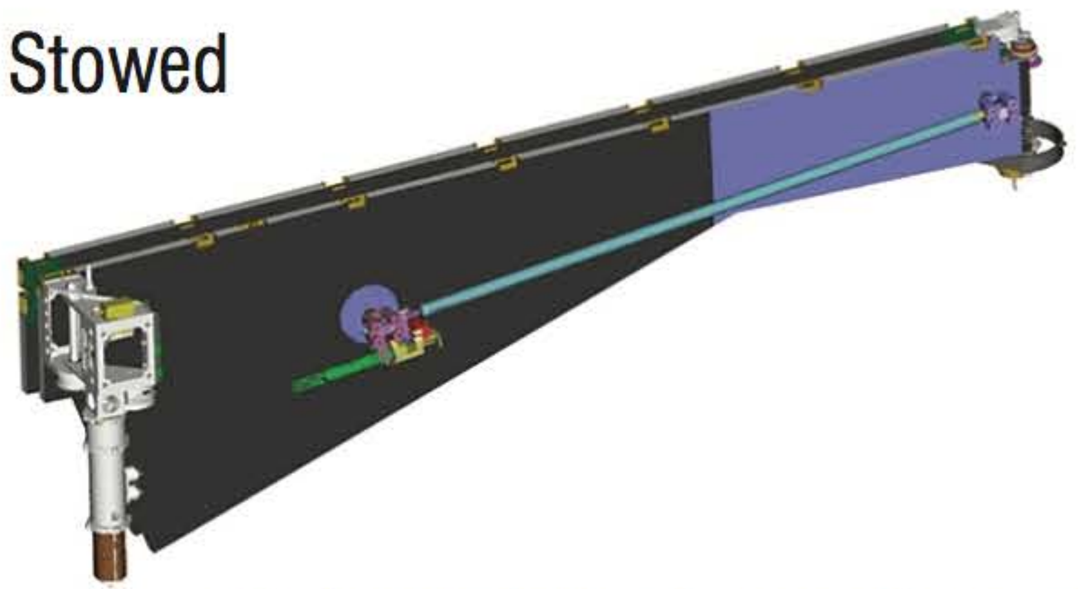
- Specific performance with 27% TJ cells:
  >150 W/kg BOL & > 40 kW/m^3 BOL
- Ultra-lightweight: < 25% weight of standard arrays
- Extremely low stowage volume:
  < 25% volume of standard arrays
- High deployed stiffness & strength:
  > 0.5 Hz demonstrated on Mars '01 Lander
  Tensioned blanket/structure forms shallow umbrella deployed shape
- Flight proven low-shock tiedown release
- Qualified stowed packaging system:
  Folded gore segments are sandwiched between foam layers in stowed configuration for launch / re-entry protection of cells
- Motor-driven deployment:
  staging, unfurling, tensioning & latching operations

Application Benefits

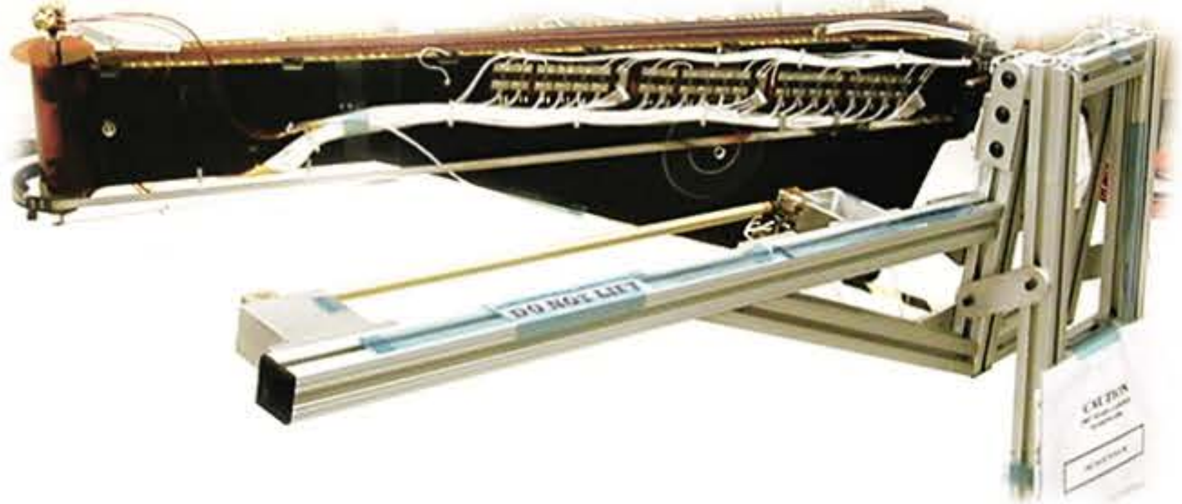
- Extremely light weight allows reduced launch costs and maximizes S/C payloads to increase mission/ science return
- High deployment reliability
- Compact stowage volume enables spacecraft and launch vehicle flexibility
- Low deployed mass moment of inertia and high stiffness minimizes attitude & control system (ACS) impacts
- Flexible substrate improves thermal life cycle survivability for long life LEO/GEO missions
- Inherent serpentine string layout accommodates high voltage application
- 1g deployment capable with smaller wings
- Wing sizes up to 15 kW BOL

UltraFlex Deployment Sequence

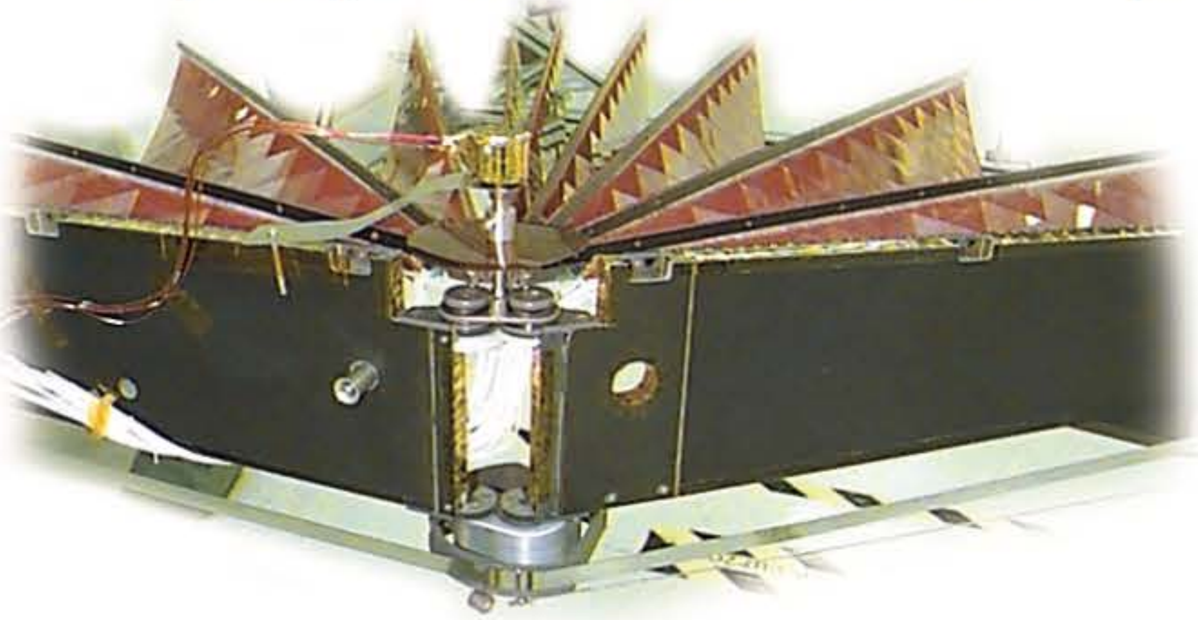
1. Stowed



2. Launch tie-down released, 90° articulation from S/C

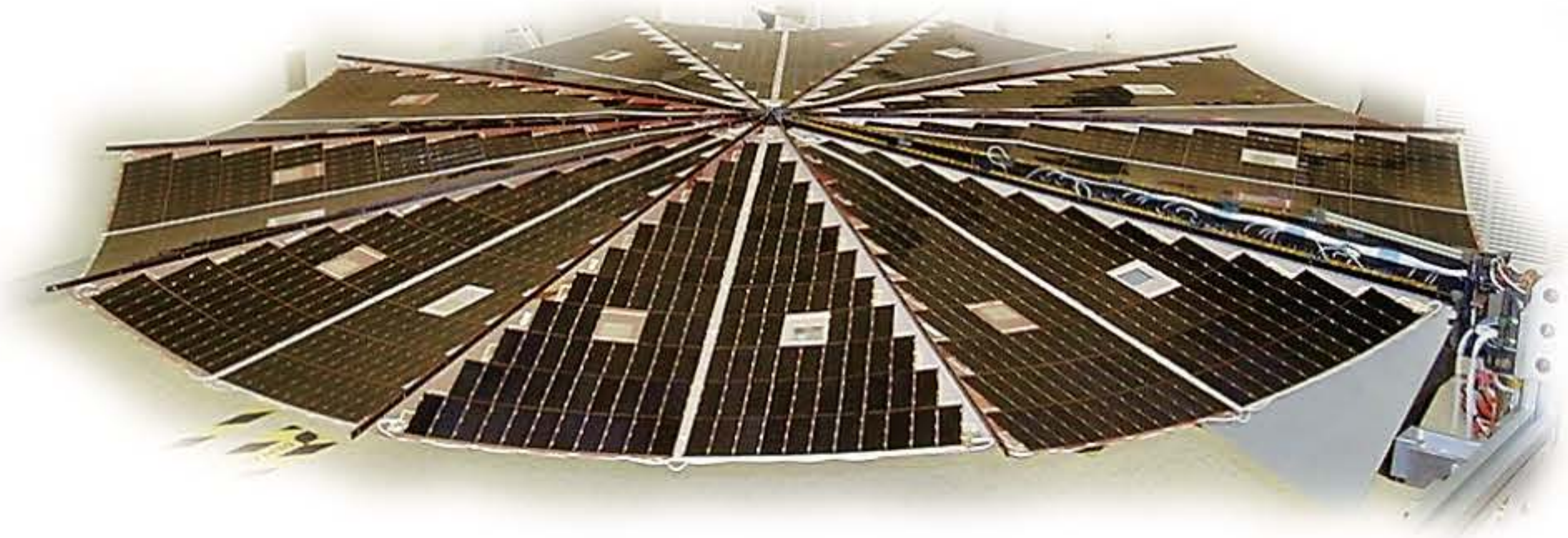


3. Motor-driven deployment, lanyard is attached to pivot panel & reeled onto motor pulley



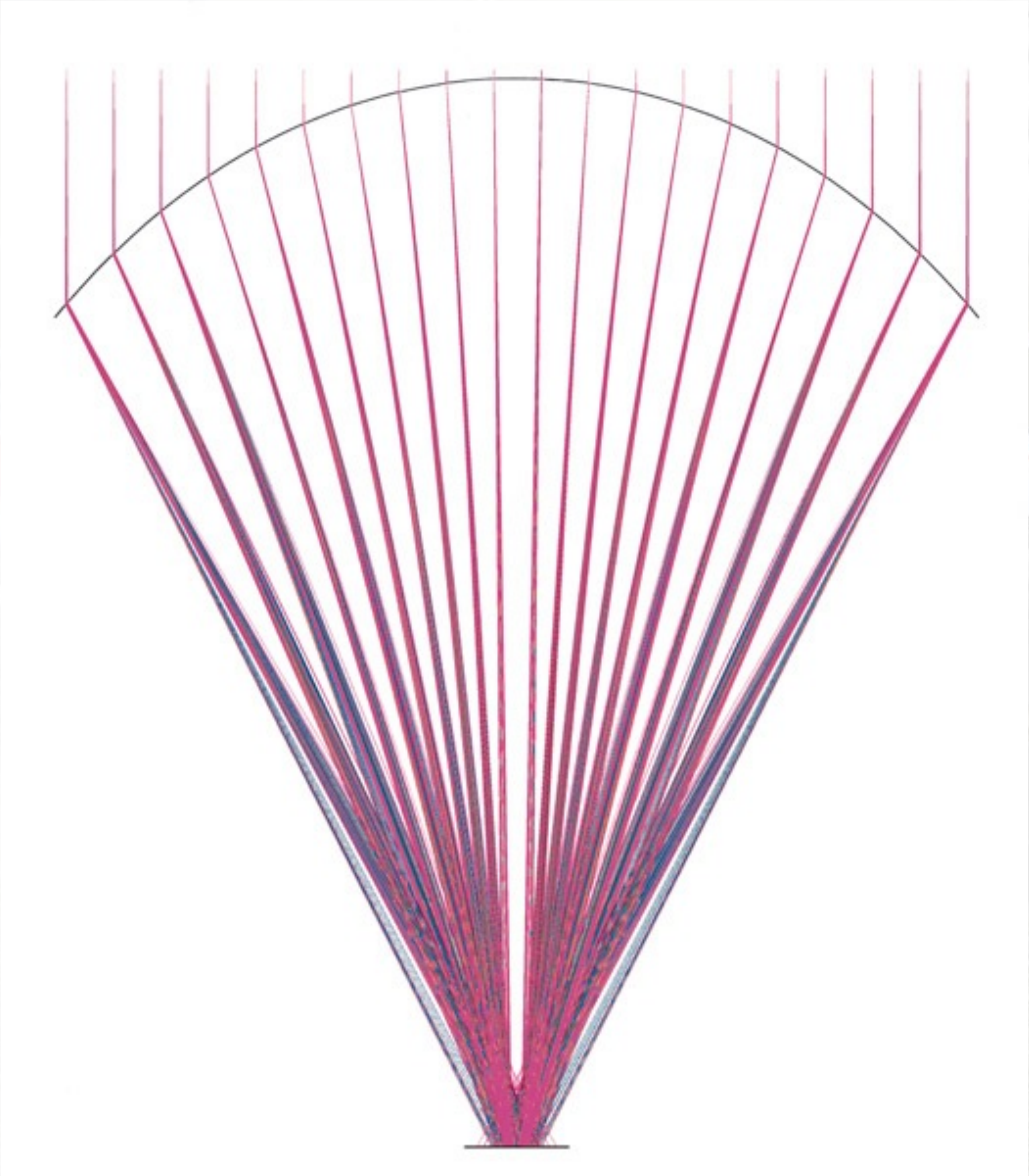
4. Deployment continues as lanyard is further reeled onto motor pulley; operation continues until pivot panel has rotated ~360°.

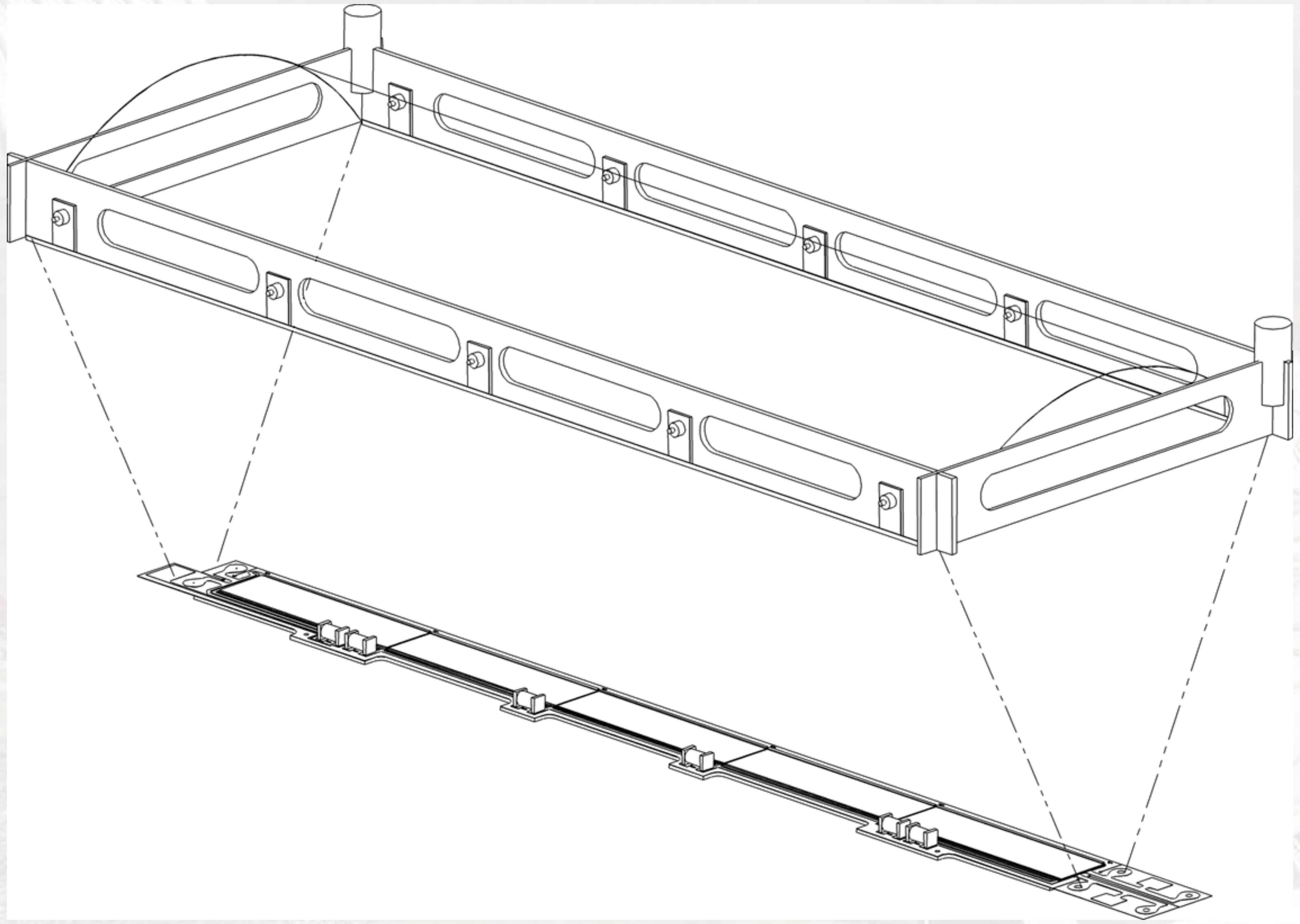
5. Fully deployed, preloaded & latched



Concentrator Multi-Band Gap Arrays

- Multi-band gap GaAs cells for high efficiency
- Concentrator increases solar insolation, reduces area of cells, provides self-annealing





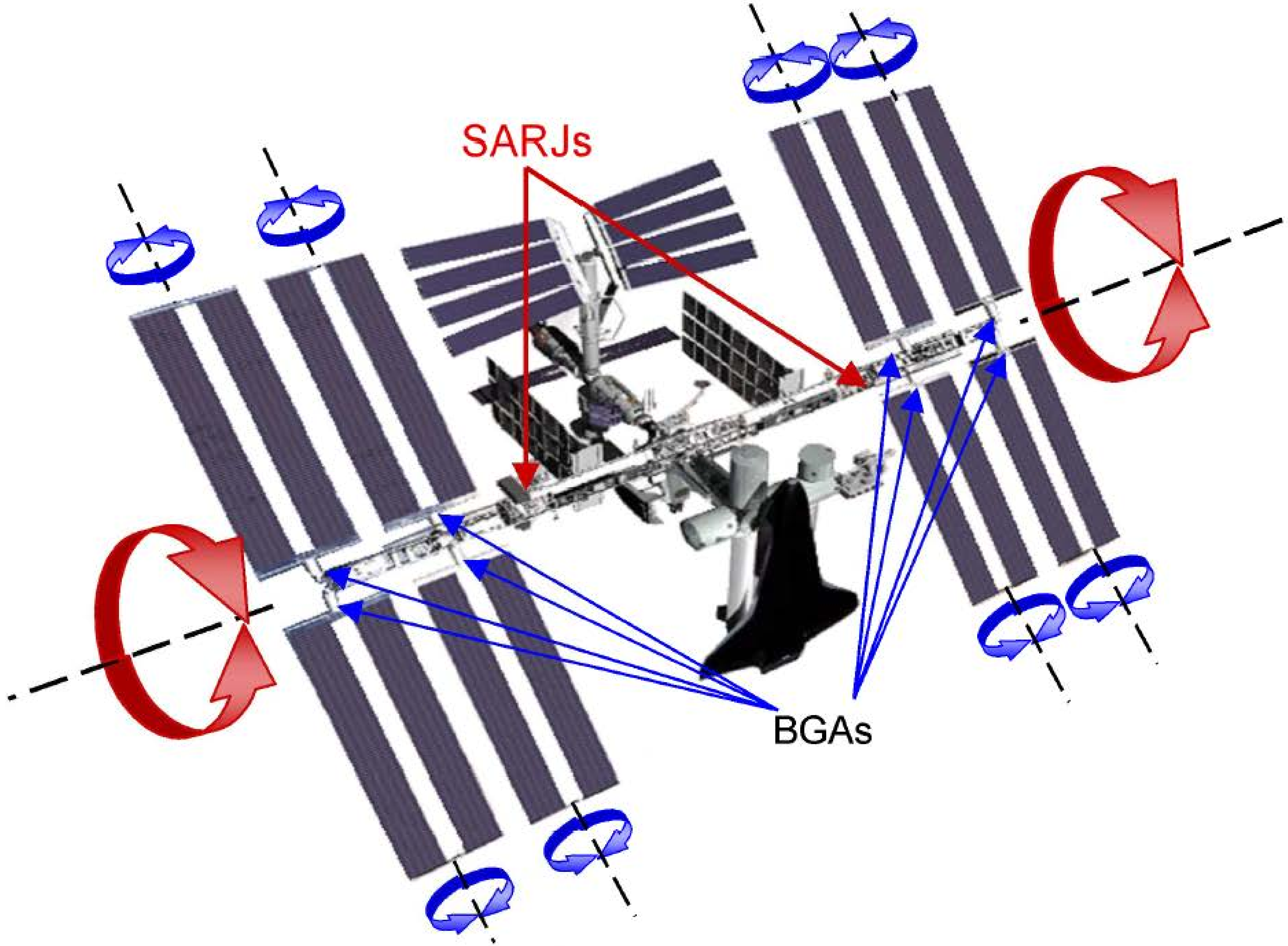
Sample Concentrator Array

- AEC-Able SCARLETT array
- Flown on Deep Space-1
- 299 W/m^2
- 44 W/kg

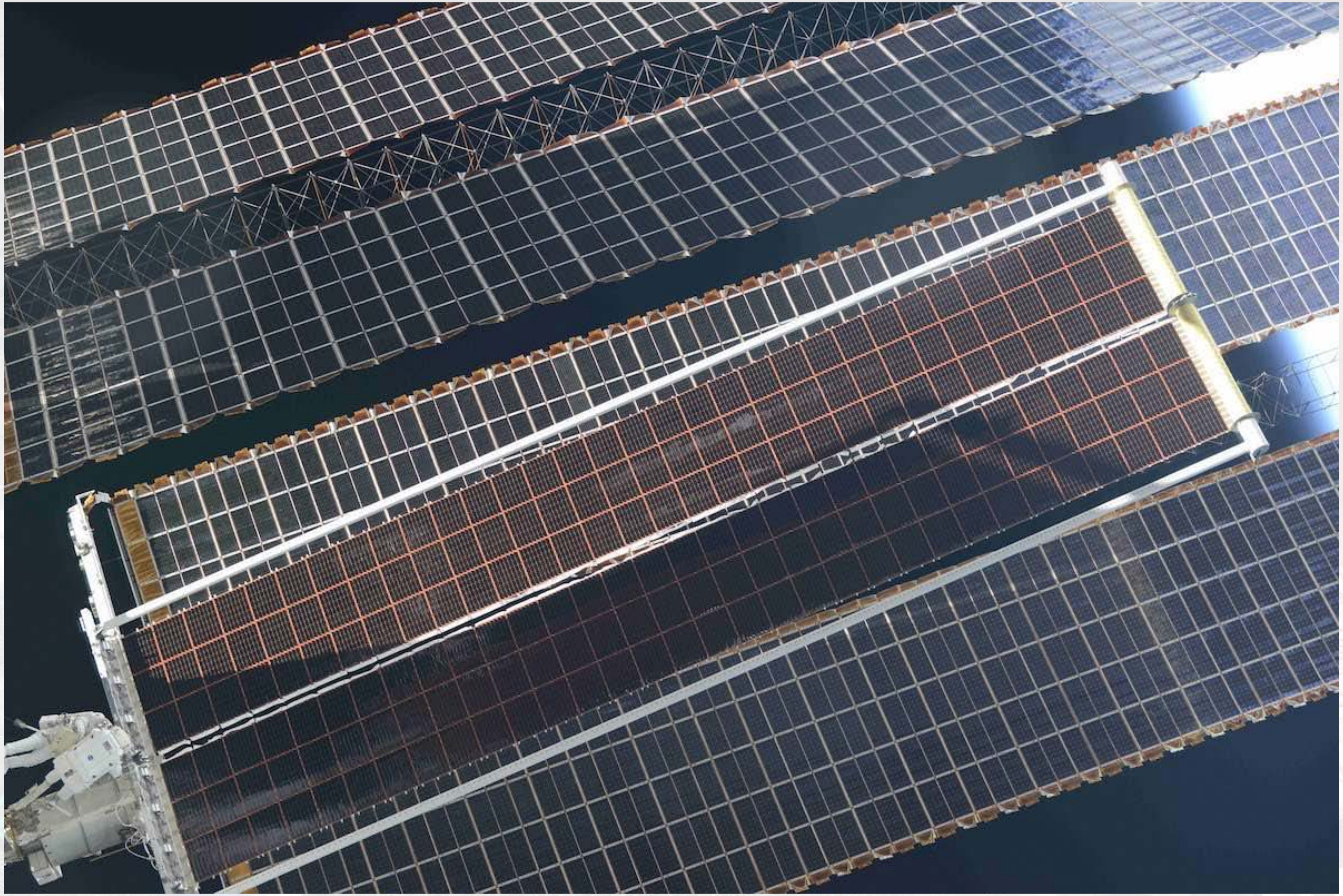
International Space Station Solar Arrays

S118E09418

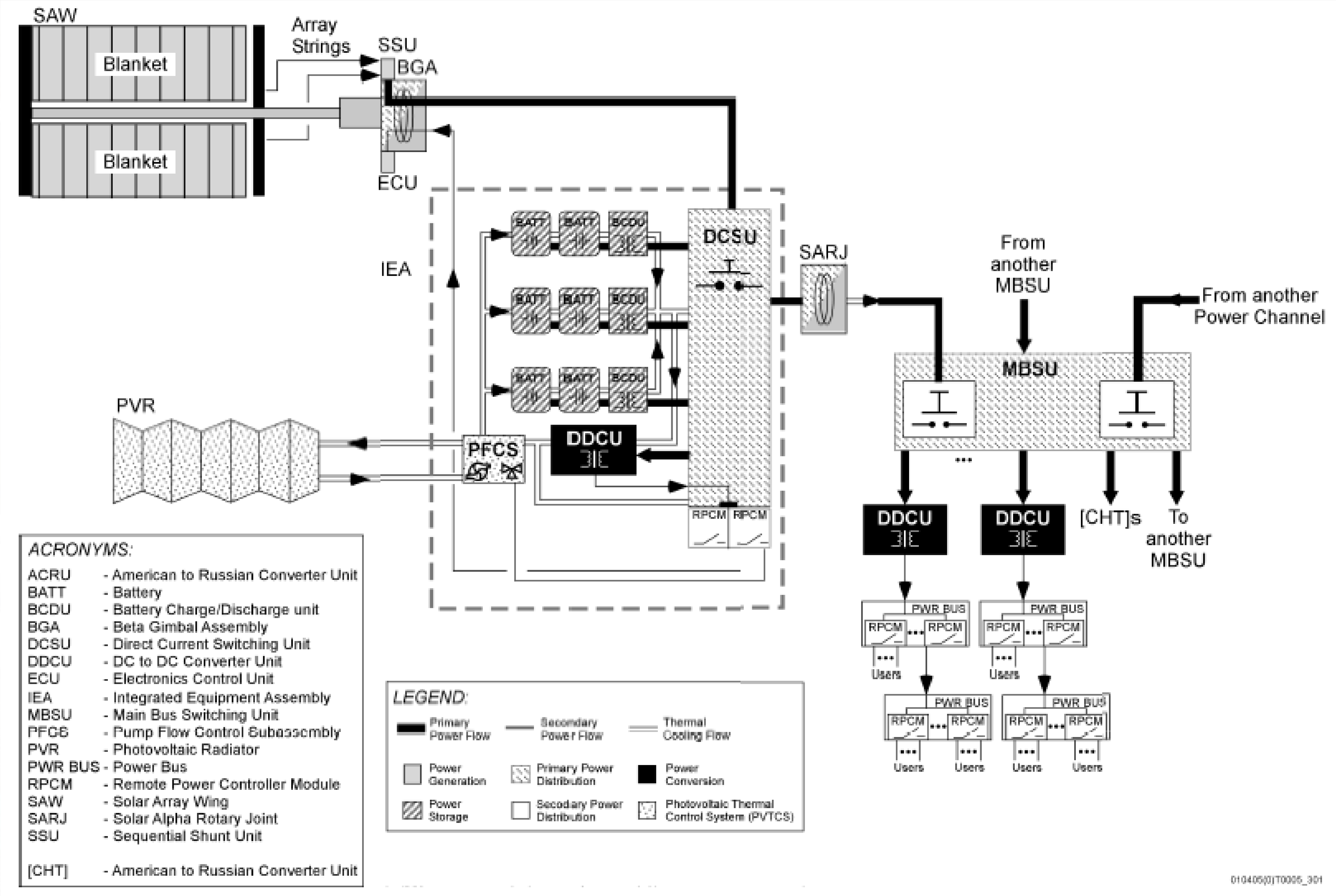
ISS Solar Array Articulation



ISS Roll-Out Solar Array (ROSA)



ISS Power Management and Distribution



ACRONYMS:

ACRU	- American to Russian Converter Unit
BATT	- Battery
BCDU	- Battery Charge/Discharge unit
BGA	- Beta Gimbal Assembly
DCSU	- Direct Current Switching Unit
DDCU	- DC to DC Converter Unit
ECU	- Electronics Control Unit
IEA	- Integrated Equipment Assembly
MBSU	- Main Bus Switching Unit
PFCS	- Pump Flow Control Subassembly
PVR	- Photovoltaic Radiator
PWR BUS	- Power Bus
RPCM	- Remote Power Controller Module
SAW	- Solar Array Wing
SARJ	- Solar Alpha Rotary Joint
SSU	- Sequential Shunt Unit
[CHT]	- American to Russian Converter Unit

Photovoltaic Array Sizing Calculation

- Power requirement = 3 kW
- Si cells, 17% efficiency

$$A = \frac{P_{req}}{I_s \eta} = \frac{3000\ W}{1394\ {}^{W}\!/_{m^2}(.17)} = 12.66\ m^2$$

- Power density = 115 W/kg

$$m_{array} = \frac{P}{\rho_{power}} = \frac{3000\ W}{115\ {}^{W}\!/_{kg}} = 26.1\ kg$$

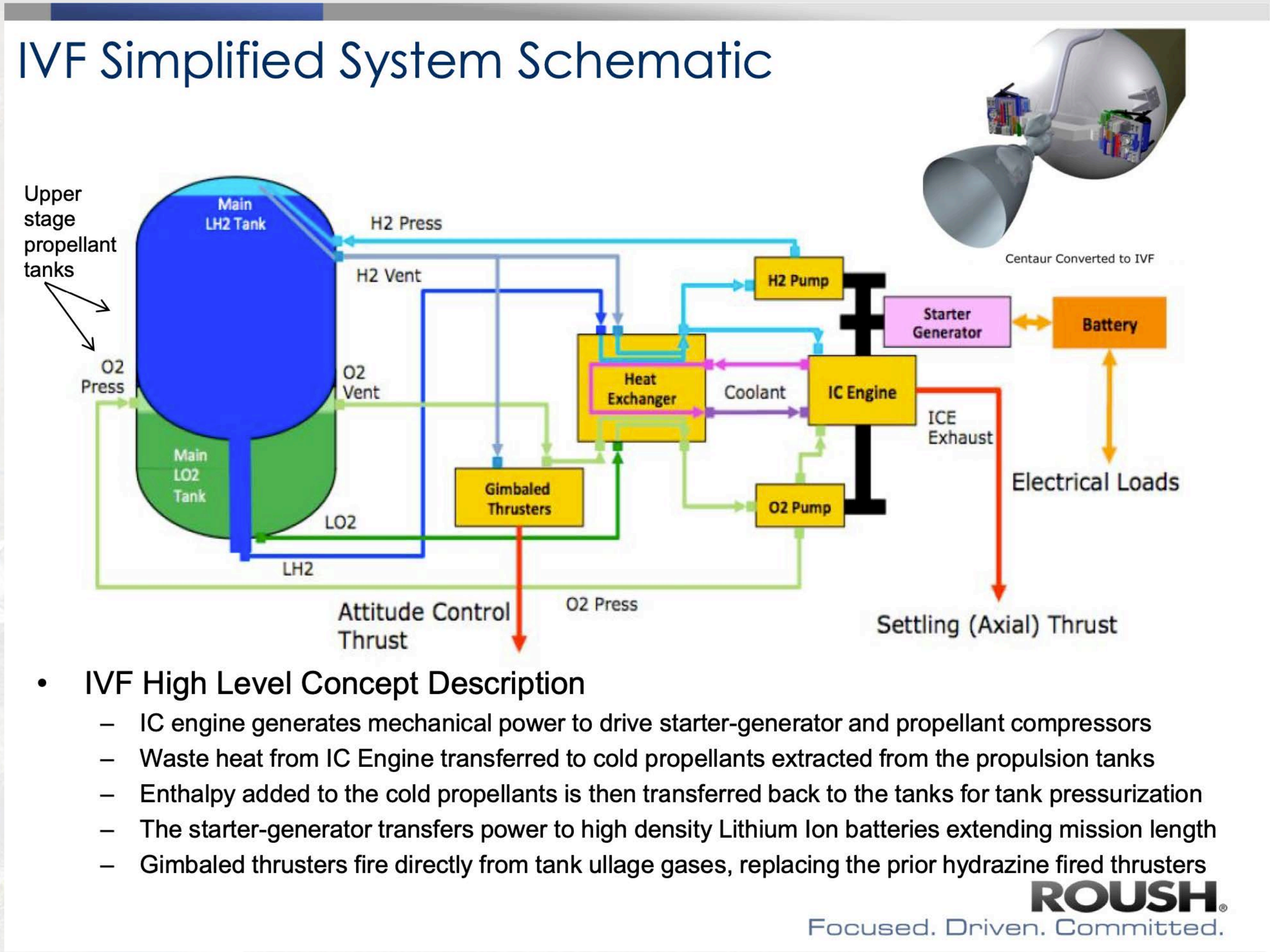
Chemical Thermal Power Systems

- Use chemical energy storage systems (high density compared to batteries)
- Have to carry both fuel and oxidizer
- Use high-efficiency thermal cycle engines to generate electrical power
  - Stirling
  - Brayton
- Generally use electrical motors for actuation

ULA Vulcan Integrated Vehicle Fluids

- Upper stages generally only function for a few hours – goal is to keep upper stage alive for days/weeks
- Replaces battery with internal combustion engine
  - Runs on boil-off of LOX/LH2
  - Supplies power for stage including autologous pressurization of propellants
  - Use engine waste heat for thermal control
- Planned for testing on Vulcan Centaur upper stage in next few years

Integrated Vehicle Fluids Schematic



IVF Simplified System Schematic

- IVF High Level Concept Description
  - IC engine generates mechanical power to drive starter-generator and propellant compressors
  - Waste heat from IC Engine transferred to cold propellants extracted from the propulsion tanks
  - Enthalpy added to the cold propellants is then transferred back to the tanks for tank pressurization
  - The starter-generator transfers power to high density Lithium Ion batteries extending mission length
  - Gimbaled thrusters fire directly from tank ullage gases, replacing the prior hydrazine fired thrusters

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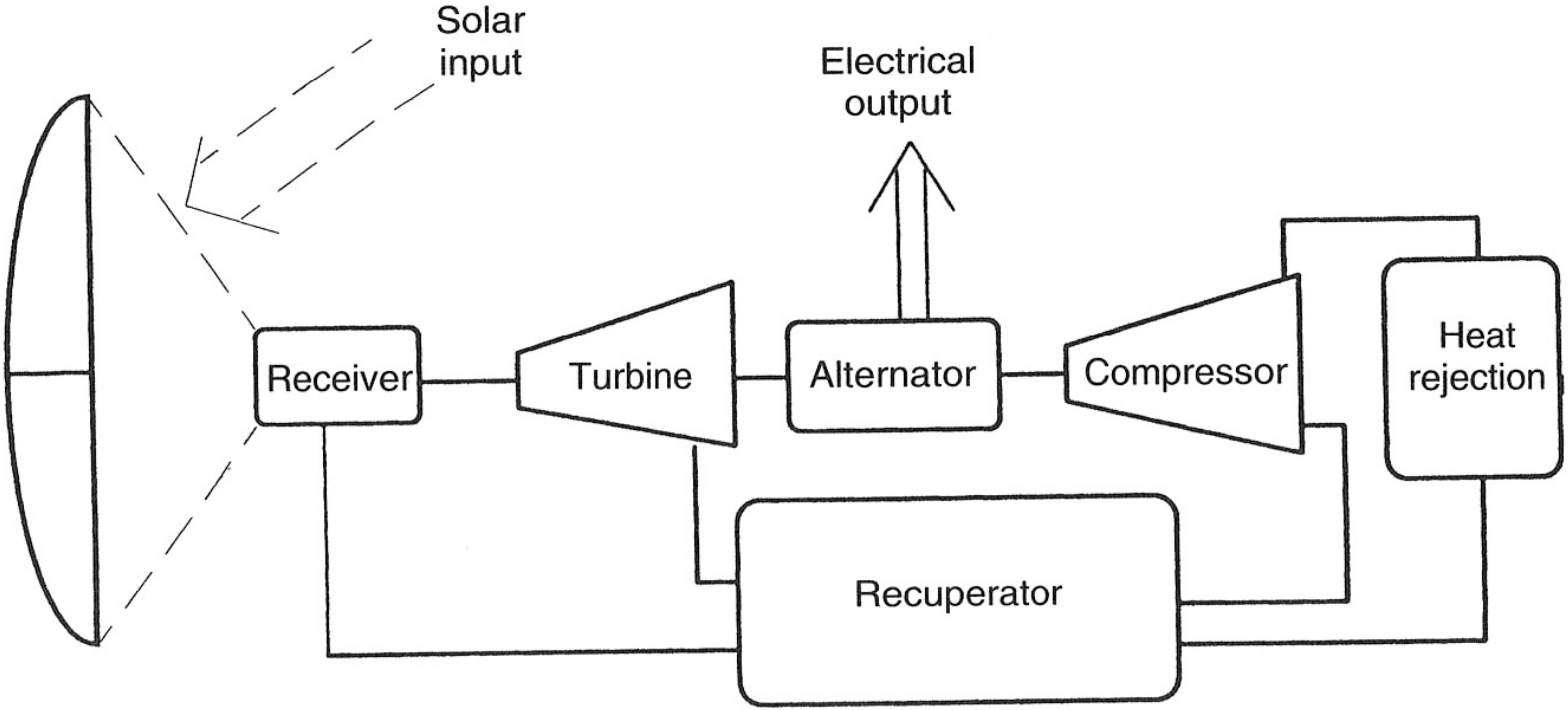
Solar Thermal Power Systems

- Use large concentrators to focus solar energy on thermal collector
- Run thermal cycle to generate electricity
- Advantages over photovoltaic
  - Higher areal efficiencies
  - Lower procurement costs
- Disadvantages
  - Moving parts, requiring maintenance
  - Pointing accuracy proportional to concentration ratio

Solar Dynamic Cycle Schematic



From Fortescue, Swinerd, and Stark, *Spacecraft Systems Engineering, 4th ed.* John Wiley and Sons, 2011

Thermodynamic Cycles in Space

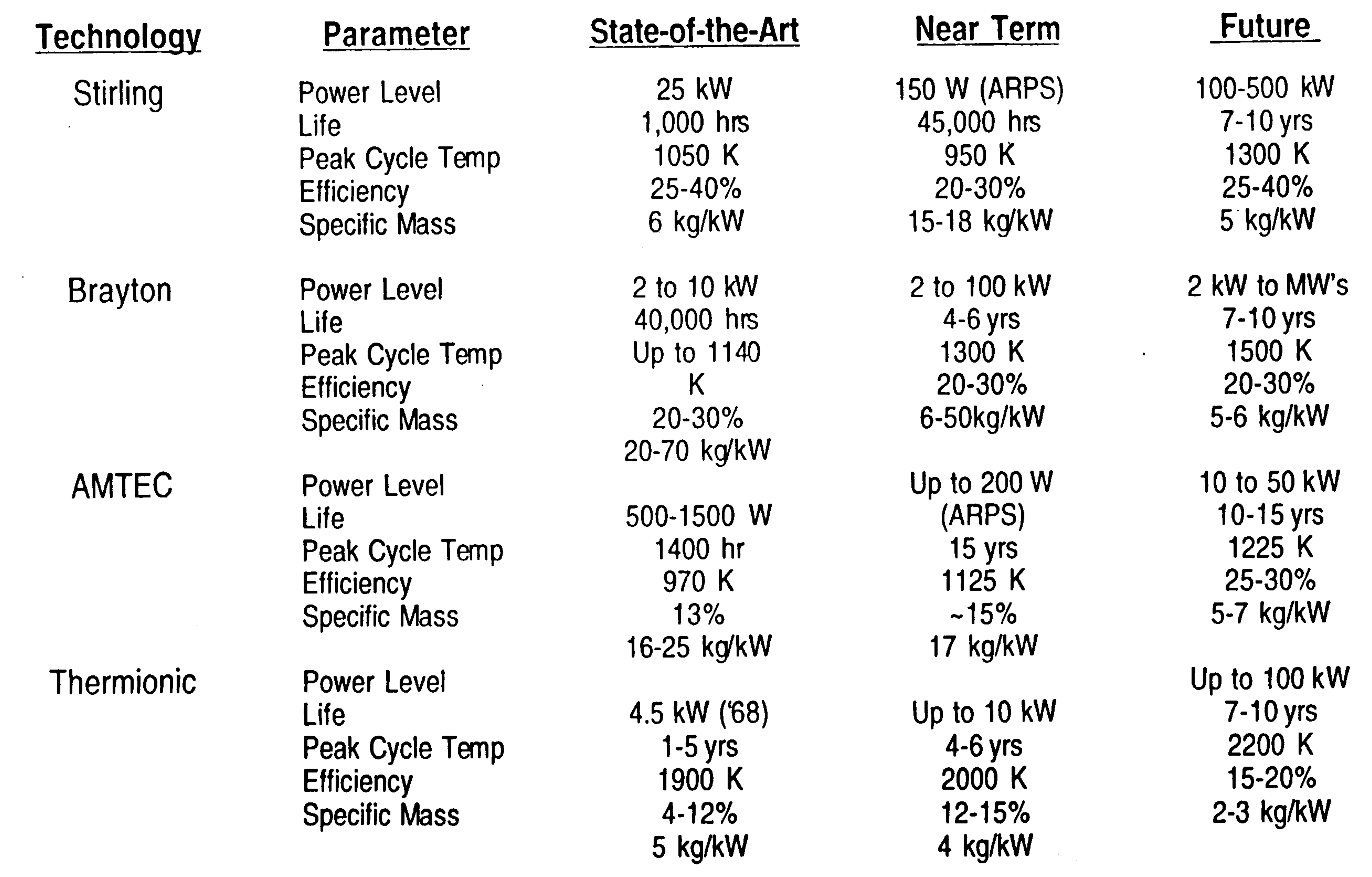
- Carnot efficiency

$$\eta_{Carnot} = \eta_{max} = 1 - \frac{T_{cold}}{T_{hot}}$$

- Radiative equilibrium

$$P = A\sigma\epsilon T^4 \longrightarrow A = \frac{P}{\sigma\epsilon T^4}$$

NASA Thermal Conversion Tech Projections

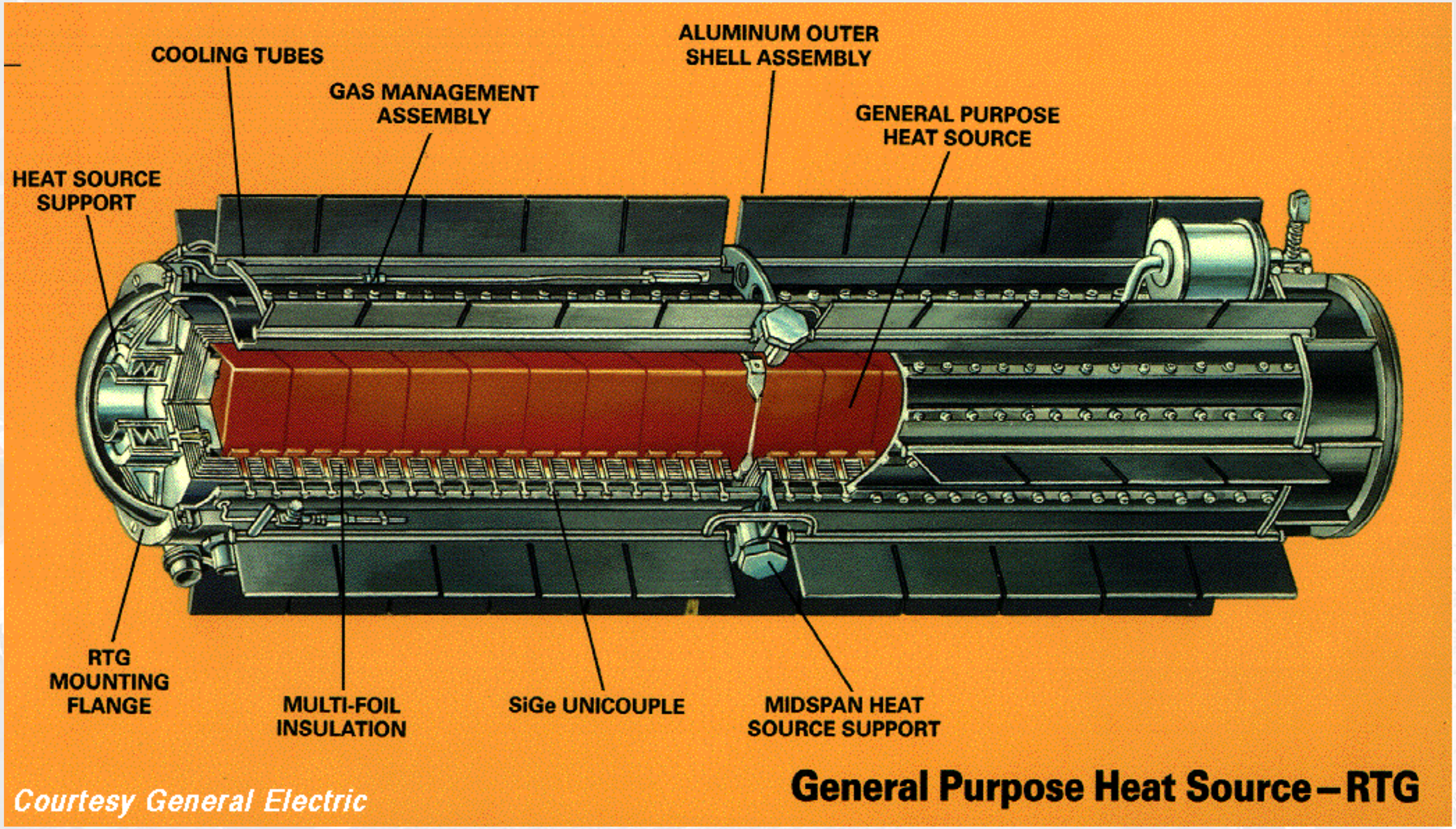


Technology	Parameter	State-of-the-Art	Near Term	Future
Stirling	Power Level	25 kW	150 W (ARPS)	100-500 kW
	Life	1,000 hrs	45,000 hrs	7-10 yrs
	Peak Cycle Temp	1050 K	950 K	1300 K
	Efficiency	25-40%	20-30%	25-40%
	Specific Mass	6 kg/kW	15-18 kg/kW	5 kg/kW
Brayton	Power Level	2 to 10 kW	2 to 100 kW	2 kW to MW's
	Life	40,000 hrs	4-6 yrs	7-10 yrs
	Peak Cycle Temp	Up to 1140 K	1300 K	1500 K
	Efficiency	20-30%	20-30%	20-30%
	Specific Mass	20-70 kg/kW	6-50kg/kW	5-6 kg/kW
AMTEC	Power Level	500-1500 W	Up to 200 W (ARPS)	10 to 50 kW
	Life	1400 hr	15 yrs	10-15 yrs
	Peak Cycle Temp	970 K	1125 K	1225 K
	Efficiency	13%	~15%	25-30%
	Specific Mass	16-25 kg/kW	17 kg/kW	5-7 kg/kW
Thermionic	Power Level	4.5 kW ('68)	Up to 10 kW	Up to 100 kW
	Life	1-5 yrs	4-6 yrs	7-10 yrs
	Peak Cycle Temp	1900 K	2000 K	2200 K
	Efficiency	4-12%	12-15%	15-20%
	Specific Mass	5 kg/kW	4 kg/kW	2-3 kg/kW

Nuclear Power

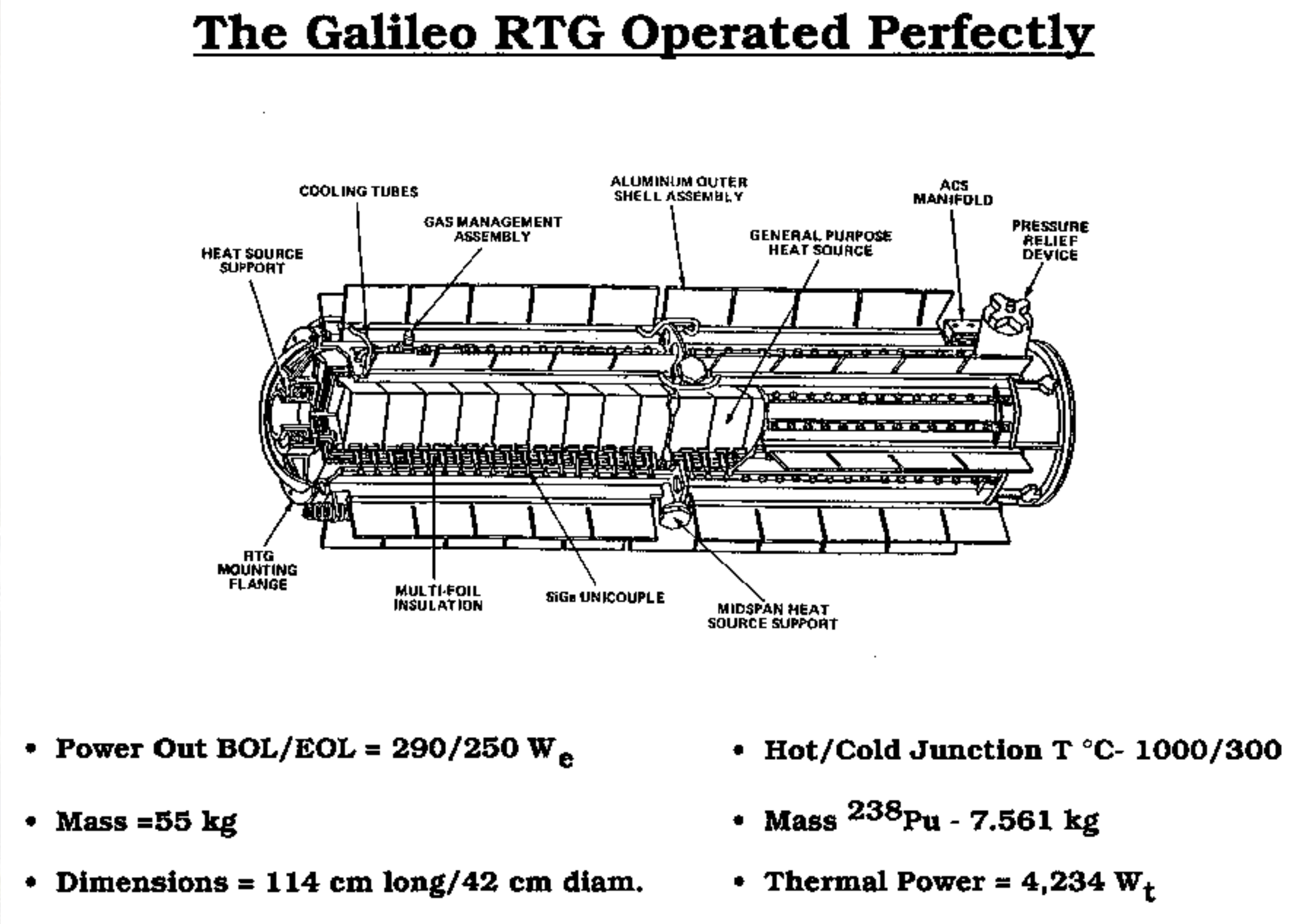
- Radioisotopic Thermal Generators (RTGs)
  - Generate electricity from heat of radioactive decay
  - Generally use ^{238}Pu as heat source, thermionic conversion
  - Units up to a few hundreds of watts
- Nuclear dynamic
  - Nuclear reactors for heat source, dynamic power system for conversion
  - Smallest effective size ~ 100 kW (or is it?)

Galileo RTG



Courtesy General Electric

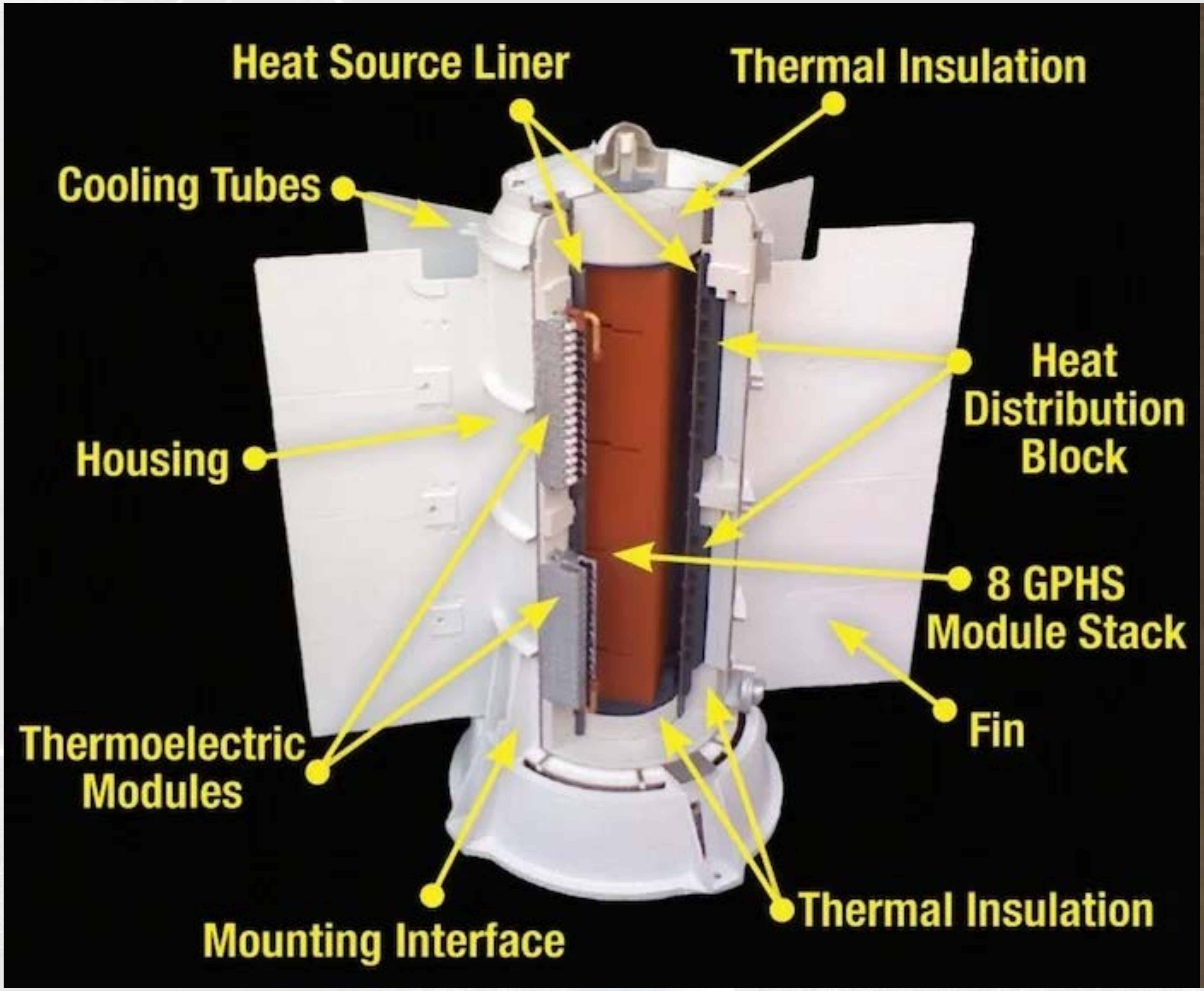
Galileo RTG Specifications

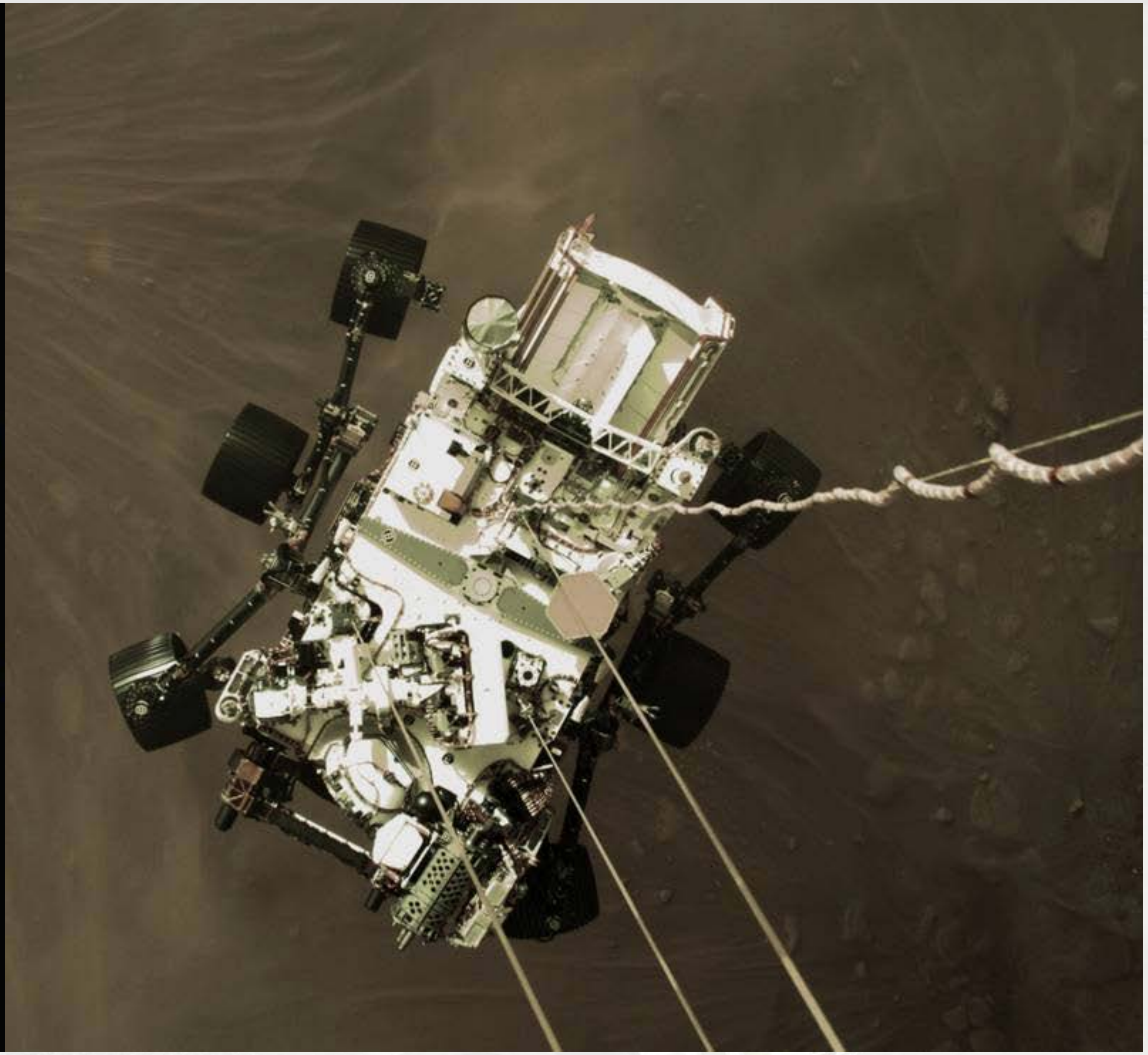


The Galileo RTG Operated Perfectly

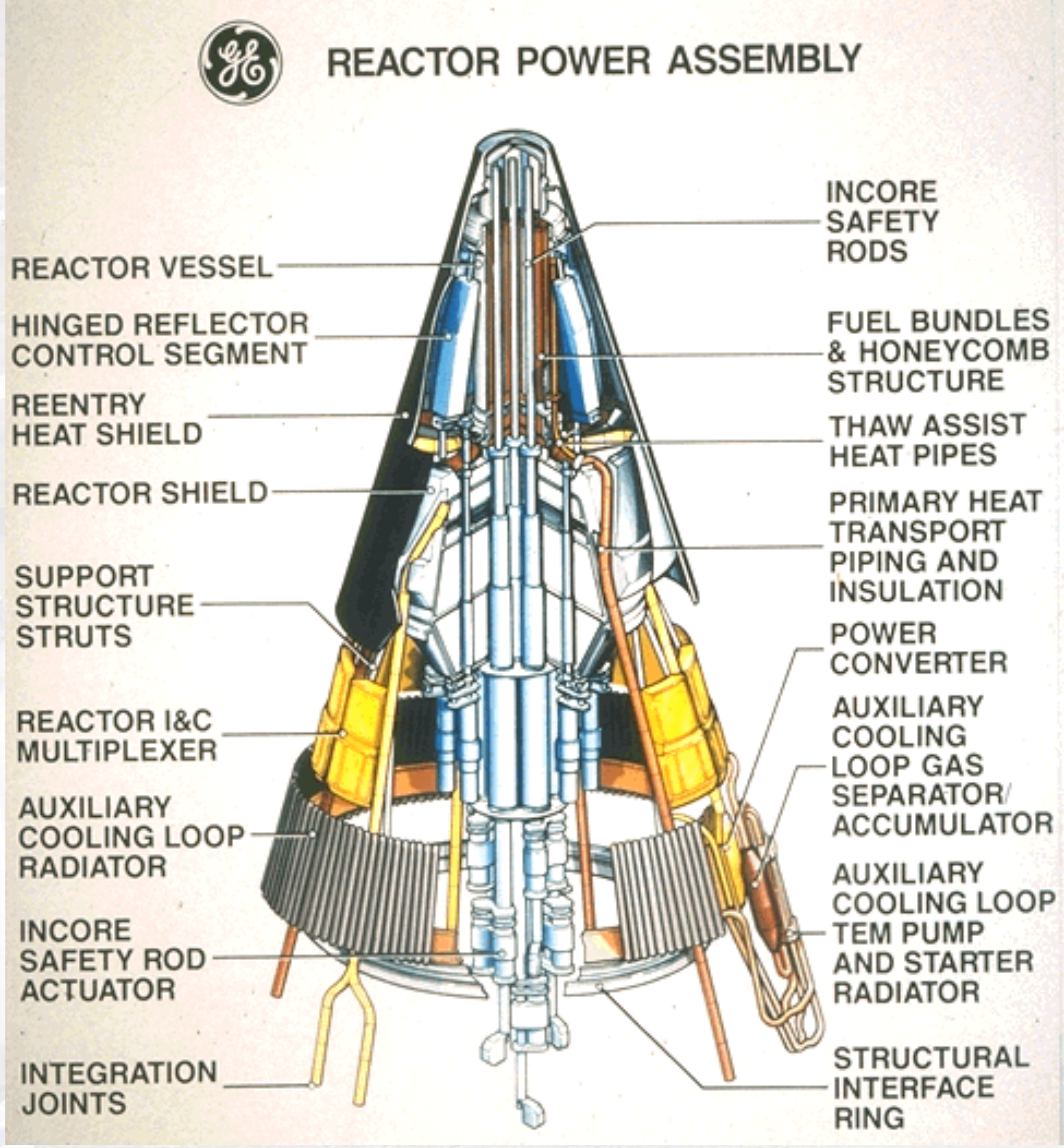
- **Power Out BOL/EOL = 290/250 W_e**
- **Mass =55 kg**
- **Dimensions = 114 cm long/42 cm diam.**
- **Hot/Cold Junction T °C- 1000/300**
- **Mass ^{238}Pu - 7.561 kg**
- **Thermal Power = 4,234 W_t**

RTG Power for Curiosity and Perseverance





SP-100 Reactor Design

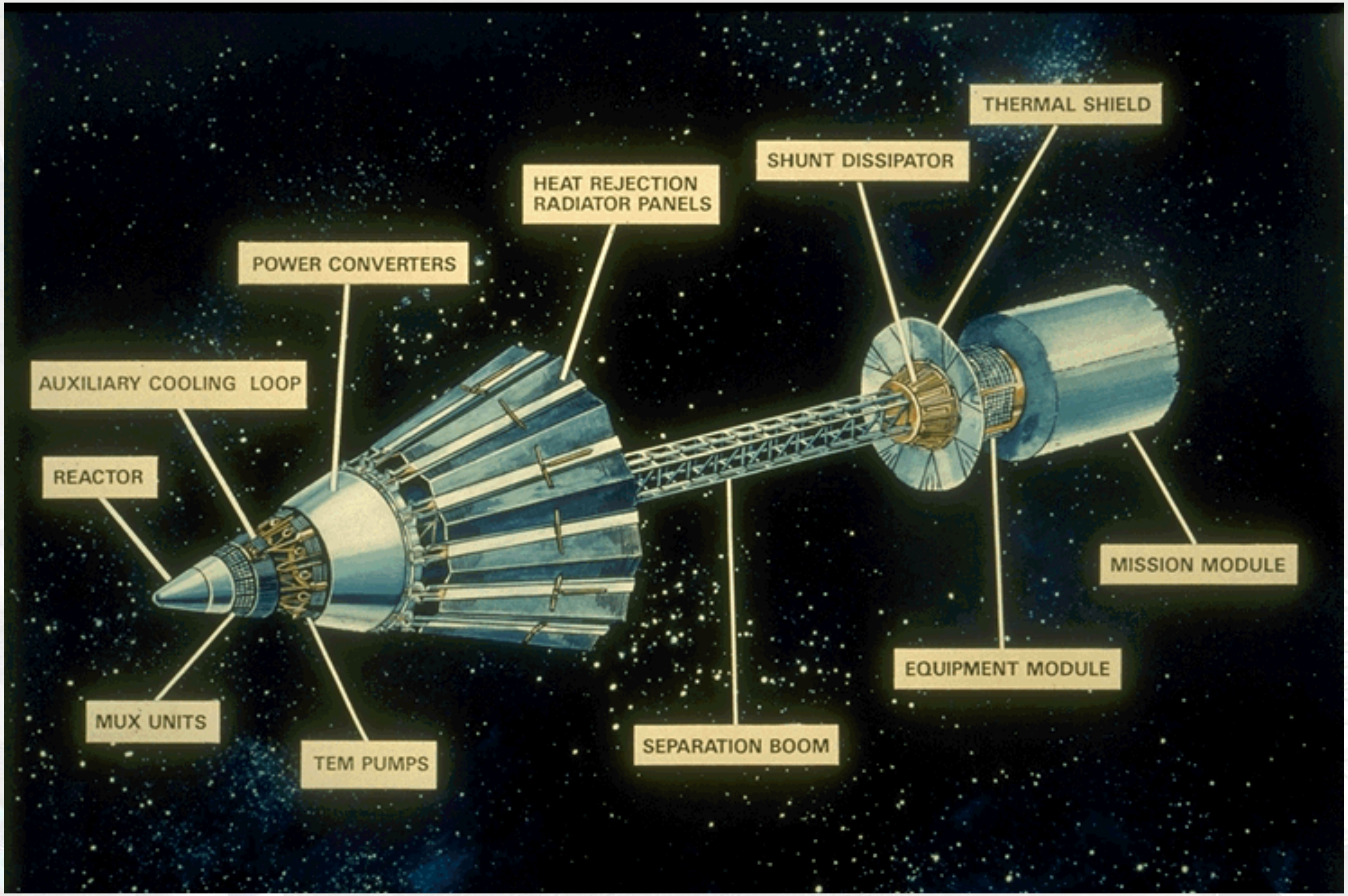


SNAP-10A

- SNAP-10A was a space-qualified nuclear reactor power system.
  - The only US space reactor
  - The reactor generated 35 kW of thermal power but only delivered about 500 watts of electrical power.
- It was launched into earth orbit in April, 1965.
- The reactor ran for an abbreviated 43-day flight test after the reactor was prematurely shut down by a faulty command receiver.

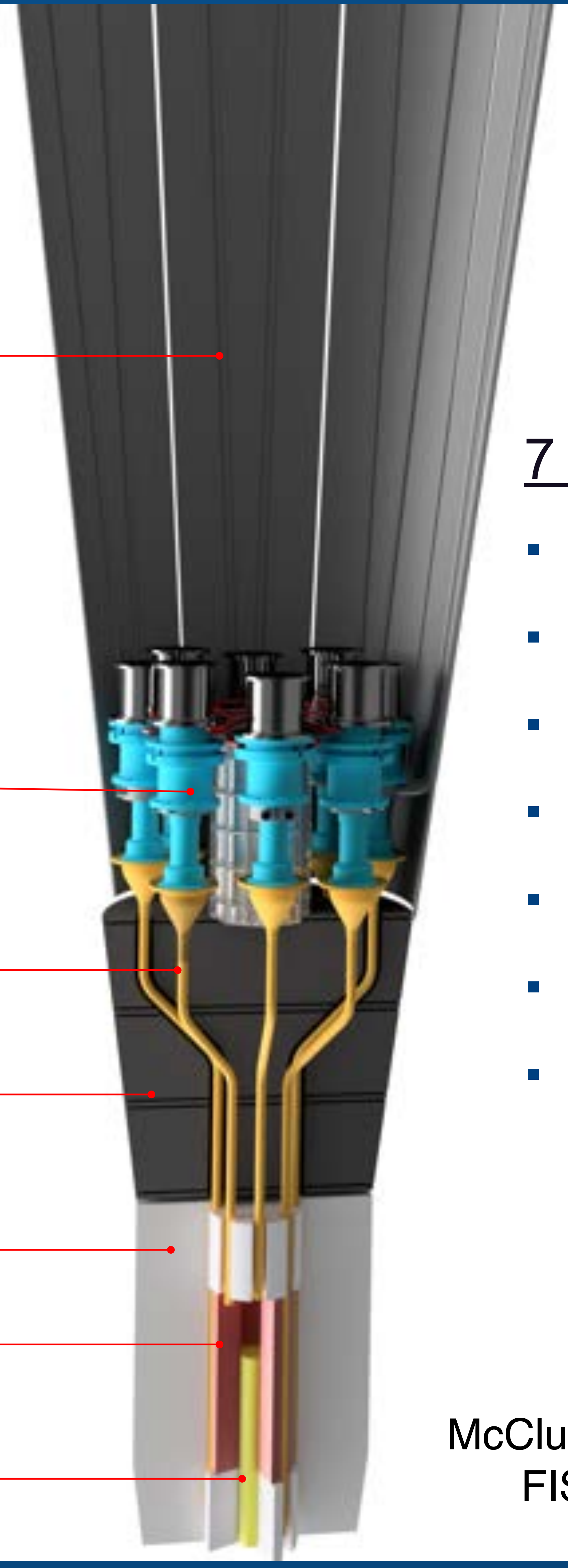
McClure, Poston, and Gibson, "Kilopower" NASA FISO Telecon Presentation July 31, 2019

SP-100 Reactor Installation



Kilopower – Reactor Concept for Deep Space

1000 W: 400 kg



Titanium/Water Heat Pipe Radiator

Stirling Power Conversion System

Sodium Heat Pipes

Lithium Hydride/Tungsten Shielding

Beryllium Oxide Neutron Reflector

Uranium Moly Cast Metal Fuel

B_4C Neutron Absorber Rod

7 COMPONENTS

- Core
- Neutron reflector
- Heat pipes
- Radiation shielding
- Start-stop rod
- Stirling engine convertors
- Radiator to remove excess heat

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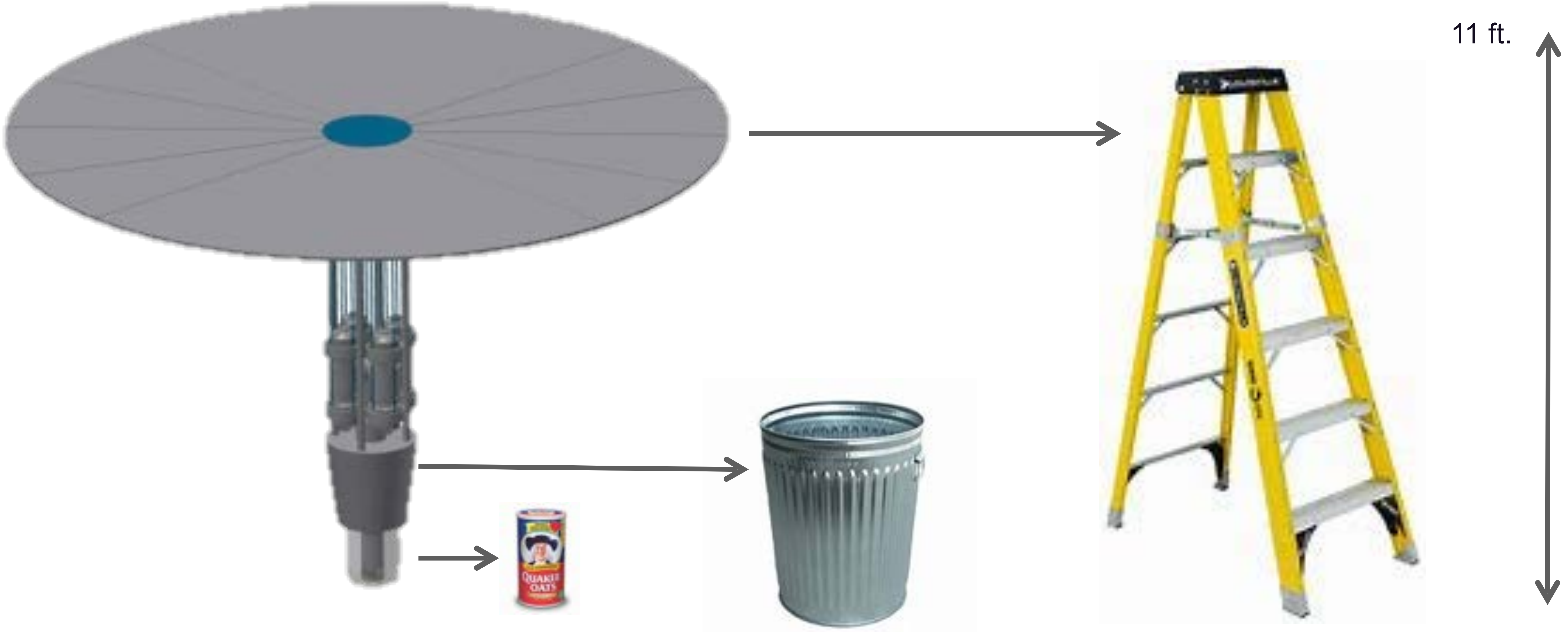
How big is Kilopower?

10 kilowatt electric Kilopower reactor



Oatmeal Box = Core   Trash Can = Reactor   Very Tall Step Ladder = System Height

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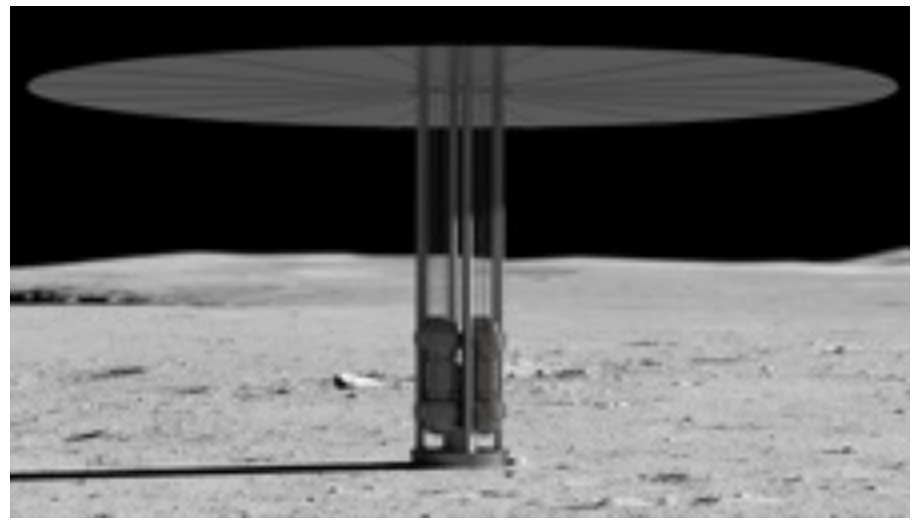
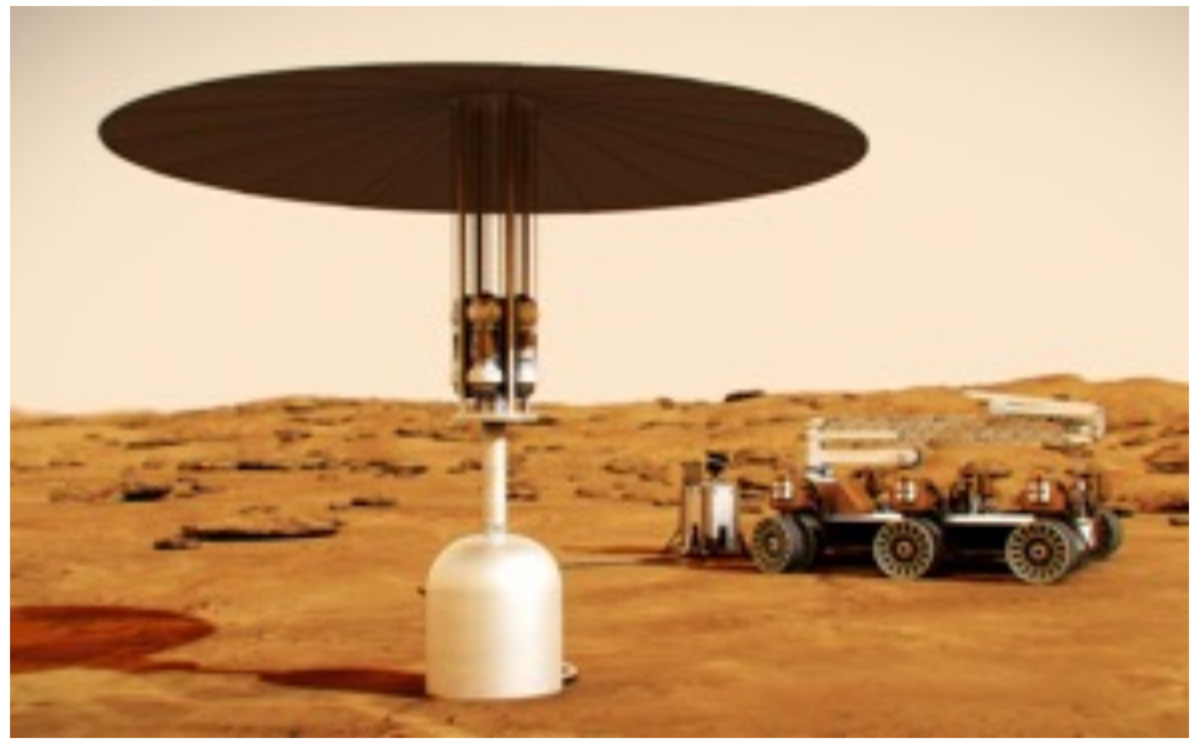
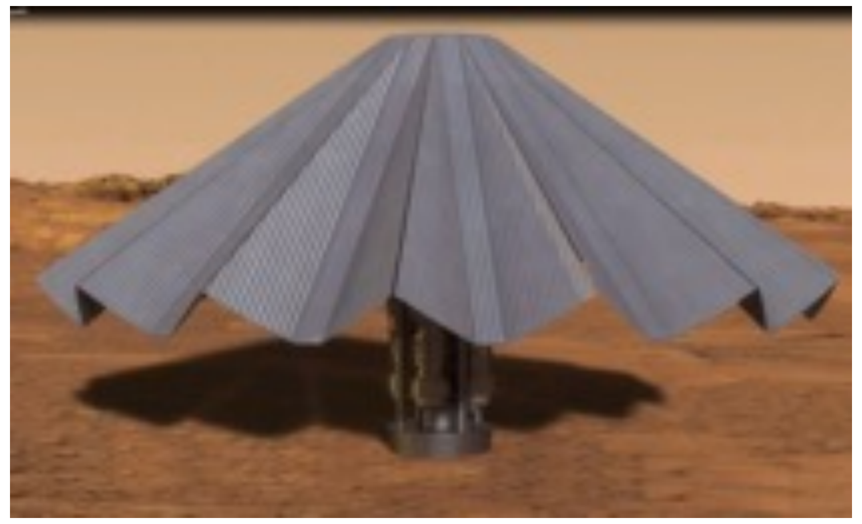
1 to 10 kWe Kilopower Surface Reactors





10 kW: 1500 kg



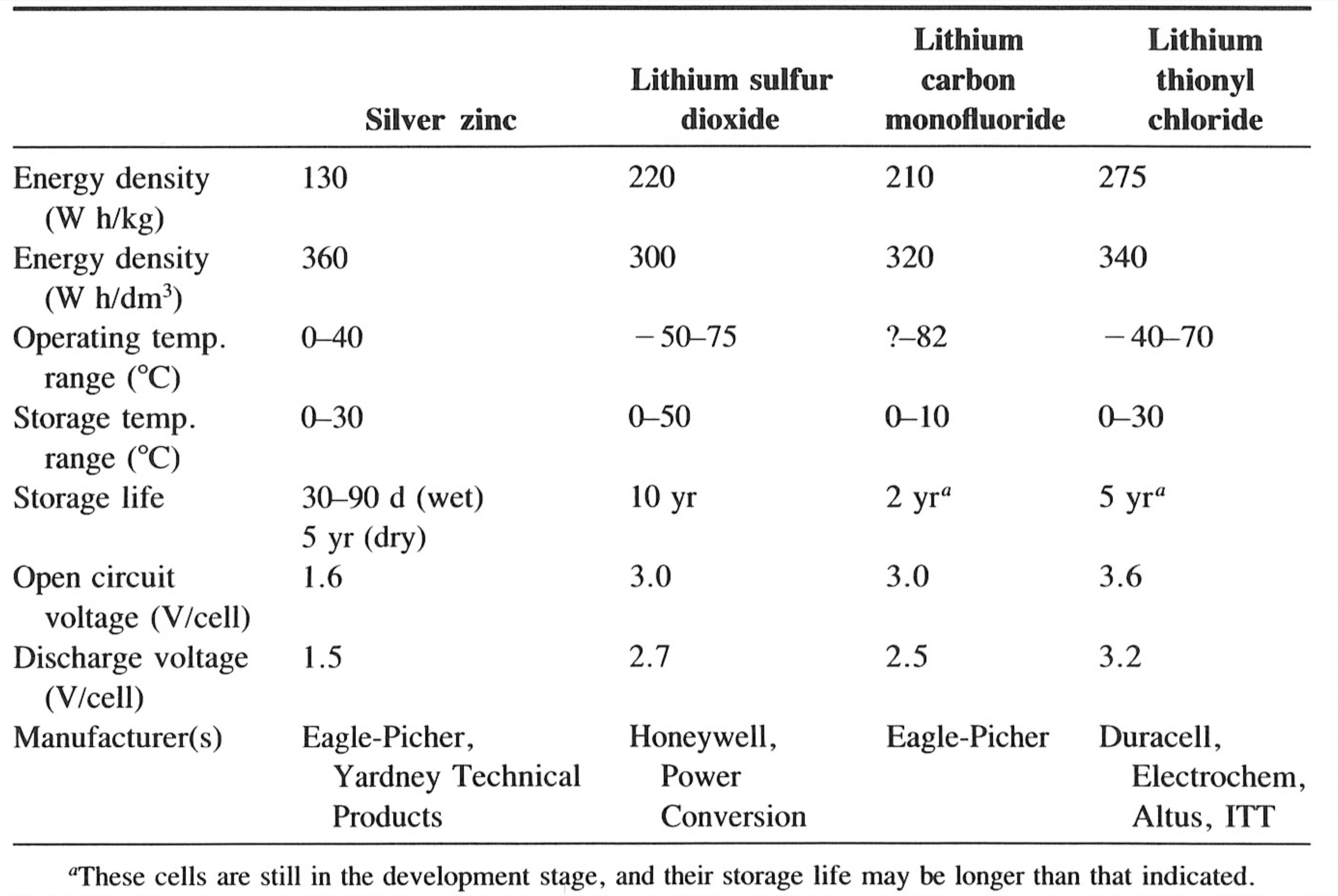
- **Use multiple 10 kWe units for human missions**
- **Utilizes a deployable radiator**
- **Buried configuration at Lunar and Mars surface**
- **Full shield for lander configurations**

McClure, Poston, and Gibson, “Kilopower” NASA FISO Telecon Presentation July 31, 2019

Batteries

- Energy storage via chemical reactions
- Primary batteries - use once and discard
- Secondary batteries - rechargable
- Critical parameters
  - Energy density
  - Discharge rate
  - Allowable depth of discharge
  - Cycle life
  - Temperature limits

Primary Batteries

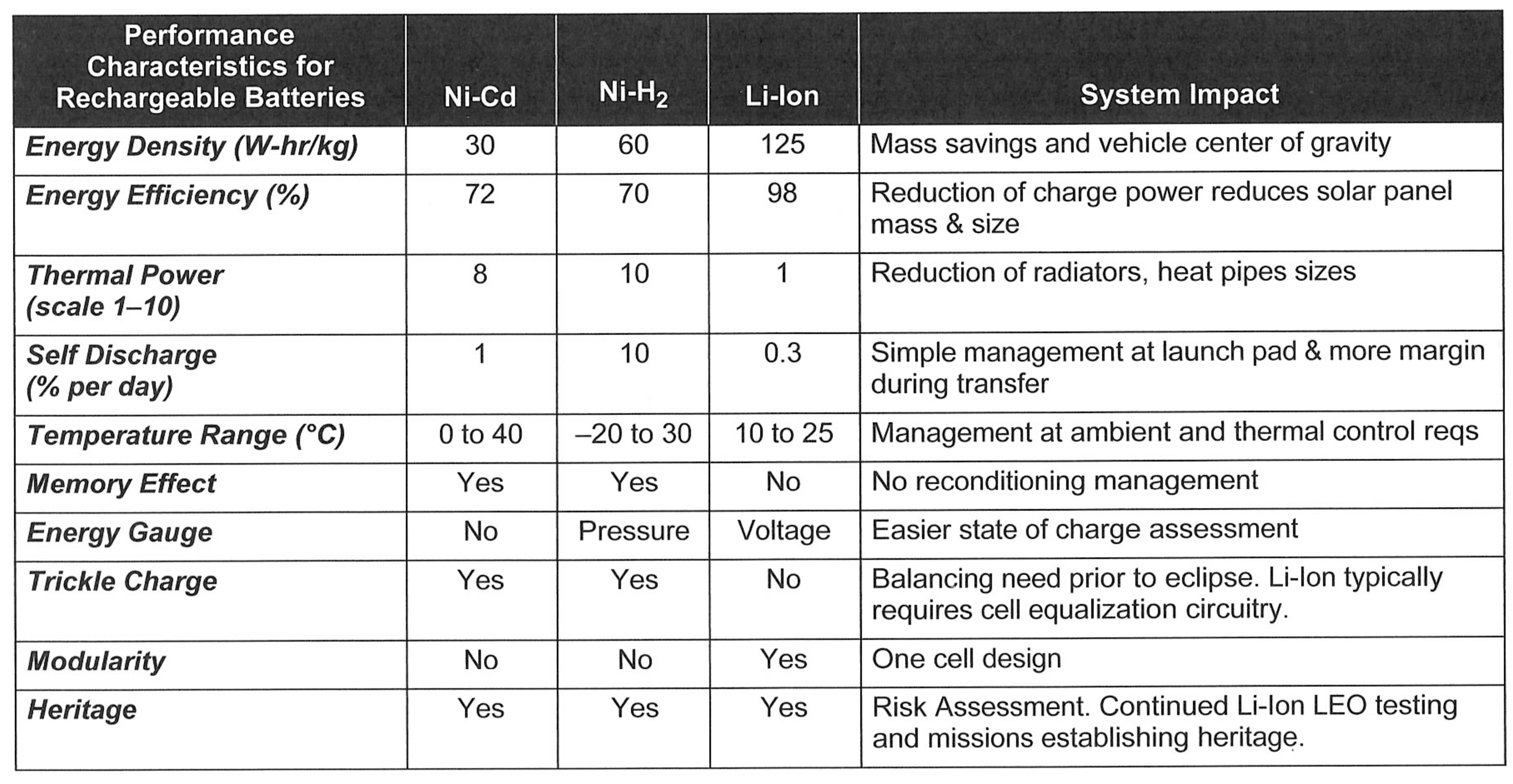


	Silver zinc	**Lithium sulfur dioxide**	**Lithium carbon monofluoride**	**Lithium thionyl chloride**
Energy density (W h/kg)	130	220	210	275
Energy density (W h/dm^3)	360	300	320	340
Operating temp. range (°C)	0–40	−50–75	?–82	−40–70
Storage temp. range (°C)	0–30	0–50	0–10	0–30
Storage life	30–90 d (wet) 5 yr (dry)	10 yr	2 yr[a]	5 yr[a]
Open circuit voltage (V/cell)	1.6	3.0	3.0	3.6
Discharge voltage (V/cell)	1.5	2.7	2.5	3.2
Manufacturer(s)	Eagle-Picher, Yardney Technical Products	Honeywell, Power Conversion	Eagle-Picher	Duracell, Electrochem, Altus, ITT

[a] These cells are still in the development stage, and their storage life may be longer than that indicated.

From Pisacane and Moore, *Fundamentals of Space Systems* Oxford University Press, 1994

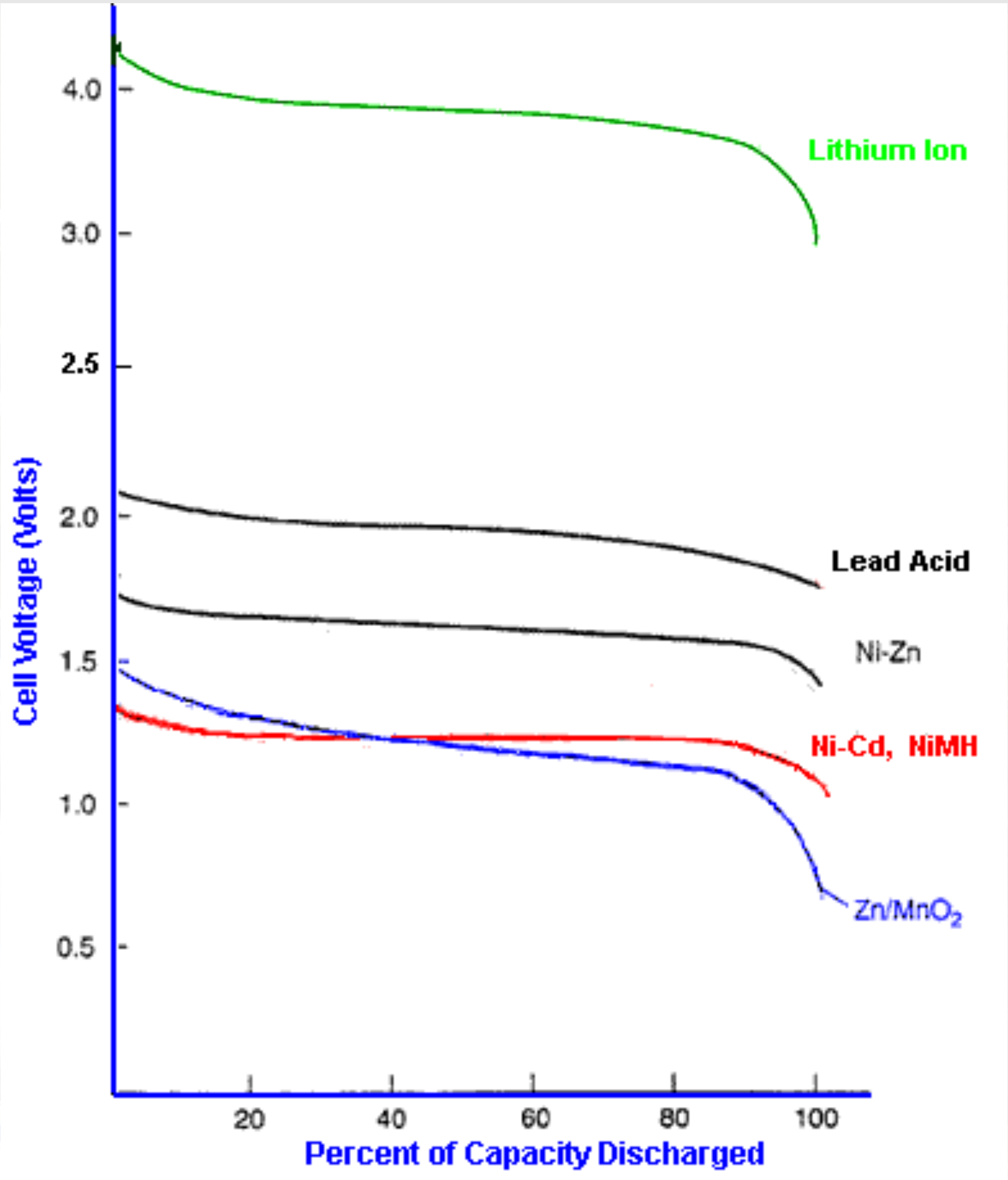
Secondary Batteries



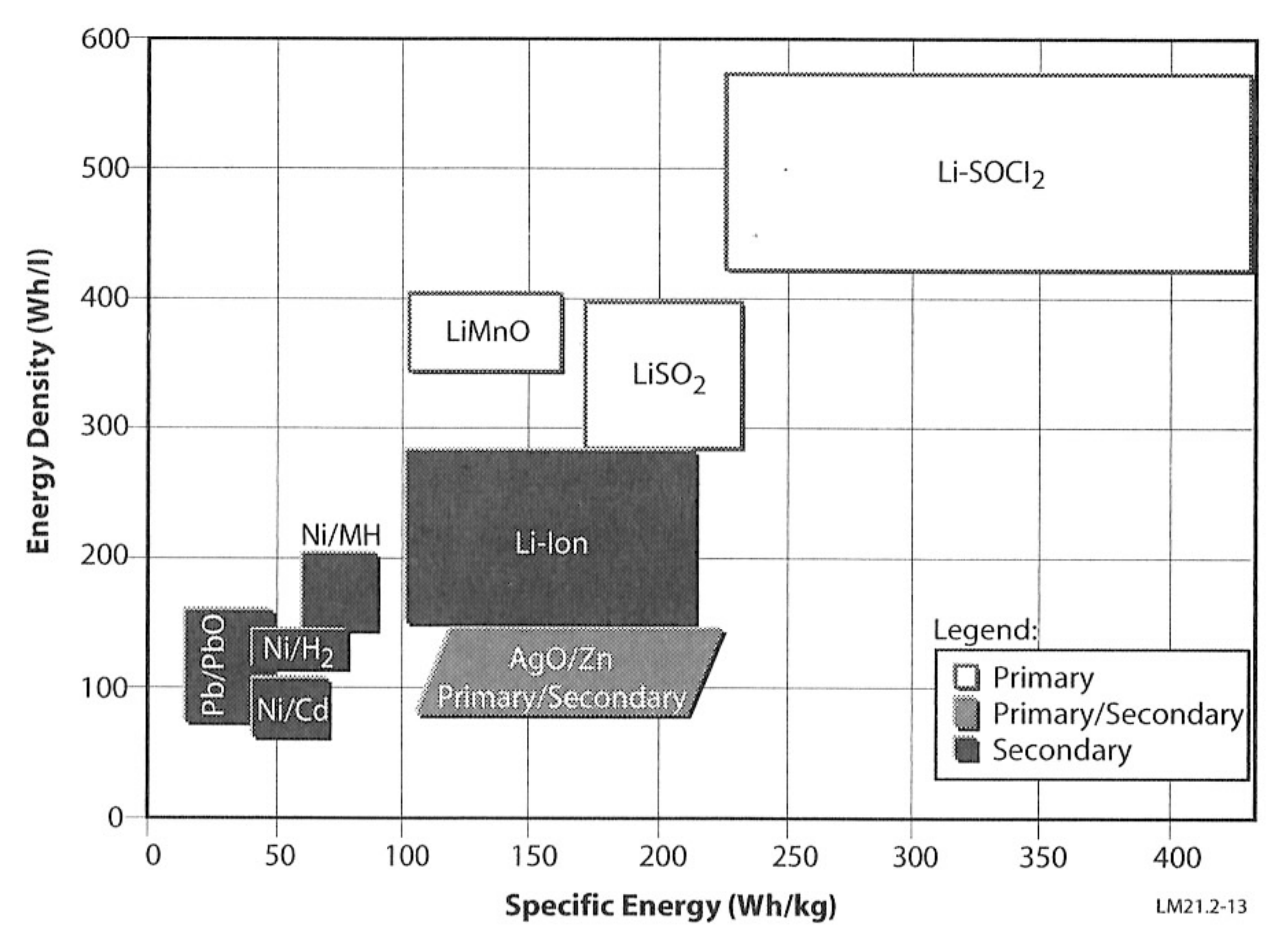
Performance Characteristics for Rechargeable Batteries	Ni-Cd	Ni-H_2	Li-Ion	System Impact
Energy Density (W-hr/kg)	30	60	125	Mass savings and vehicle center of gravity
Energy Efficiency (%)	72	70	98	Reduction of charge power reduces solar panel mass & size
Thermal Power (scale 1–10)	8	10	1	Reduction of radiators, heat pipes sizes
Self Discharge (% per day)	1	10	0.3	Simple management at launch pad & more margin during transfer
Temperature Range (°C)	0 to 40	–20 to 30	10 to 25	Management at ambient and thermal control reqs
Memory Effect	Yes	Yes	No	No reconditioning management
Energy Gauge	No	Pressure	Voltage	Easier state of charge assessment
Trickle Charge	Yes	Yes	No	Balancing need prior to eclipse. Li-Ion typically requires cell equalization circuitry.
Modularity	No	No	Yes	One cell design
Heritage	Yes	Yes	Yes	Risk Assessment. Continued Li-Ion LEO testing and missions establishing heritage.

From Wertz, Everett, and Puschell, *Space Mission Engineering: The New SMAD* Microcosm Press, 2011

Battery Voltage Supply Curves



Battery Application Domains



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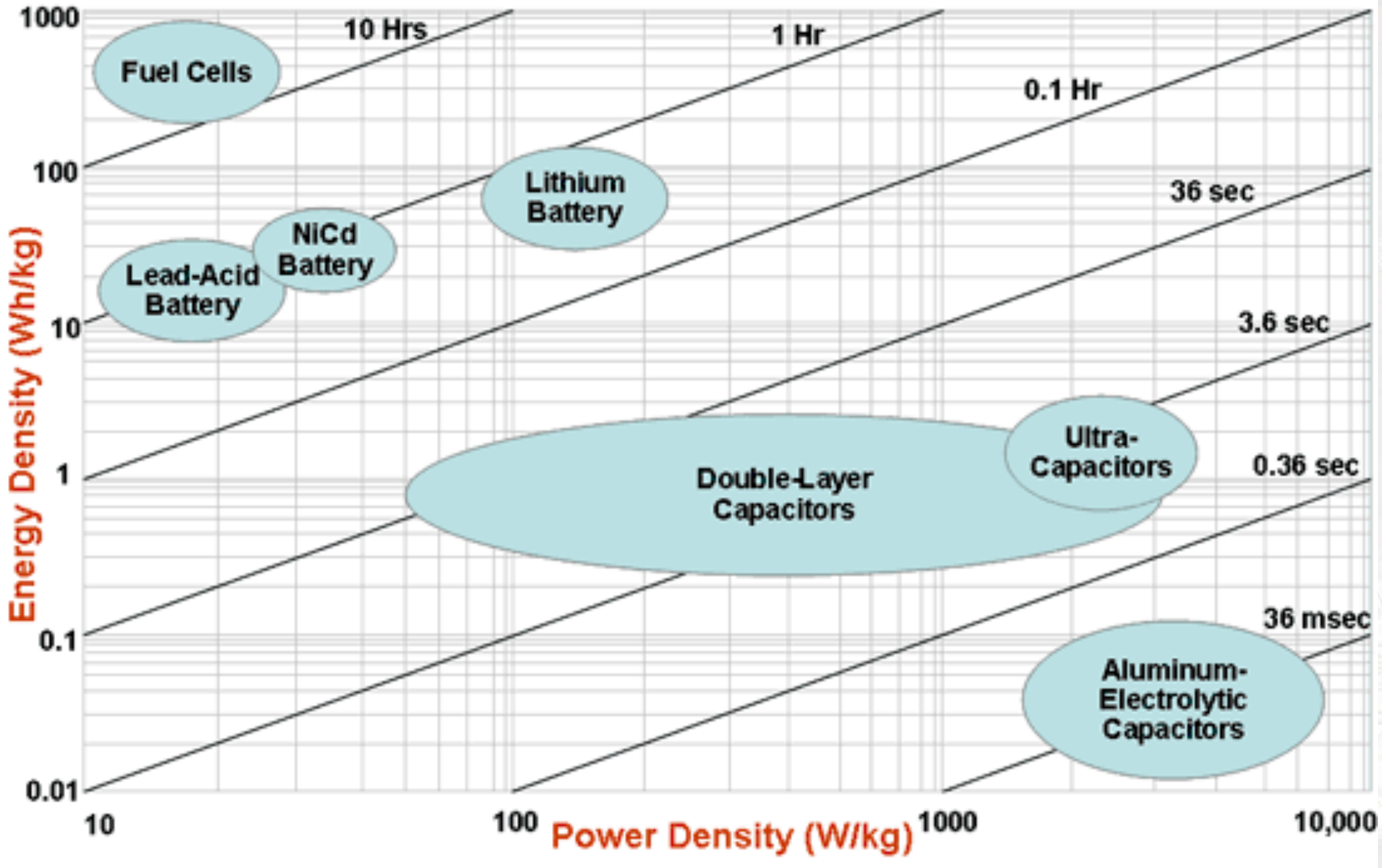
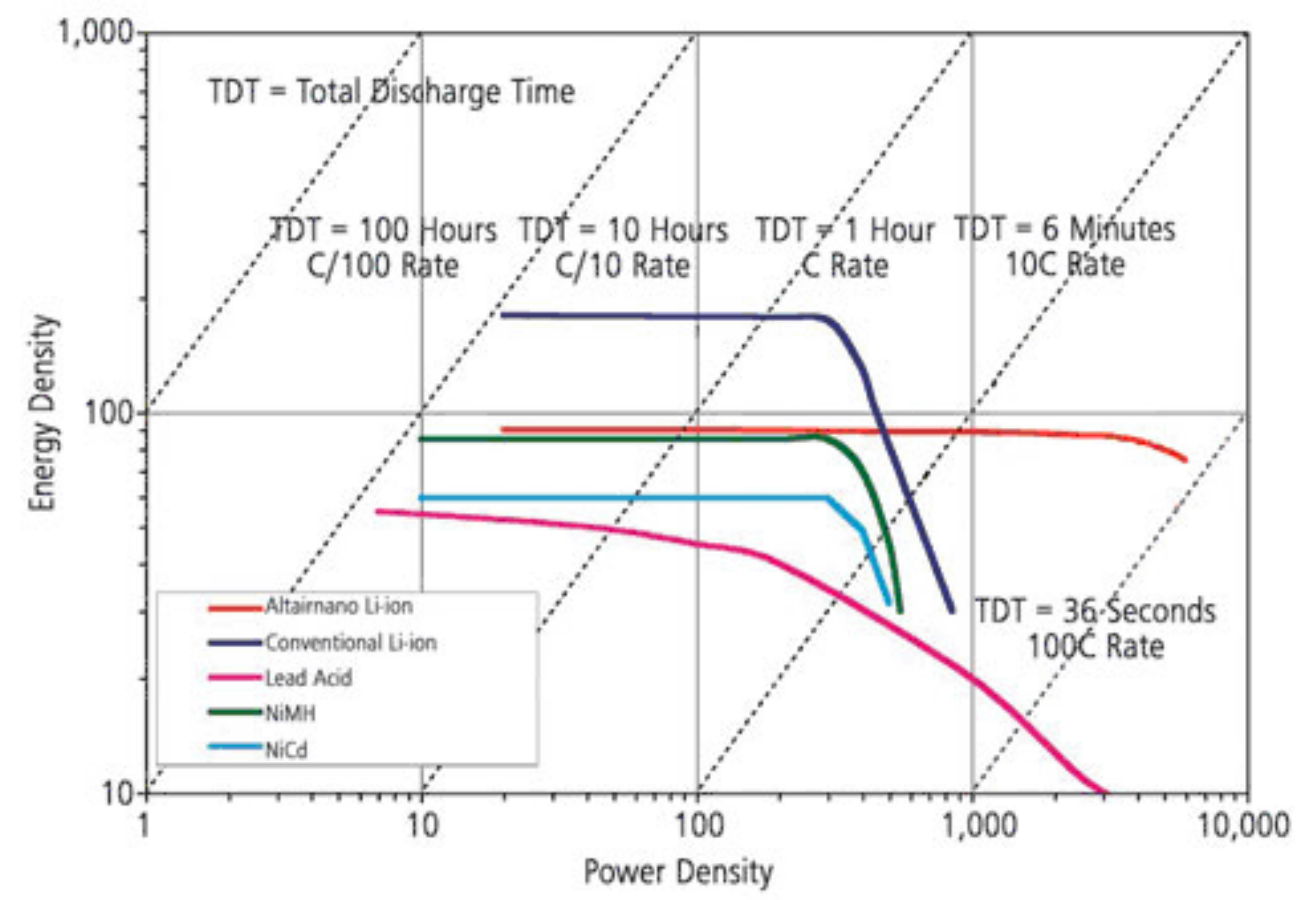
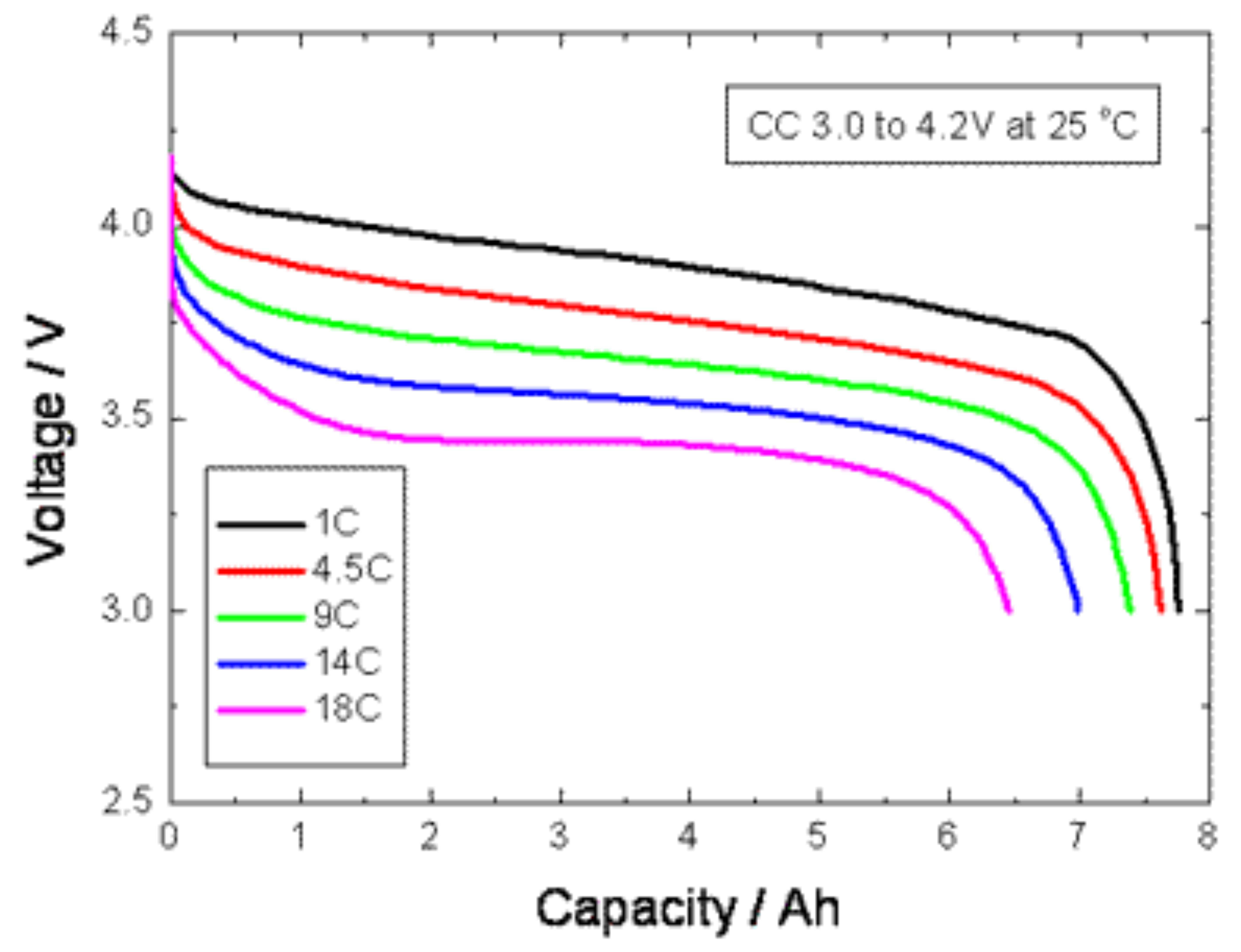


Source US Defence Logistics Agency

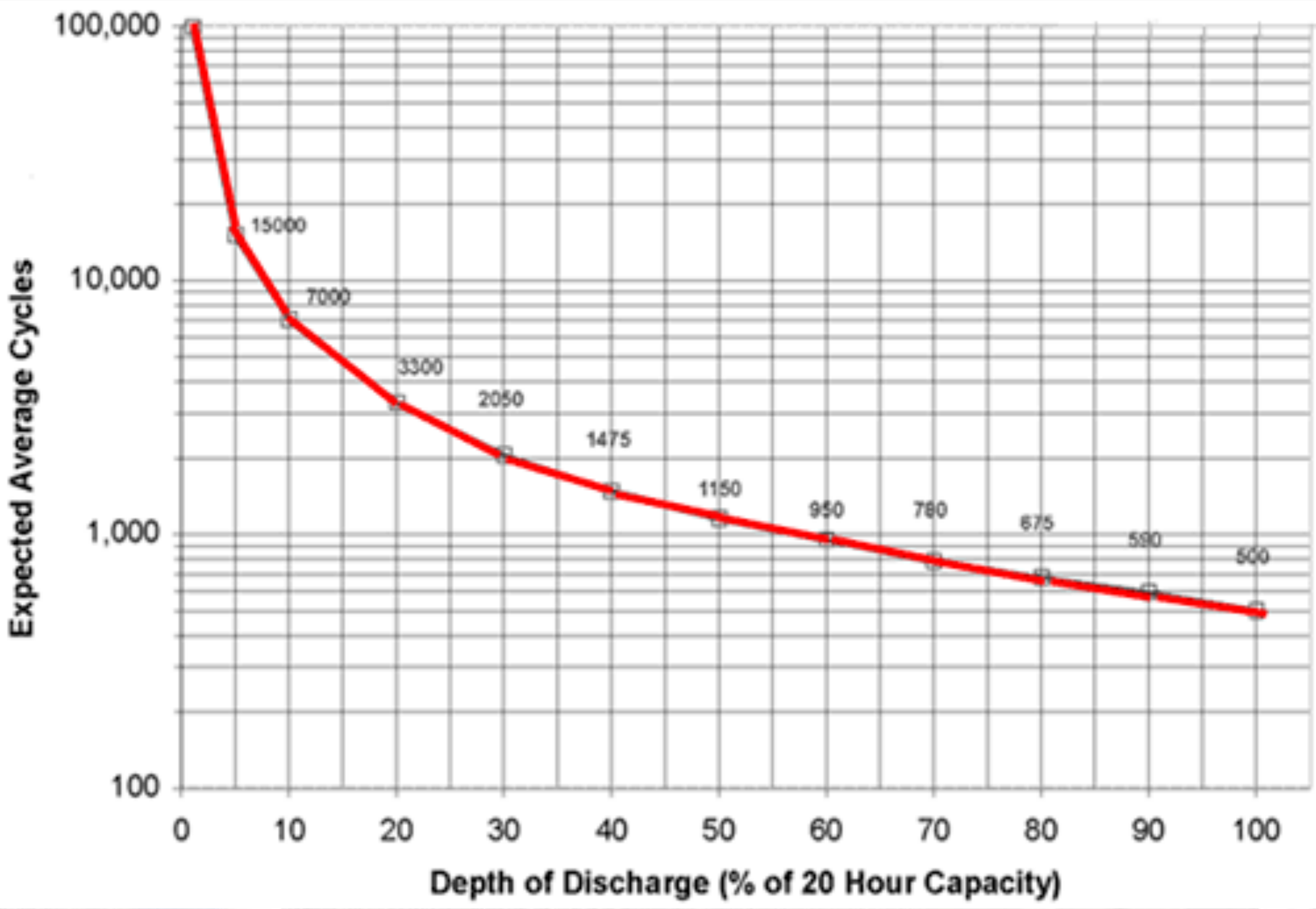
Energy and Power Density - Ragone Plot



Effect of Battery Discharge Rates



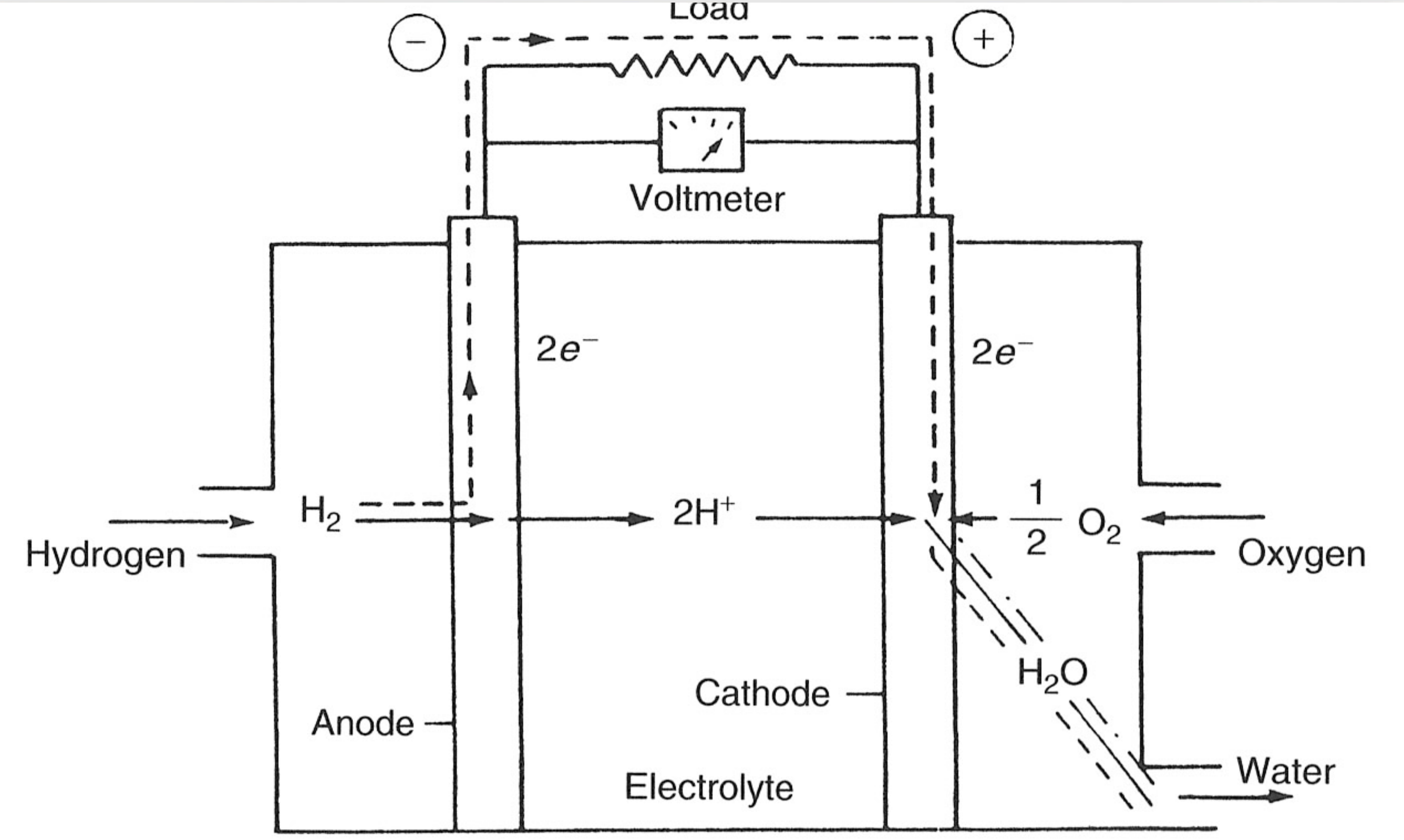
Effect of Depth of Discharge



Fuel Cells

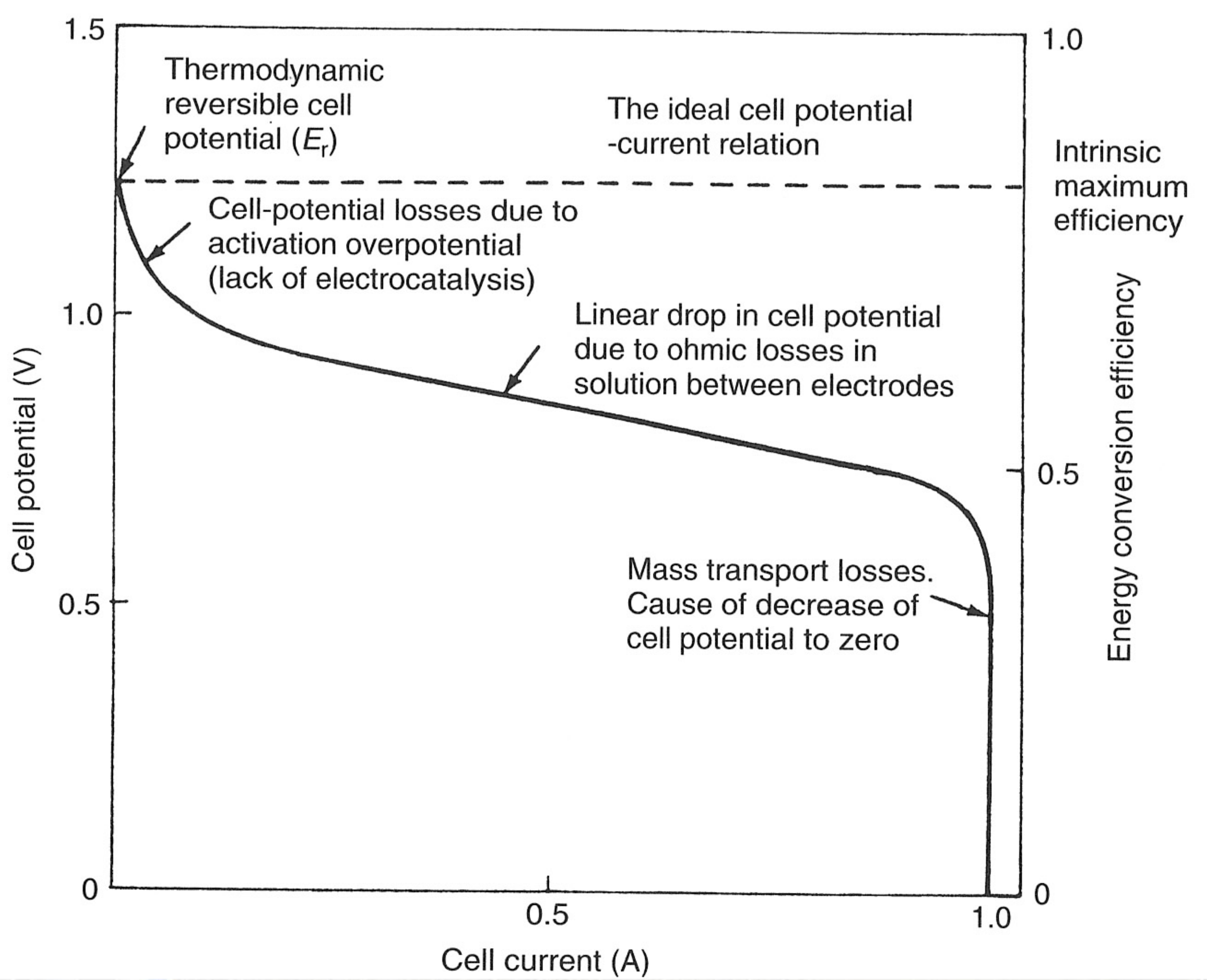
- Electrochemical system:
  $2H_2+O_2 \text{-->} 2H_2O + e^-$
- Energy storage system, not power generation – requires consumables to continue to generate power
- One-way system generates potable water
- Regenerative systems under development to act like high-capacity batteries

Fuel Cell Schematic



From Fortescue, Swinerd, and Stark, *Spacecraft Systems Engineering, 4th ed.* John Wiley and Sons, 2011

Fuel Cell Output



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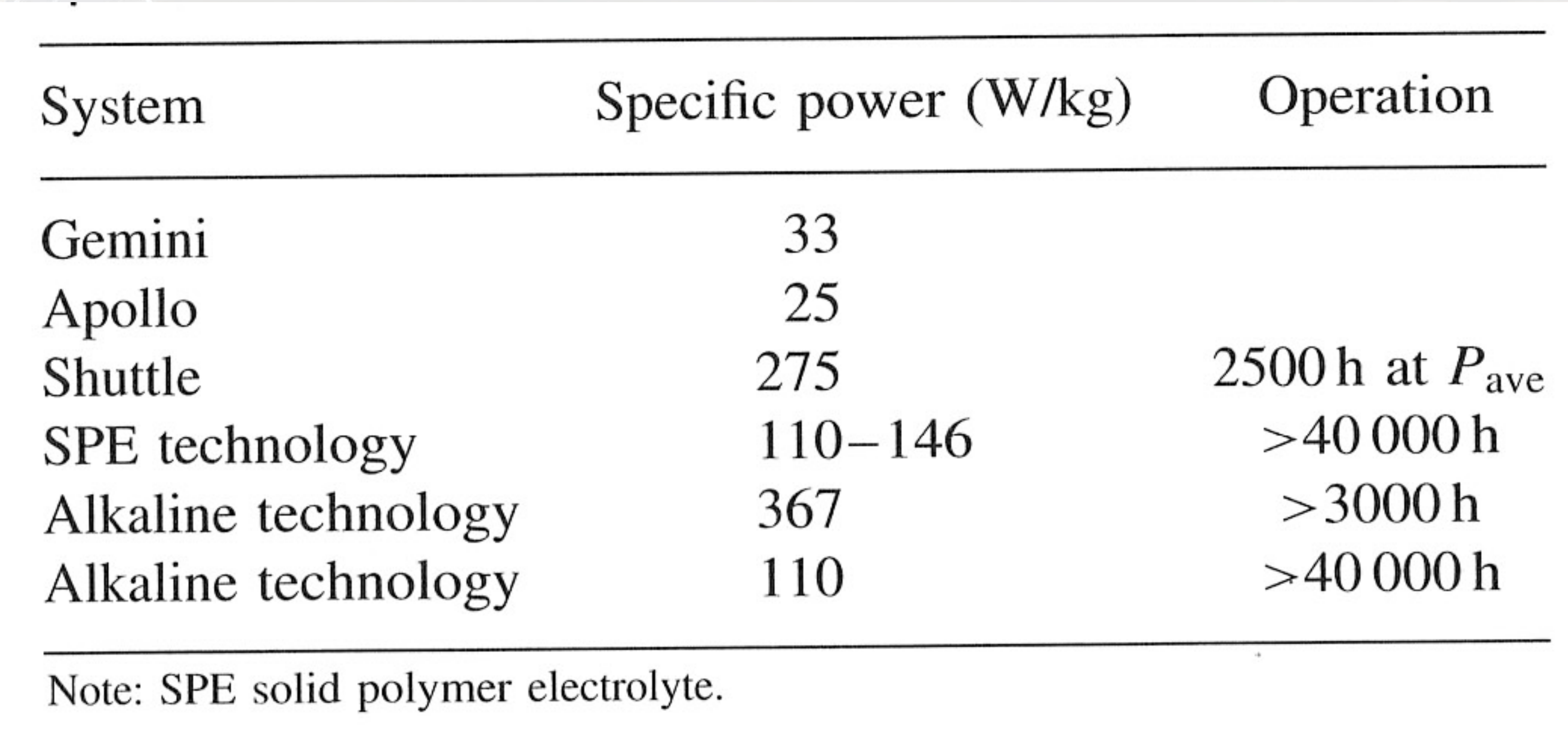
Fuel Cell Performance



System	Specific power (W/kg)	Operation
Gemini	33	
Apollo	25	
Shuttle	275	2500 h at P_{ave}
SPE technology	110–146	>40 000 h
Alkaline technology	367	>3000 h
Alkaline technology	110	>40 000 h

Note: SPE solid polymer electrolyte.

From Fortescue, Swinerd, and Stark, *Spacecraft Systems Engineering, 4th ed.* John Wiley and Sons, 2011

Example: Shuttle Fuel Cells

- LOX Tank: 36.8” dia., empty mass 201 lbs, holds 781 lbs of LOX
- LH2 Tank: 45.5” dia., empty mass 216 lbs, holds 92 lbs of LH2
- Reactor: 14”x15”x40”, 255 lbs
  28VDC output; 7kW continual, 12kW peak
- Nominal consumables usage rates:
  4 lb/hr LOX, 0.6 lb/hr LH2 at 220 A --> 0.339 kg/kW-hr or 2950 W-hr/kg reactants

Integrated Power Systems

- Photovoltaics excel at mid-levels of power generation - as long as the sun is visible
- Need energy storage to make it through dark periods (e.g., night side of low earth orbits)
- Power generation requirements must be increased to recharge energy storage devices before next dark period

Integrated Power System Example (1)

- Need 2000 W to support spacecraft in LEO
- ~50 minutes of daylight, 40 minutes of night on each orbit
- (2000W)(.667 hrs)=1333 W-hr of energy each night
- 1333W/90% charging efficiency=1481 W-hr needed to charge
- 1481 W-hr/(150 Whr/kg×50% depth of discharge)=20 kg Lithium battery
- Recharge during day pass --> 1481 W-hr/(0.833 hrs×85% efficiency)=2091 W extra needed to charge

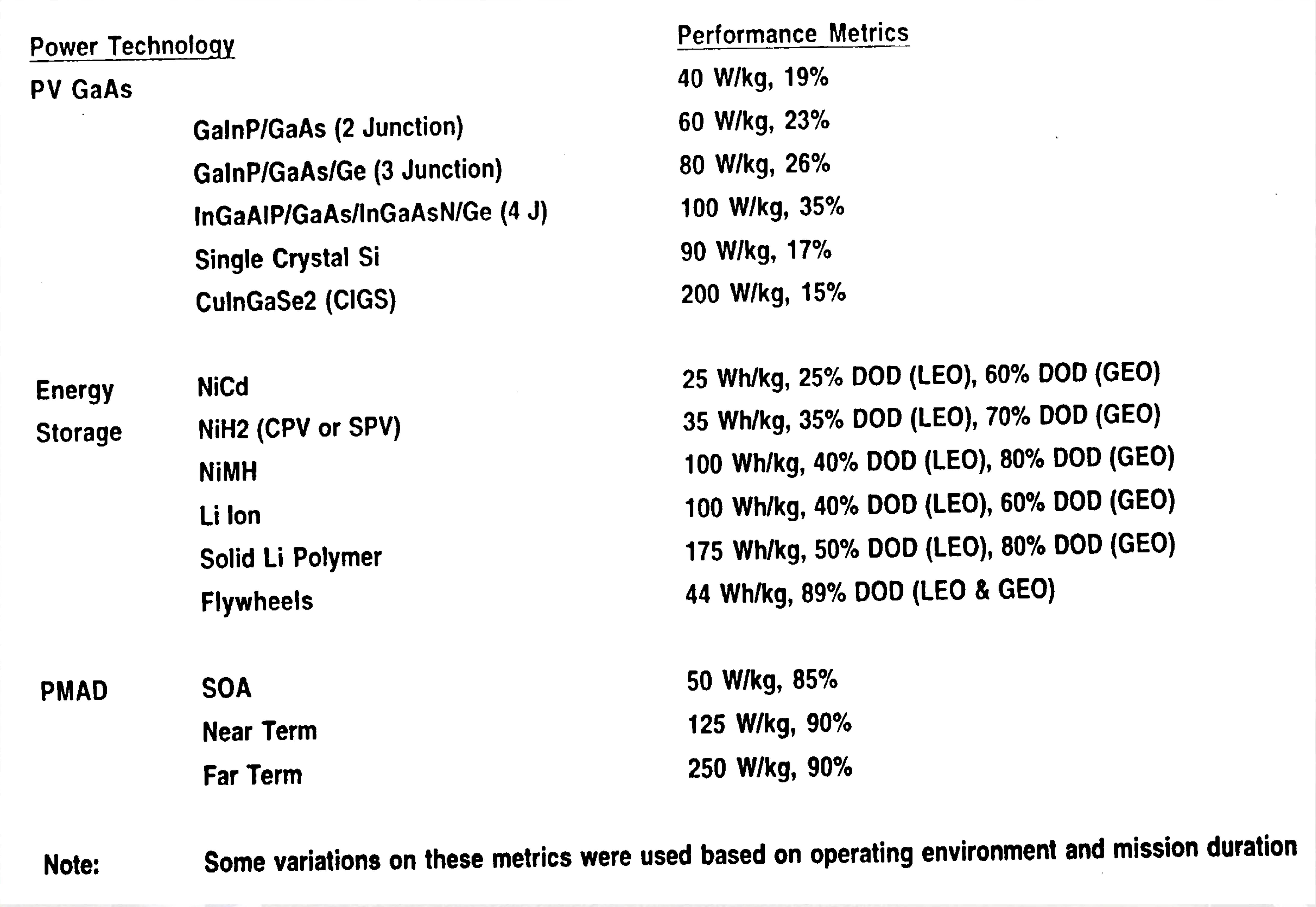
Integrated Power System Example (2)

- Total PV power requirement = 2000+2091=4091 W
- 4091 W/(Sun@1 AU=1394 W/m^2 ×30% efficient cells)=9.8 m^2 of solar array area
- 200 W/kg$\Longrightarrow$20.5 kg of PV array
- Total power system mass=20.5 kg array + 20 kg battery=40.5 kg

Power Management and Distribution

- Power has to be regulated to desired voltage, transmitted, controlled, and monitored
- Traditionally 28VDC system (heritage from aircraft)
- Resistive power loss is I^2R (prefer higher voltage, lower current
- New technologies under consideration (100VDC [ISS], 400VAC/2000Hz)

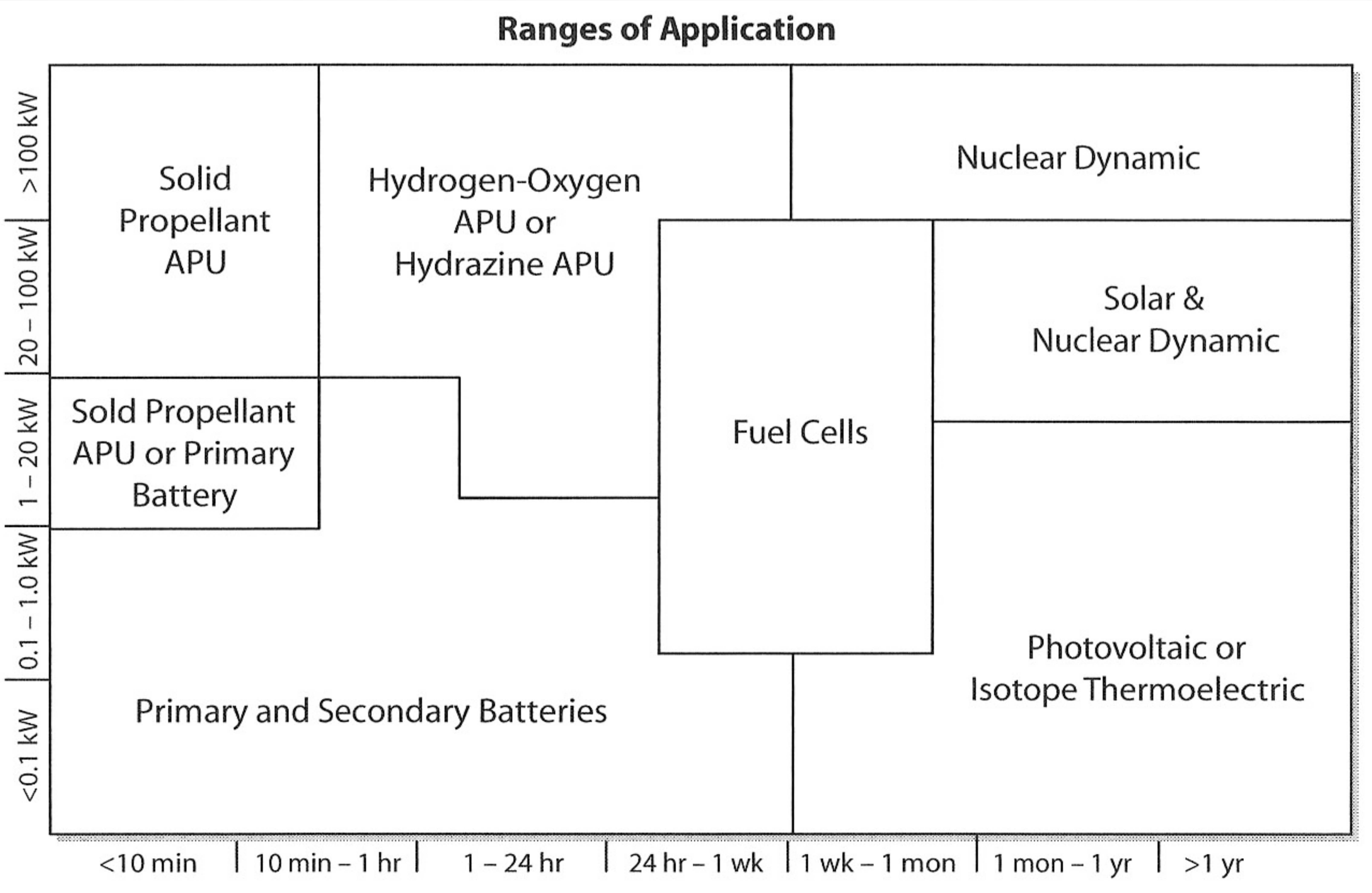
Synopsis of NASA Power Tech Estimates



Power Technology		Performance Metrics
PV GaAs		40 W/kg, 19%
	GaInP/GaAs (2 Junction)	60 W/kg, 23%
	GaInP/GaAs/Ge (3 Junction)	80 W/kg, 26%
	InGaAlP/GaAs/InGaAsN/Ge (4 J)	100 W/kg, 35%
	Single Crystal Si	90 W/kg, 17%
	CuInGaSe2 (CIGS)	200 W/kg, 15%
Energy Storage	NiCd	25 Wh/kg, 25% DOD (LEO), 60% DOD (GEO)
	NiH2 (CPV or SPV)	35 Wh/kg, 35% DOD (LEO), 70% DOD (GEO)
	NiMH	100 Wh/kg, 40% DOD (LEO), 80% DOD (GEO)
	Li Ion	100 Wh/kg, 40% DOD (LEO), 60% DOD (GEO)
	Solid Li Polymer	175 Wh/kg, 50% DOD (LEO), 80% DOD (GEO)
	Flywheels	44 Wh/kg, 89% DOD (LEO & GEO)
PMAD	SOA	50 W/kg, 85%
	Near Term	125 W/kg, 90%
	Far Term	250 W/kg, 90%

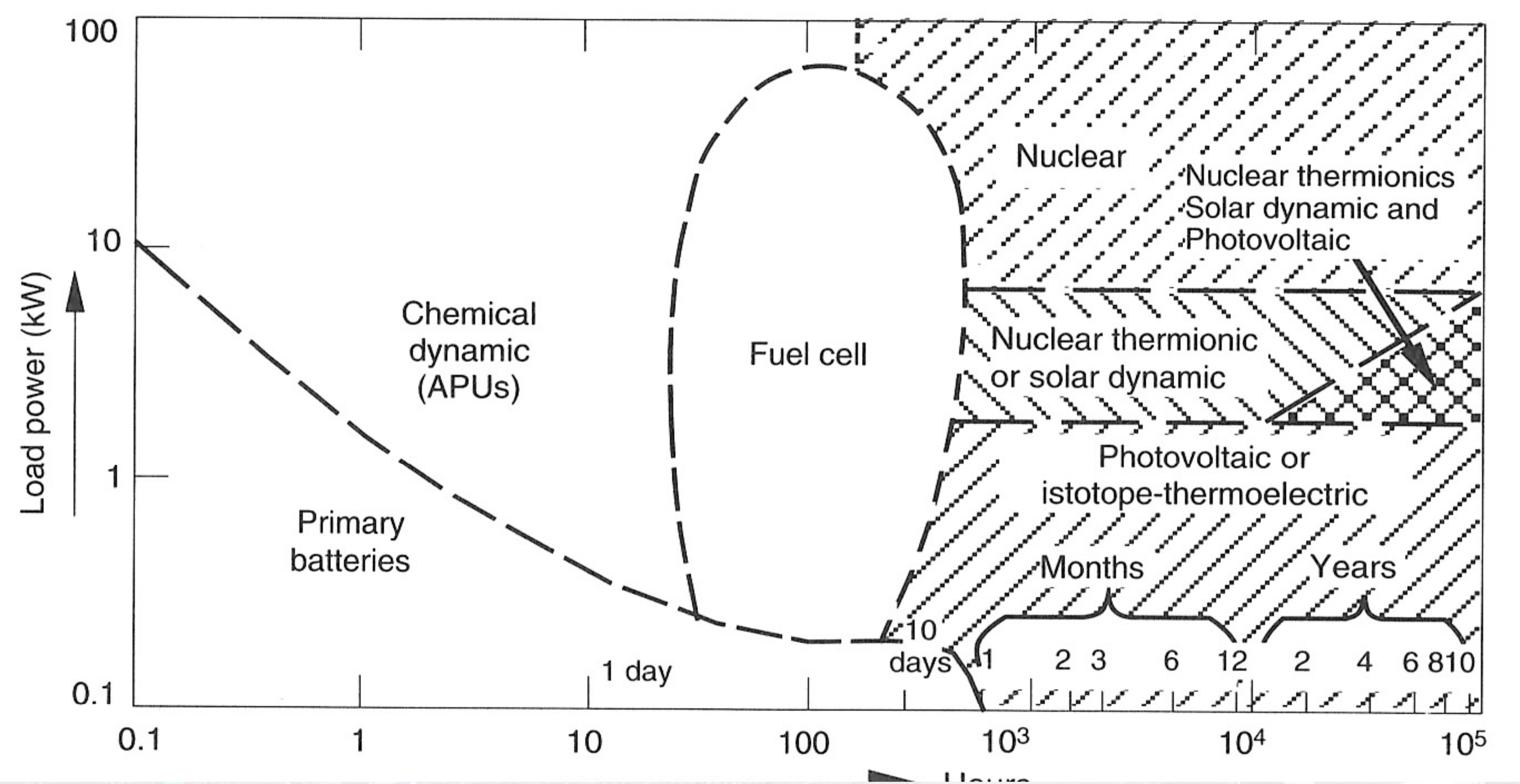
Note: Some variations on these metrics were used based on operating environment and mission duration

Notional Application Region Chart



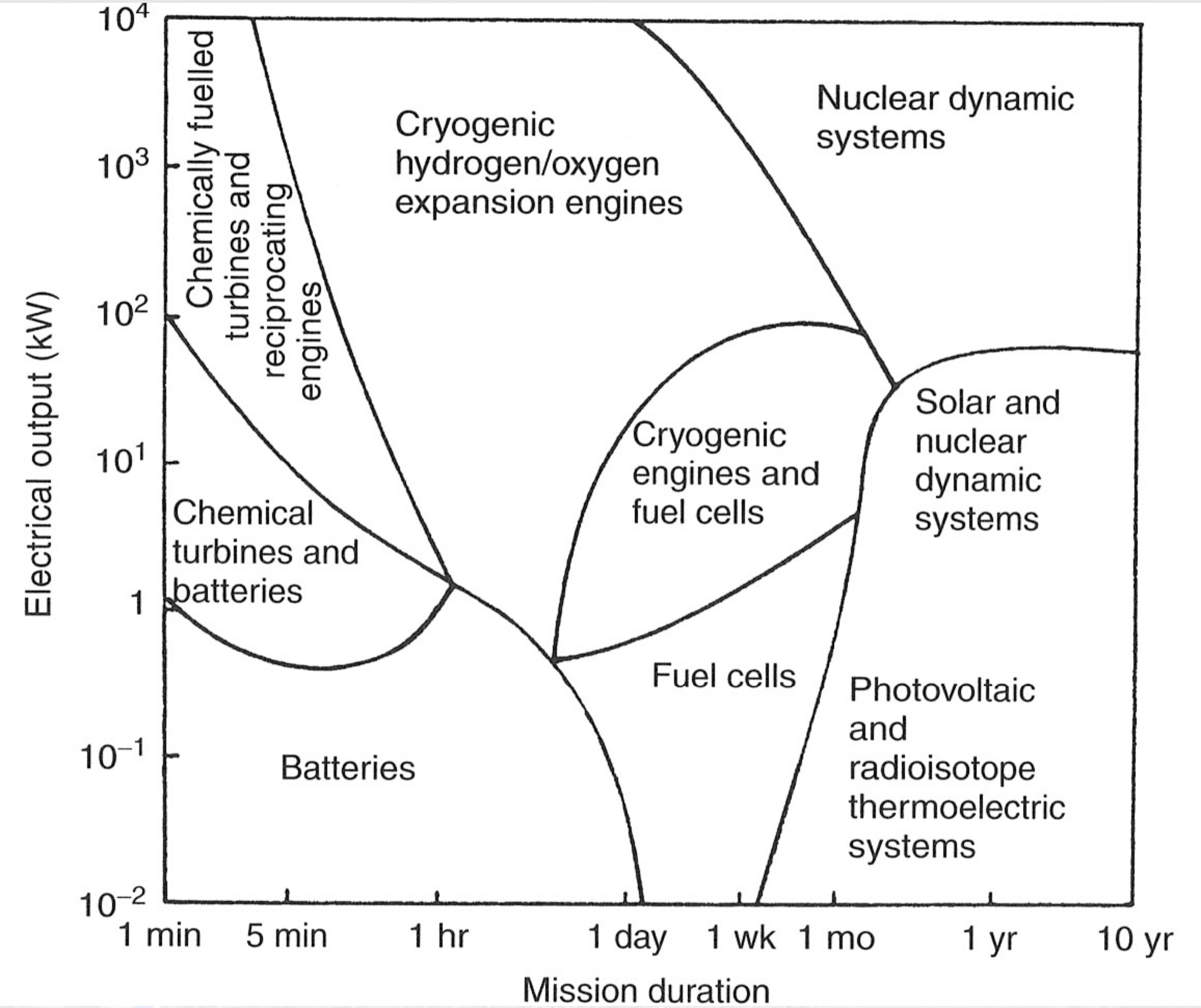
From Wertz, Everett, and Puschell, *Space Mission Engineering: The New SMAD* Microcosm Press, 2011

Another Application Region Chart



From Pisacane and Moore, *Fundamentals of Space Systems* Oxford University Press, 1994

Yet Another Application Region Chart



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