# Power Systems Design

- Definitions of energy and power
- Power generation systems
- Energy storage systems
- Integrated systems analysis


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# **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.

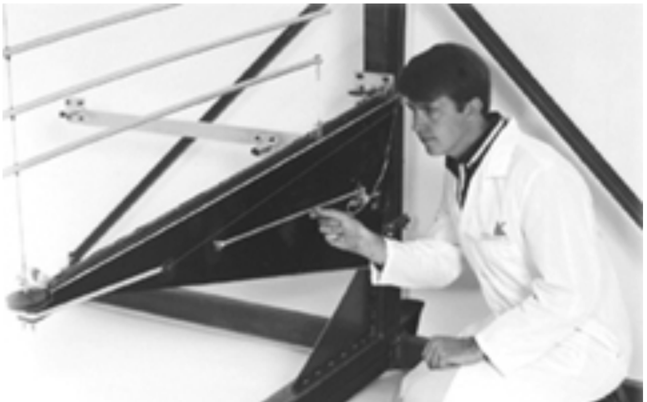
# Solar Power

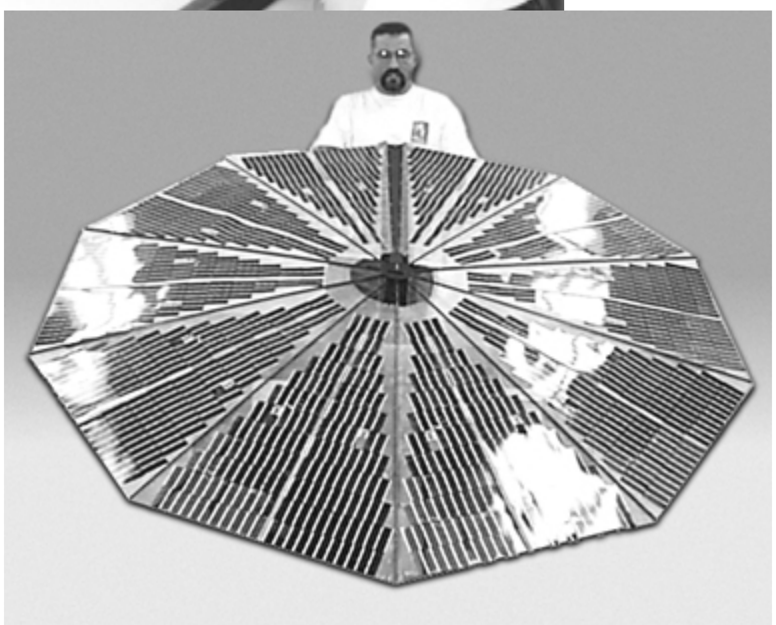
- Insolation constant = 1394 $W/m^2$ at 1 AU
- Varies with inverse square of distance
- Power conversion technologies
  - Photovoltaic
  - Thermodynamic cycle

# Future Advances 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)
- Both technologies aimed at <$300/W

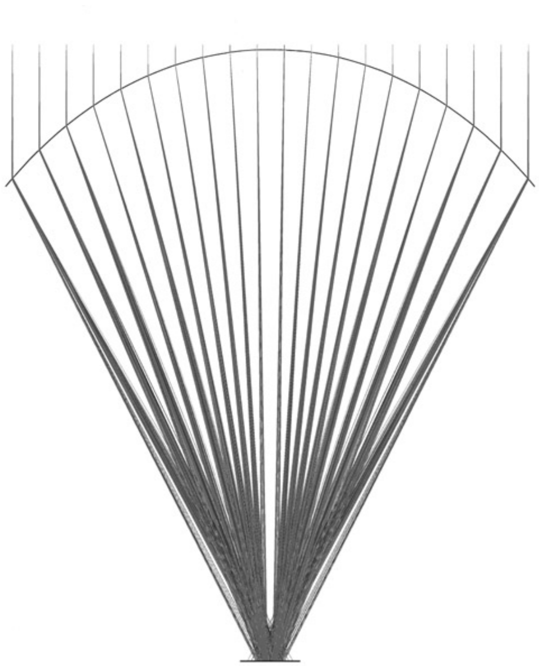
# Ultra-lightweight Photovoltaic Arrays

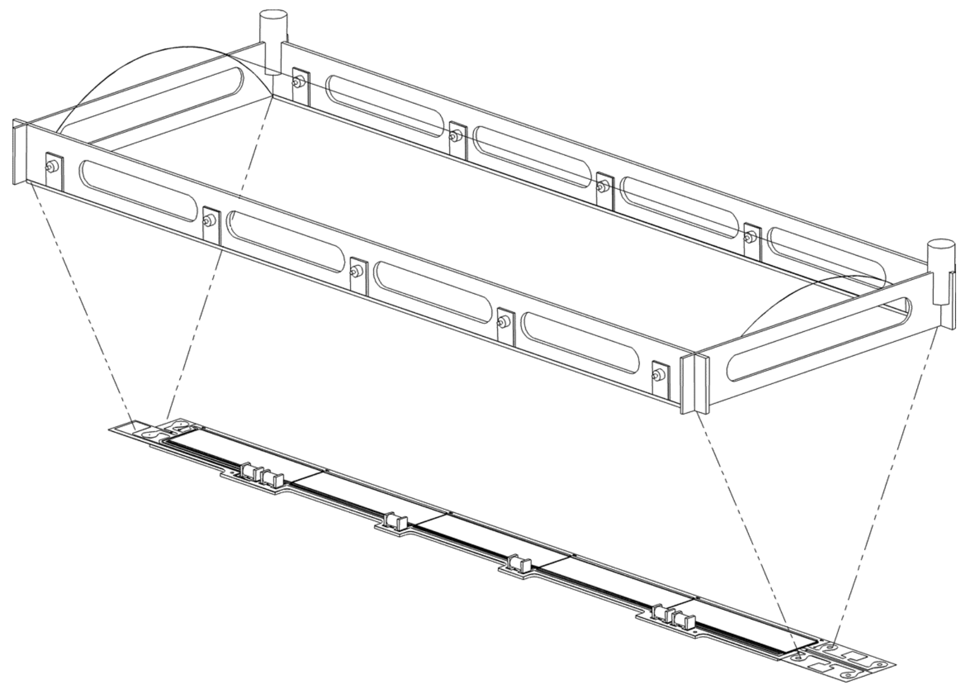




- Solely optimized for minimum areal mass
- Tends to use simpler (lower efficiency cells)
- AEC-Able Ultraflex
  - 115 W/kg (Si 17%)
  - 140 W/kg (GaAs 23%)

# 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

# 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

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

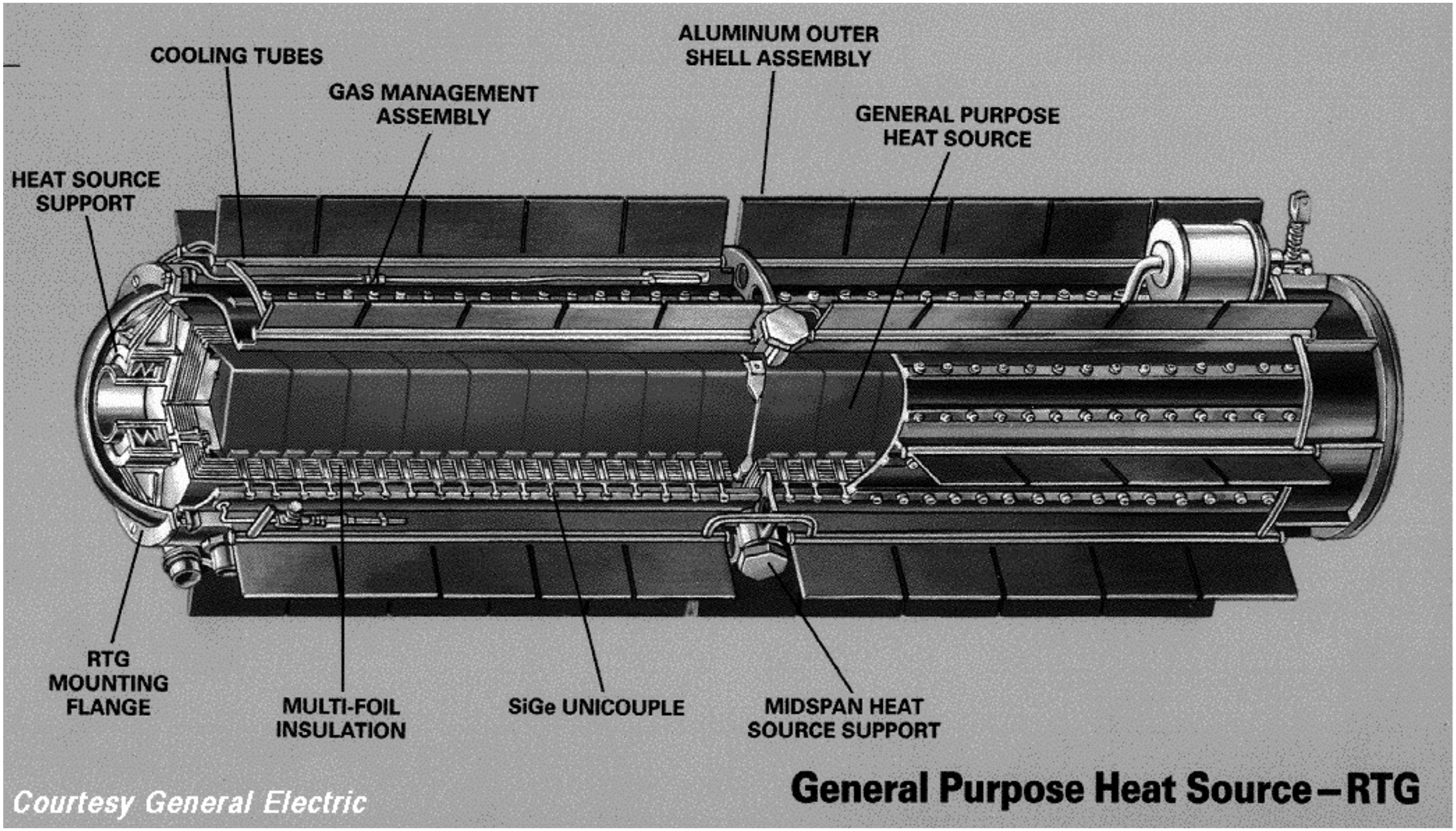
# NASA Solar Array Technology Projections

| | State of Technologies | Near Term | Future |
|---|---|---|---|
| **Crystalline Cell Technology** | Silicon - 14.5%<br>GaAs/(Ge) - 18.5%<br>Production Levels | $GaInP_2$ GaAs/Ge - 24%<br>in large area, production<br>$GaInP_2$ GaAs/Ge - 26%<br>limited quantities | +35% Cells<br>(planar or concentrator applications) |
| **Thin Film Cell Technology** | Not Available | Amorphous S i - 9% AMO<br>CIGS - 6% AMO<br>- Terrestrial - | > 15% CIS, CIGS, $CIS_2$, AmSi<br>High efficiency thin film tech., low cost, lightweight, monolithic interconnections |
| **Array Technology** | 30-50 W/ kg - Rigid Panels<br>60 W/kg - Flexible panels<br>Cost ~ \$1000-\$2000/W | Ultraflex - 115 W/kg (Si), 140 W/kg (GaAs)<br>both mission and sizing specified/limited<br>SCARLET concentrator - 50-60 W/kg<br>radiation hardness, low cost \$500 - \$700/W<br>300W/M² | Lightweight array structures (inflatables, shaped memory mech., hybrid designs) Goal: MBG → 2-300 W/kg, 500 W/m²<br>TF → 1000W/kg, 200 W/m²<br>\$300/W<br>High voltage array designs, 300-1000V<br>reduce/eliminate PMAD, direct drive EP<br>Large area concentrators/dense arrays<br>Synergistic SC subsystems, combine power & communications, power and propulsion at the SC level<br>Integrated energy conversion/power storage concepts |

# 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

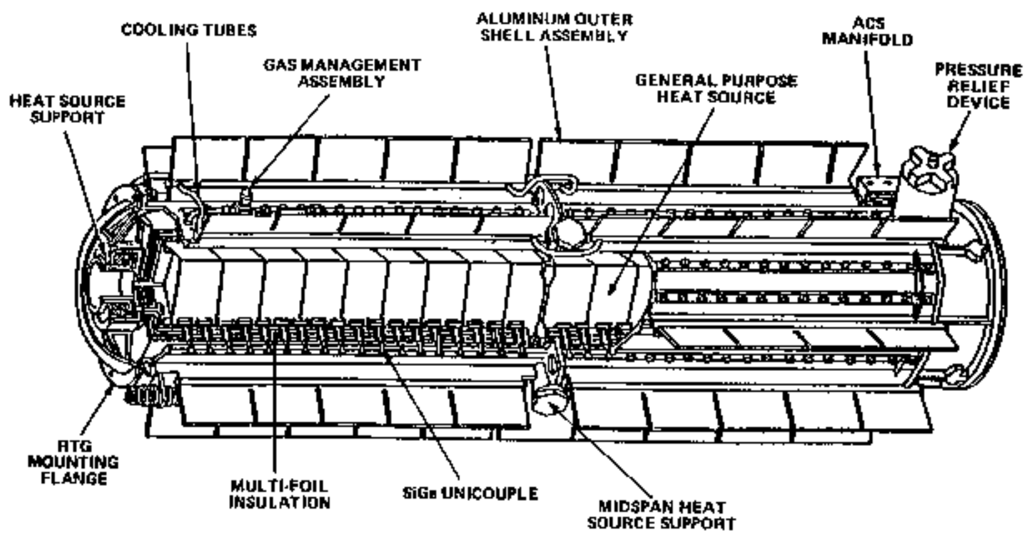
# Galileo RTG



COOLING TUBES
GAS MANAGEMENT ASSEMBLY
ALUMINUM OUTER SHELL ASSEMBLY
GENERAL PURPOSE HEAT SOURCE
HEAT SOURCE SUPPORT
RTG MOUNTING FLANGE
MULTI-FOIL INSULATION
SiGe UNICOUPLE
MIDSPAN HEAT SOURCE SUPPORT
General Purpose Heat Source – RTG
Courtesy General Electric

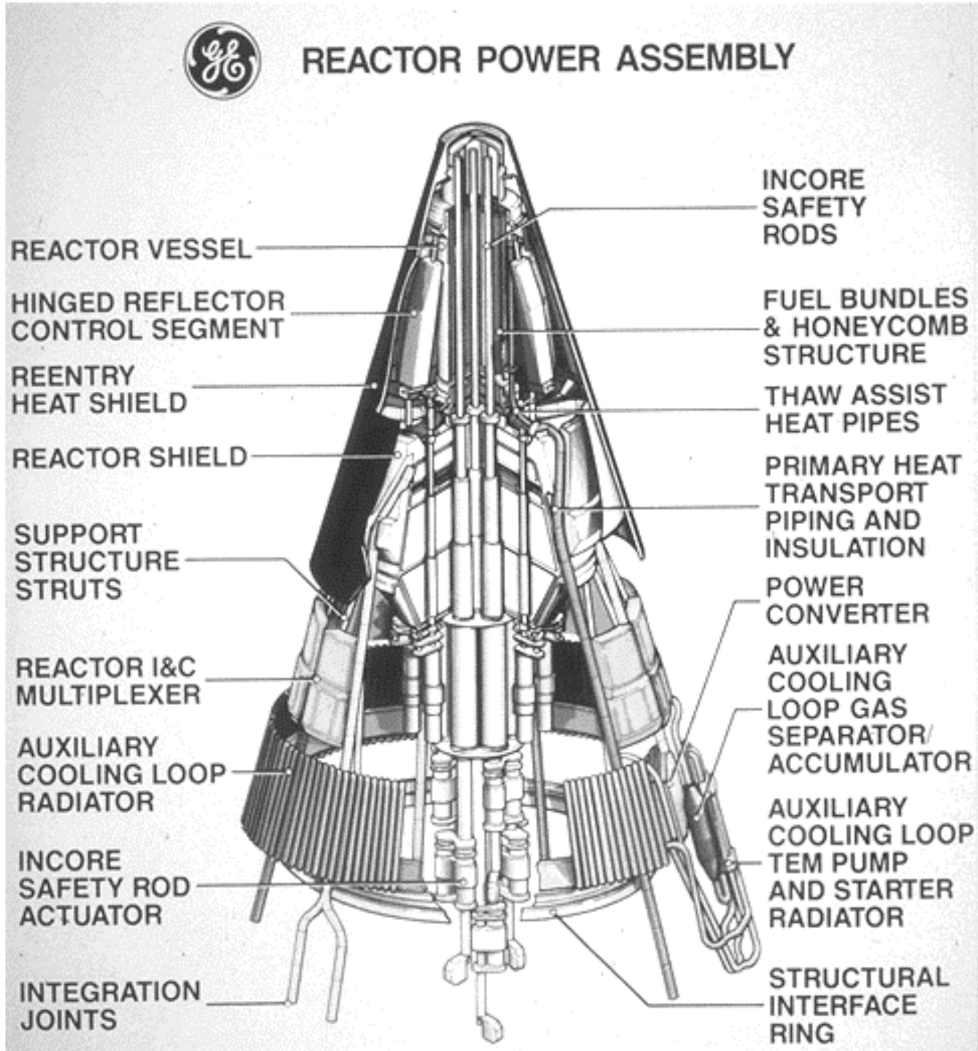
# Galileo RTG Specifications

## The Galileo RTG Operated Perfectly

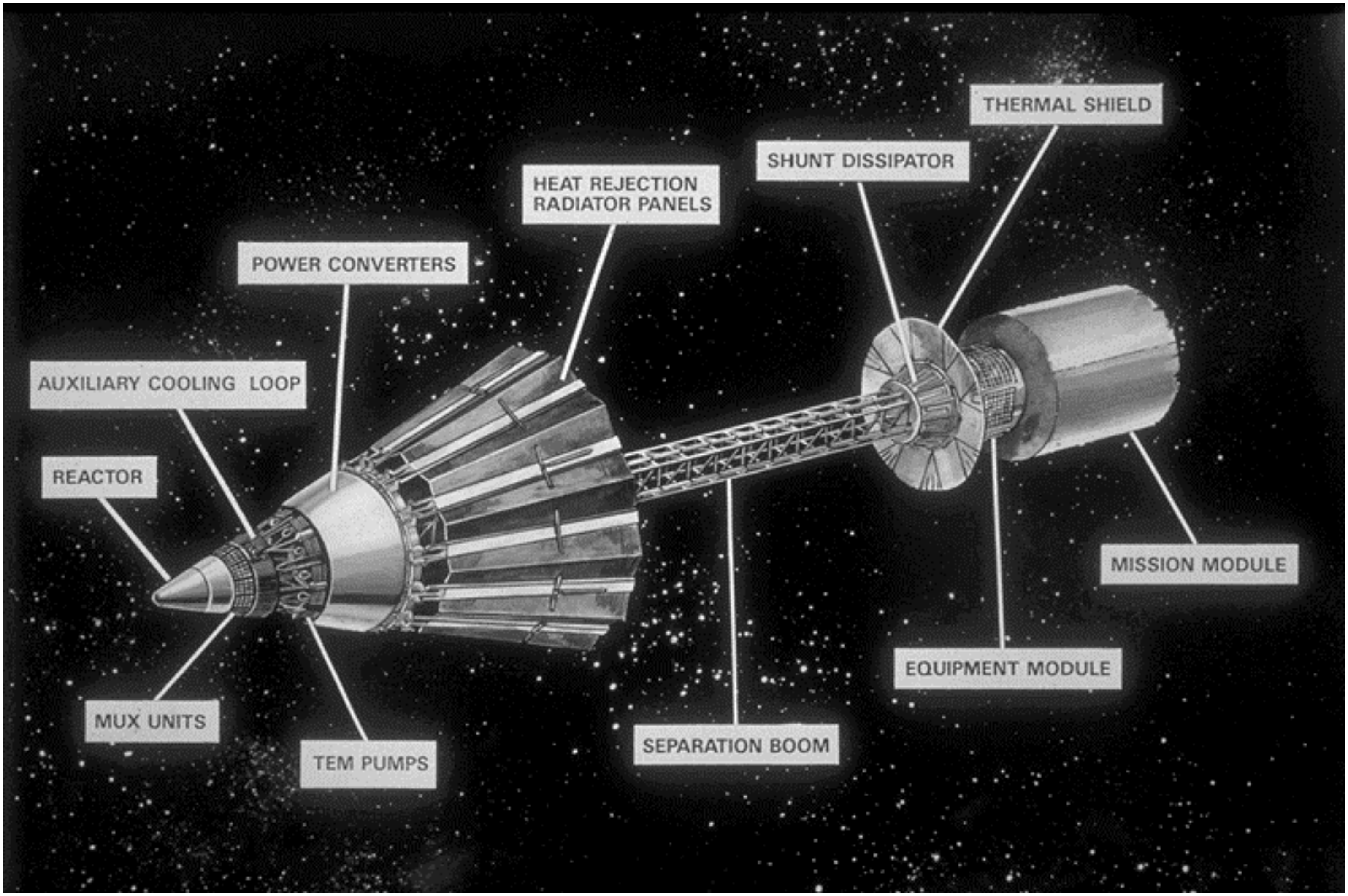



- **Power Out BOL/EOL = 290/250 $W_e$**
- **Mass =55 kg**
- **Dimensions = 114 cm long/42 cm diam.**
- **Hot/Cold Junction T °C- 1000/300**
- **Mass $^{238}$Pu - 7.561 kg**
- **Thermal Power = 4,234 $W_t$**

# SP-100 Reactor Design



# SP-100 Reactor Installation



# Representative Space Nuclear Power Data

| | United States | | Former Soviet Union | | |
|---|---|---|---|---|---|
| Features | SNAP-10A | SP-100 | Romashka | RORSAT | TOPAZ-I |
| Flt. Status | 1965 | Design | 1965-? | 1967-? | 1987-? |
| Power-$kW_t$ | 46 | 2,000 | 40 | <100 | 150 |
| Power-$kW_e$ | 0.65 | 100 | 0.8 | <5 | 5-10 |
| Convertor | TE | TE | TE | TE | TI |
| Fuel | $U\text{-}ZrH_x$ | UN | $UC_2$ | U-Mo | $UO_2$ |
| kg $^{235}U$ | 4.3 | 140 | 49 | 25 | 12 |
| Reactor Mass-kg | 435 | 5,422 | 455 | <390 | 320 |
| Coolant | NaK | Li | None | NaK | NaK |

# 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 | 1300 K | 1500 K |
| | Efficiency | K | 20-30% | 20-30% |
| | Specific Mass | 20-30% | 6-50kg/kW | 5-6 kg/kW |
| | | 20-70 kg/kW | | |
| AMTEC | Power Level | | Up to 200 W | 10 to 50 kW |
| | Life | 500-1500 W | (ARPS) | 10-15 yrs |
| | Peak Cycle Temp | 1400 hr | 15 yrs | 1225 K |
| | Efficiency | 970 K | 1125 K | 25-30% |
| | Specific Mass | 13% | ~15% | 5-7 kg/kW |
| | | 16-25 kg/kW | 17 kg/kW | |
| Thermionic | Power Level | | | Up to 100 kW |
| | Life | 4.5 kW ('68) | Up to 10 kW | 7-10 yrs |
| | Peak Cycle Temp | 1-5 yrs | 4-6 yrs | 2200 K |
| | Efficiency | 1900 K | 2000 K | 15-20% |
| | Specific Mass | 4-12% | 12-15% | 2-3 kg/kW |
| | | 5 kg/kW | 4 kg/kW | |

# NASA Battery Technology Projections

## Space Power Technology Paths - Batteries

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| Technology | Parameter | State-of-the-Art | Near Term | Future |
|---|---|---|---|---|
| Ni-Cd | Cell Wh/kg | 30-45 | | |
| | Battery Wh/kg | 25-37 | | |
| | Wh/ℓ | 30-45 | | |
| | Life-years LEO/GEO | 3/6 | | |
| | DOD - % - LEO/GEO | 15/60 | | |
| | | Space Station - LEO | | Lightweight Ni |
| IPV $Ni-H_2$ | Cell Wh/kg | 47 | 80 | 100 |
| | Battery Wh/kg | 27 | 55 | 75 |
| | Wh/ℓ | 10 | 25 | 40 |
| | Life-years LEO/GEO | 5/12 | 8/15 | 10/20 |
| | DOD - % - LEO/GEO | 35/70 | 40/70 | 40/80 |
| | Rel. Cost | 1.0 | 0.8 | 0.5 |
| | | | | Lightweight Ni/Optimized Design |
| CPV $Ni-H_2$ | Cell Wh/kg | 45-60 | 80 | 100 |
| | Battery Wh/kg | 36-50 | 70 | 85 |
| | Wh/ℓ | 30 | 40 | 60 |
| | Life-years LEO/GEO | 5/12 | 8/15 | 10/20 |
| | DOD - % - LEO/GEO | 35/70 | 40/70 | 40/80 |
| | Rel. Cost | 1.0 | 0.6 | 0.5 |
| | | Prismatic | Bipolar | Bipolar/Lightweight Ni |
| Ni-MH | Cell Wh/kg | 53 | N/A | N/A |
| | Battery Wh/kg | 44 | 80 | 100 |
| | Wh/ℓ | 50-75 | 175 | 250 |
| | Life-years LEO/GEO | 5-LEO | 3/10 | 5/20 |
| | DOD - % - LEO/GEO | 35 | 40/60 | 4075 |
| | Rel. Cost | 1.0 | 0.5 | 0.5 |
| | | Commercial | Liquid | Polymer |
| Li-Ion | Cell Wh/kg | 100 | >100 | >200 |
| | Battery Wh/kg | 80 | 85 | 175 |
| | Wh/ℓ | 160 | 130 | 220 |
| | Life-years LEO/GEO | N/A | 2/10 | 5/20 |
| | DOD - % - LEO/GEO | N/A | 40/60 | 50/75 |
| | Rel. Cost | 1.0 | 0.5 | 0.2 |
| NaS | Cell Wh/kg | 110 | -- | -- |
| | Battery Wh/kg | 90 | | |
| | Wh/ℓ | 60 | | |
| | Life-years LEO/GEO | 3/10 | | |
| | DOD - % - LEO/GEO | 60/80 | | |

# 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

# 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

# NASA Flywheel Technology Projections

| Metric | Existing Battery Systems** | Flywheel SOA* | Flywheel Goals |
|---|---|---|---|
| Effective, Usable Specific Energy (SE) in LEO | < 3 Whr/lb | ~10 Whr/lb | >20 Whr/lb |
| Cycle life (at above SE levels) | ~30,000 | TBD (estimated at 50,000) | >75,000 |
| Energy Storage (turn around) Efficiency | 68-80% | 85% | >90% |
| Cost | $0.5-3M | Comparable | > 25% reduction |

* Based on laboratory units extrapolated to flight configuration. Current TRL ~ 4.3-5.3

** Includes associated hardware (e.g., battery regulator)

# 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

# Boost Module Power Generation

- Need 200 W to support boost module systems during LEO loitering prior to vehicle assembly
- ~50 minutes of daylight, 40 minutes of night on each orbit
- Need 133 W-hr of energy each night
- NiMH batteries at 40 W-hrs/kg --> 3.33 kg
- Have to recharge during day pass --> 160 W
- Total PV power requirement = 360 W
- Actually need additional power for non-ideal efficiencies, losses, DOD, etc.

# 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 $I^2/R$ (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% |
| | InGaAIP/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