Activities in Thermoelectrics at Teledyne Energy Systems, Inc.

2004 DOE High Efficiency Thermoelectric Workshop

San Diego, CA, February 17-20

Presented by Malachy McAlonan

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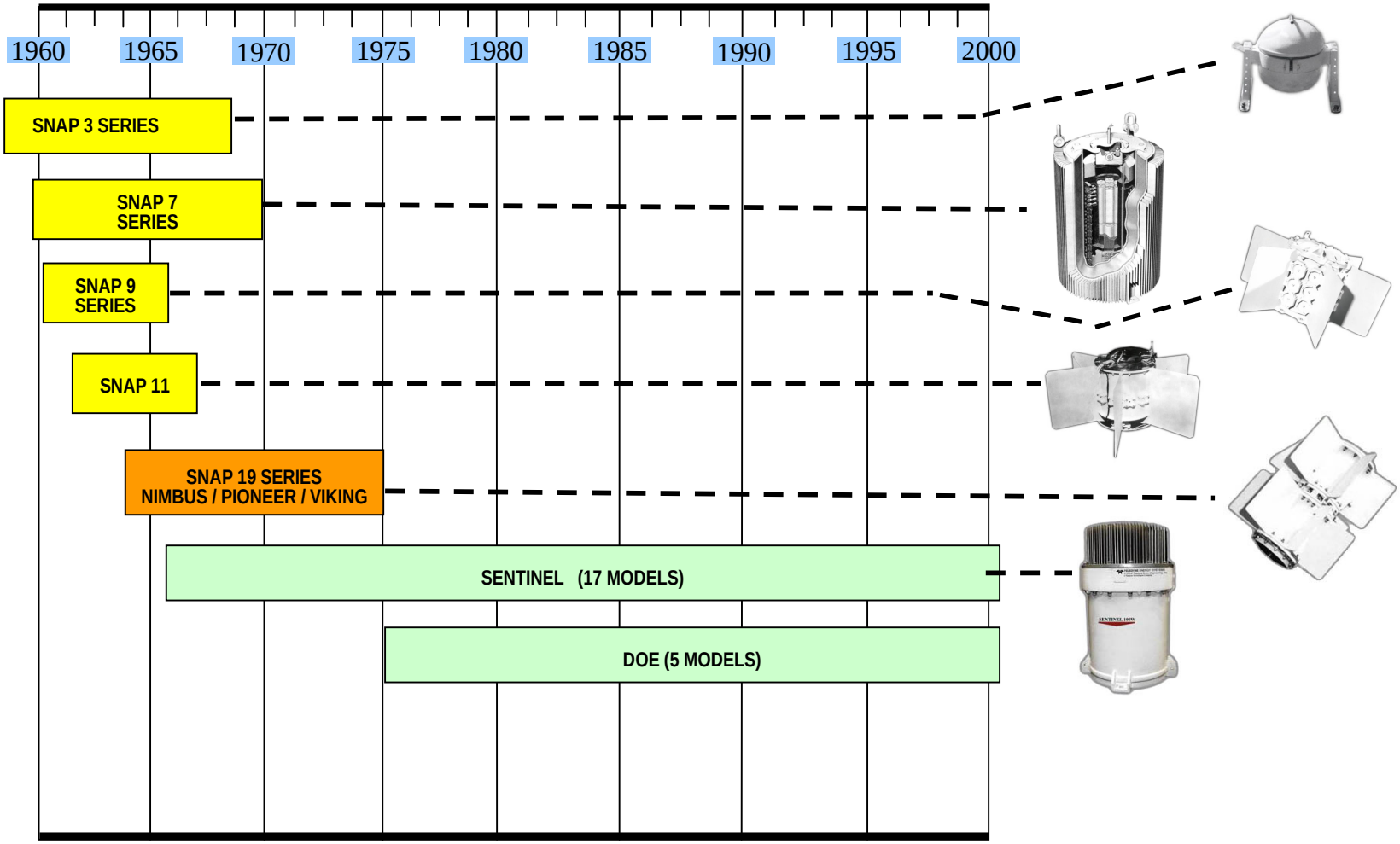
Overview

- Thermoelectric Heritage
  - RTG for Space and Terrestrial Applications
  - Military Applications
  - Commercial Applications
- Current Projects
  - Muti-Mission RTG
  - NASA NRA's
  - Advanced Space Applications

RADIOISOTOPE POWER HERITAGE



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Teledyne Energy Systems Sr - 90 RTG Applications (1)

Customer	Model	Year(s)	Location	Use	T/E Materials
U.S. Weather Bureau	Sentry	1961-65	Axel Heiberg Island	First RTG Powered Weather Station	PbTe/PbTe
USCG	SNAP 7A	1961-67	Curtis Bay, MD	Light Buoy	PbTe/PbTe
USCG	SNAP 7B	1964	Baltimore Harbor	Lighthouse	PbTe/PbTe
Phillips Petroleum	SNAP 7B	1966	Gulf of Mexico	Oil Platform	PbTe/PbTe
NSF	SNAP 7C	1962-69	Antarctica	Weather Station - Minna Bluff	PbTe/PbTe
USN	SNAP 7D	1964-71	Gulf of Mexico	First RTG Powered Weather Buoy	PbTe/PbTe
USN	SNAP 7E	1964-69	Atlantic Ocean	First RTG Powered Acoustic Beacon	PbTe/PbTe
USN	SNAP 7E	1970-80	Naval Avionics Center	Test and Evaluation	PbTe/PbTe
Phillips Petroleum	SNAP 7F	1966	Gulf of Mexico	Navigational Aids	PbTe/PbTe
USN	LCG 25A	1966-81	Bering Straits	Data Telemetry	PbTe/PbTe
	Sentinel 25F	1981-95			PbTe/TAGS
USN	Sentinel 8	1968-90 (22 years)	California	Weather Station	PbTe/PbTe
USN	Sentinel 25E	1969	Pacific Ocean	Data Collection (Sea Spider Buoy)	PbTe/TAGS
USAF	LCG 25A	1973-Present (27 years)	Alaska	Data Telemetry (Nuclear Test Ban Treaty)	PbTe/PbTe
	Sentinel 25E	1985-Present			PbTe/TAGS
	Sentinel 25F	1985-Present			PbTe/TAGS
	Sentinel 100F	1985-Present			PbTe/TAGS
USN	MW 3000	4 years	California	Test and Evaluation	PbTe/PbTe
Sinclair Oil & Gas	MW 3000	1968	Gulf of Mexico	Wellhead Control	PbTe/PbTe
Cameron Iron Works	LCG 25B	4 years	Gulf of Mexico	Wellhead Control	PbTe/PbTe
USN	LCG 25C1	1969-76	Pacific Ocean	Acoustic Transponder (San Juan Seamount)	PbTe/TAGS

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Teledyne Energy Systems Sr - 90 RTG Applications (2)

Customer	Model	Year(s)	Location	Use	T/E Materials
NSF	LCG 25C1	1980-90	Antarctica	Weather Station	PbTe/TAGS
NOAA	LCG 25C3	1970		Test and Evaluation (ESSA)	PbTe/TAGS
USN	LCG 25C3	1971-73	Pacific Ocean	Transducers	PbTe/TAGS
NSF	LCG 25C3	1979-90	Antarctica	Weather Station - Marble Point	PbTe/TAGS
USN	Sentinel 25D	1970-71	Gulf of Mexico	Weather Buoy - Nomad	PbTe/TAGS
USN	Sentinel 25D	1973-82	Gulf of Mexico	Data Telemetry	PbTe/TAGS
USN	Sentinel 100F	1974	Eleuthera	Uniterruptable Power Supply	PbTe/TAGS
USN	Sentinel 25E	1969		Sea Spider Buoy	PbTe/TAGS
USN	Sentinel 25F	1974-75	Alaska	Weather Station	PbTe/TAGS
Inst. Acoustic Research	Sentinel 25F	1976	Atlantic Ocean	Thermo-acoustic Sensors	PbTe/TAGS
FAA	Sentinel 25E	1977-81	Alaska	First RTG Powered Air to Ground Communications	PbTe/TAGS
	Sentinel 25F				PbTe/TAGS
	Sentinel 25E	Shipped 1978		Demonstration	PbTe/TAGS
NSF	Sentinel 25F	1979-90	Antarctica	Weather Station - Ross Ice Shelf	PbTe/TAGS
Saudi Arabia	Sentinel 25F	installed 1976/77	Saudi Arabia	Weather Station	PbTe/TAGS
	Sentinel 8S	Shipped 1970-82		Communications	PbTe/TAGS
	Sentinel 1S	Shipped 1986-95		Communications	BiTe
	Sentinel 5S	Shipped 1986		Communications	PbTe/TAGS
DOE	BUP 500	1986	Oak Ridge, TN	Largest RTG Ever Built	PbTe/TAGS
	Sentinel 20S	Shipped 1993		Communications	PbTe/TAGS
	Sentinel 2S	Shipped 1998		Communications	PbTe/TAGS/BiT
	Sentinel 15S	Shipped 2000		Communications	PbTe/TAGS

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Teledyne Energy Systems Pu 238 RTG Applications

Customer/User	Model	Year(s)	Location	Use	T/E Materials
USN	SNAP - 3B	1961-62	Still Orbiting	Transit 4A/B Navigation Satellites	PbTe/PbTe
				First Satellite Powered by an RTG	
USN	SNAP - 9A	1963-64	Still Orbiting	Transit 5B Navigation Satellites	PbTe/PbTe
NASA	SNAP - 19B	1966-67	Still Orbiting	Nimbus B/III Weather Satellites	PbTe/PbTe
NASA	SNAP - 19	1972-Present	Interstellar Space	Pioneer 10 & 11	PbTe/TAGS
				First to Explore Jupiter and Saturn	
				Longest Succesfully Operating Space System	
NASA	SNAP - 19	1975-82	Mars	Viking 1 & 2 /Mars Landers	PbTe/TAGS
DOE	HPG MOD3	1976-Present			PbTe/TAGS
USN	Half-Watt	1976-78		Communications Repeaters	BiTe
DOE	HPG MOD4	1980	TES		PbTe/TAGS
DOE	Five Watt	1985-95			BiTe
USN	Two Watt	1986-91	On Test at TES	Segmented Mini-Couple Development	PbTe/TAGS/BiTe
DOE	50 Watt	1995-Present			PbTe/TAGS/BiTe

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RTG Heritage - Summary

- Teledyne has been producing Radioisotope Thermoelectric Generators continuously for the past forty years using PbTe, PbSnTe, BiTe, and TAGS thermoelectric materials.

- PbTe/TAGS thermoelectric couples have continued in production since the Viking and Pioneer missions.
  - The Viking 1 and 2 RTGs performed flawlessly for their missions.
  - The Pioneer 10 and 11 RTGs exceeded all mission requirements;
    - Pioneer 10 was still operating after 29 years in space.

- PbTe/BiTe//PbSnTe/TAGS/BiTe segmented couples introduced in the past 16 years offer higher efficiency for lower cold junction temperature applications.

Pioneer and Viking Mission Dates

	Launch	Jupiter Encounter	Saturn Encounter
Pioneer 10	March 1972	December 1973	----------
Pioneer 11	April 1973	December 1974	September 1979

	Launch	Mars Landing	Lander Shutdown
Viking 1	August 1975	July 1976	November 1982
Viking 2	September 1975	September 1976	February 1980

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Pioneer/Viking RTG Design Comparison

	Pioneer	Viking
Electrical power output specification	30W @ .995 min. reliability at Jupiter encounter (36 months after delivery)	35W @ .99 min. reliability after 90 days on Mars surface (26 months after delivery)
Nominal BOL RTG design power output and load voltage	41.2W @ 4.0V	42.5 @ 4.4V
Hot junction temperature	954ºF	1015ºF
Thermal inventory	648W	683W
Thermoelectric materials	PbTe(N)/TAGS(P) (90 couples total)	
Weight	30 lbs.	33.5 lbs.

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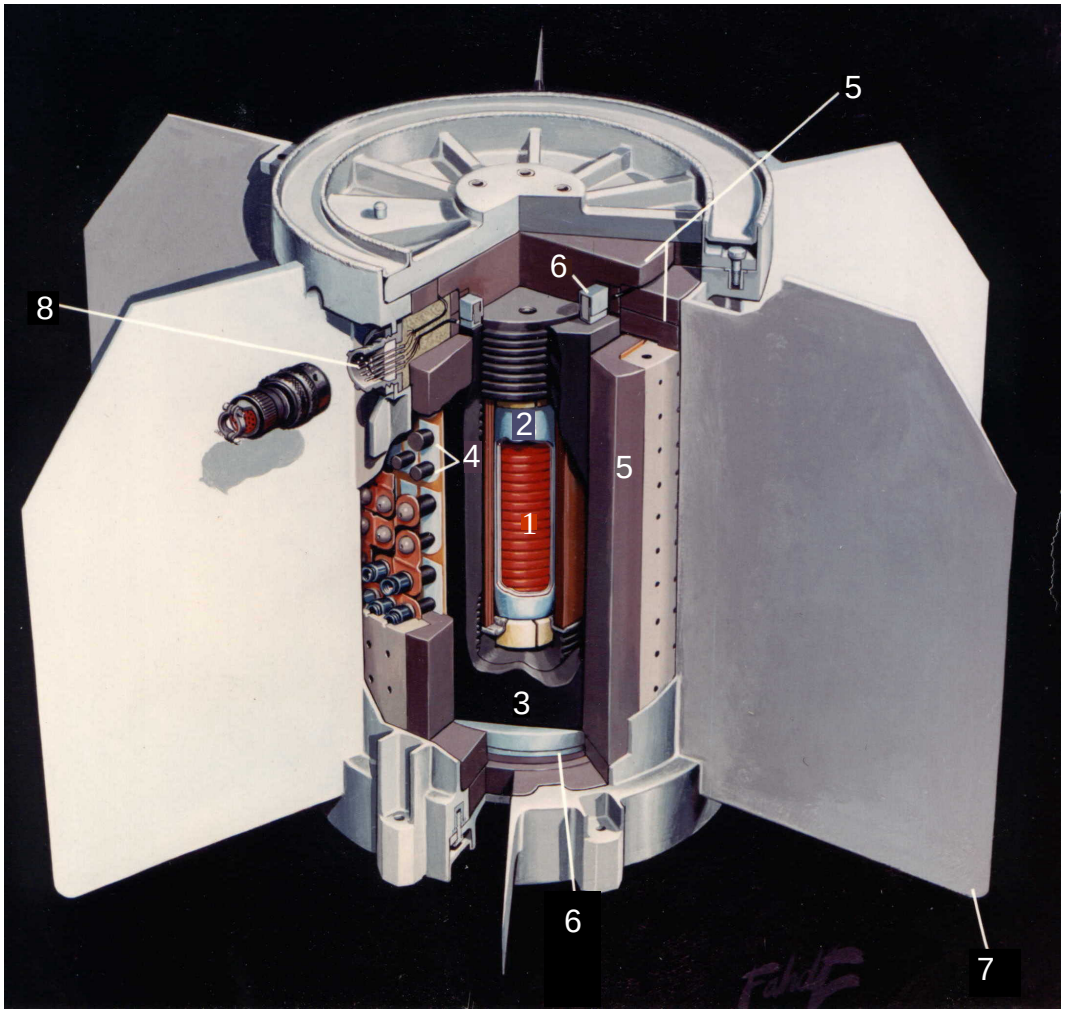
SNAP 19 Pioneer RTG

Legend:

1. Plutonia radioisotope fuel
2. Radioisotope fuel capsule
3. Re-entry graphite heat shield
4. Thermoelectric elements
5. Min-K thermal insulation
6. Getter ring
7. Heat rejection fins
8. Power output connector



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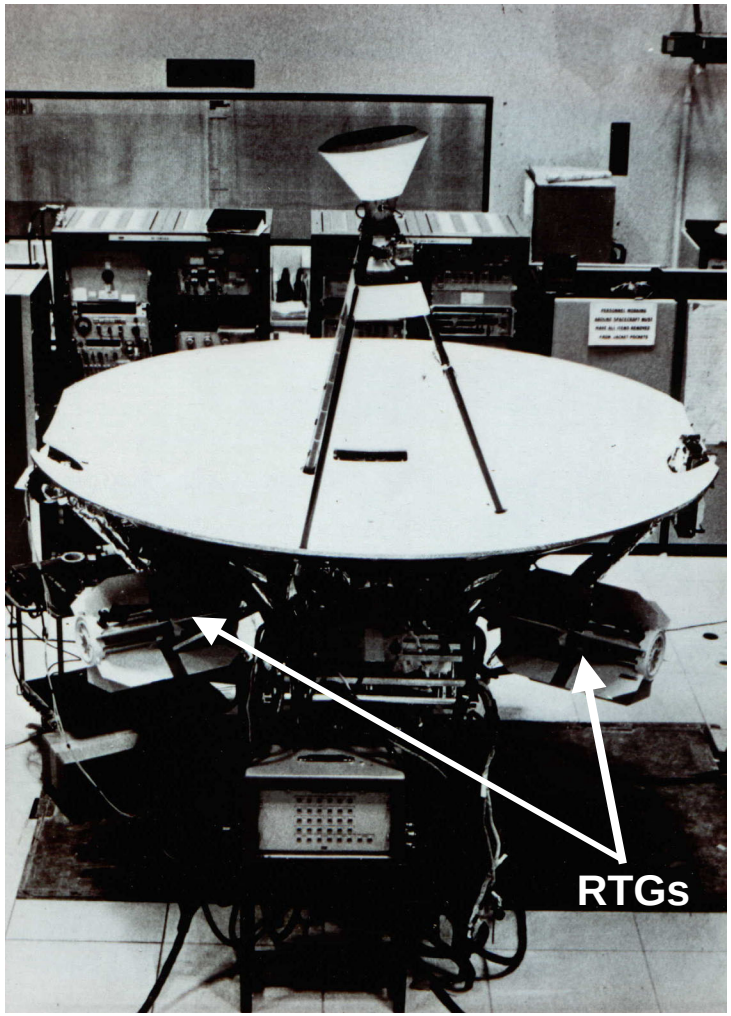
SNAP 19 RTGs on Pioneer/Jupiter Spacecraft



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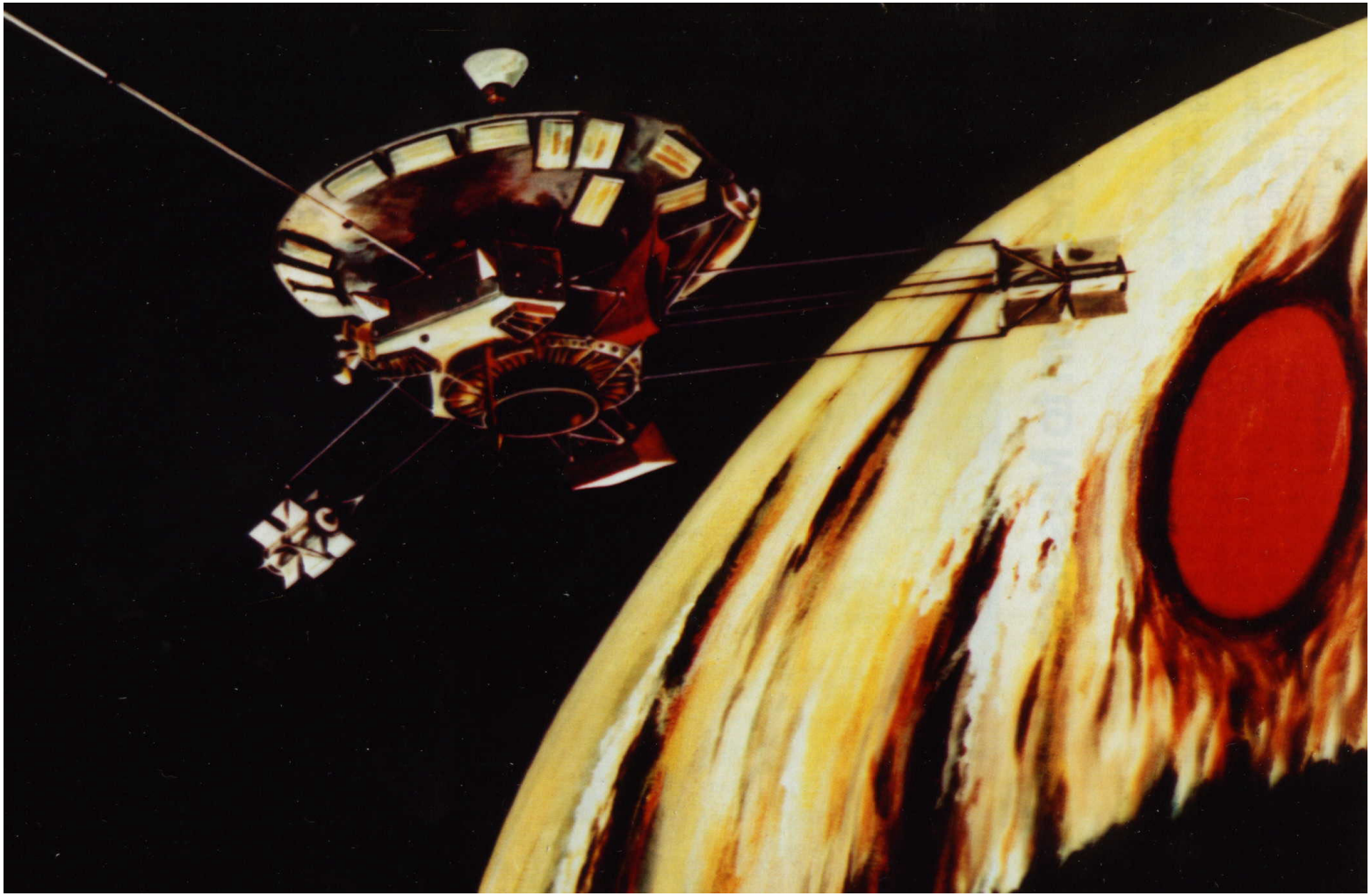
Concept of Pioneer Jupiter Flyby



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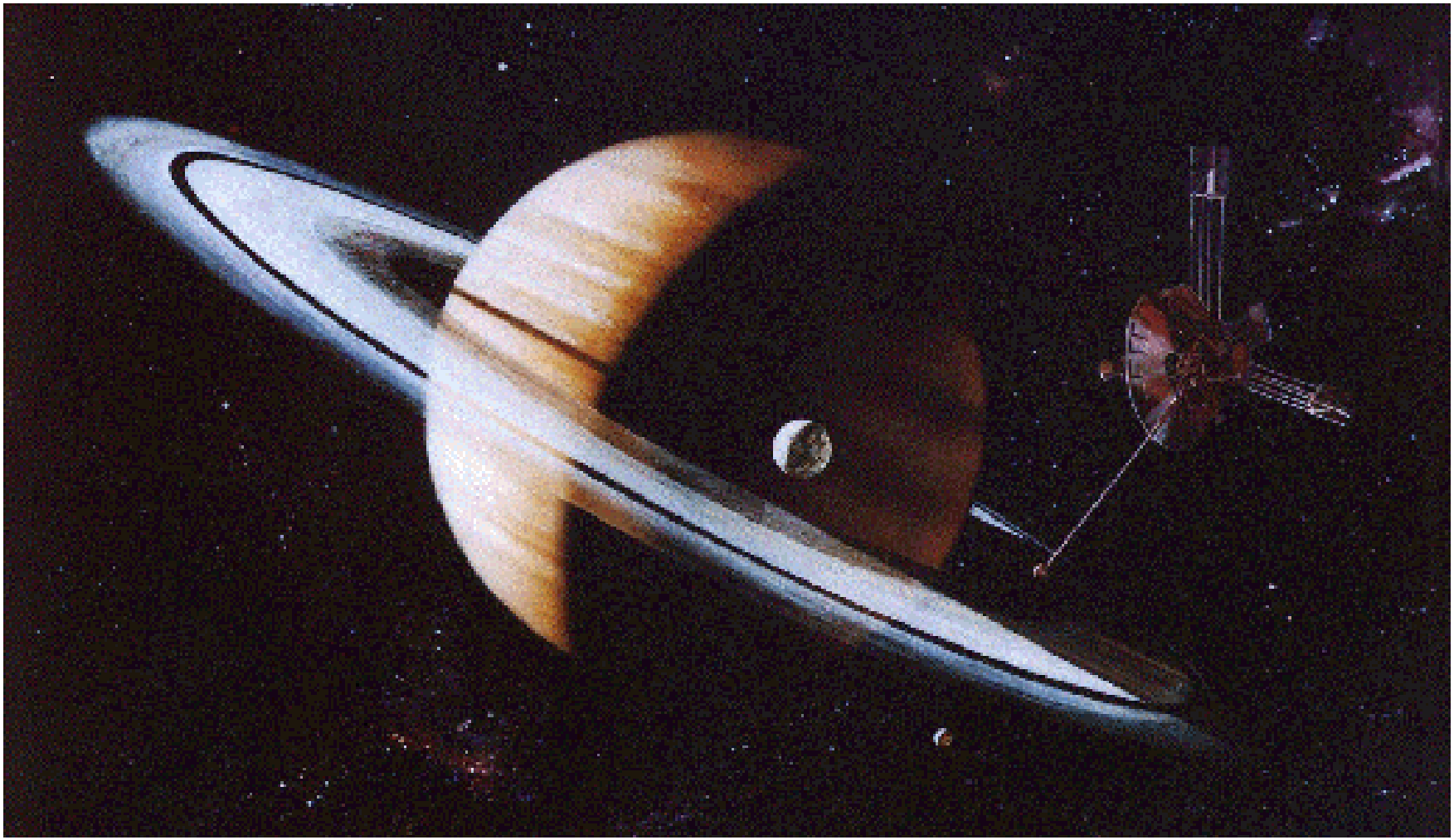
Concept of Pioneer 11 Saturn Flyby



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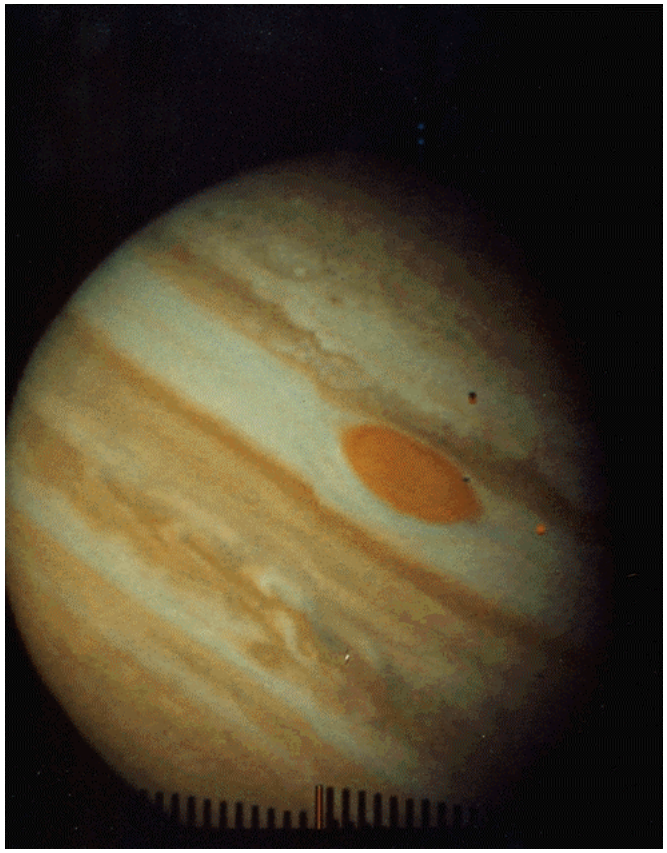
Pioneer 10 and 11 Images of Jupiter and Saturn



Pioneer 10

Pioneer 11

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Pioneer Mission Accomplishments

- At Jupiter encounter, the SNAP 19 RTGs on the Pioneer 10 and 11 spacecraft exceeded the mission power requirement by approximately 20%.

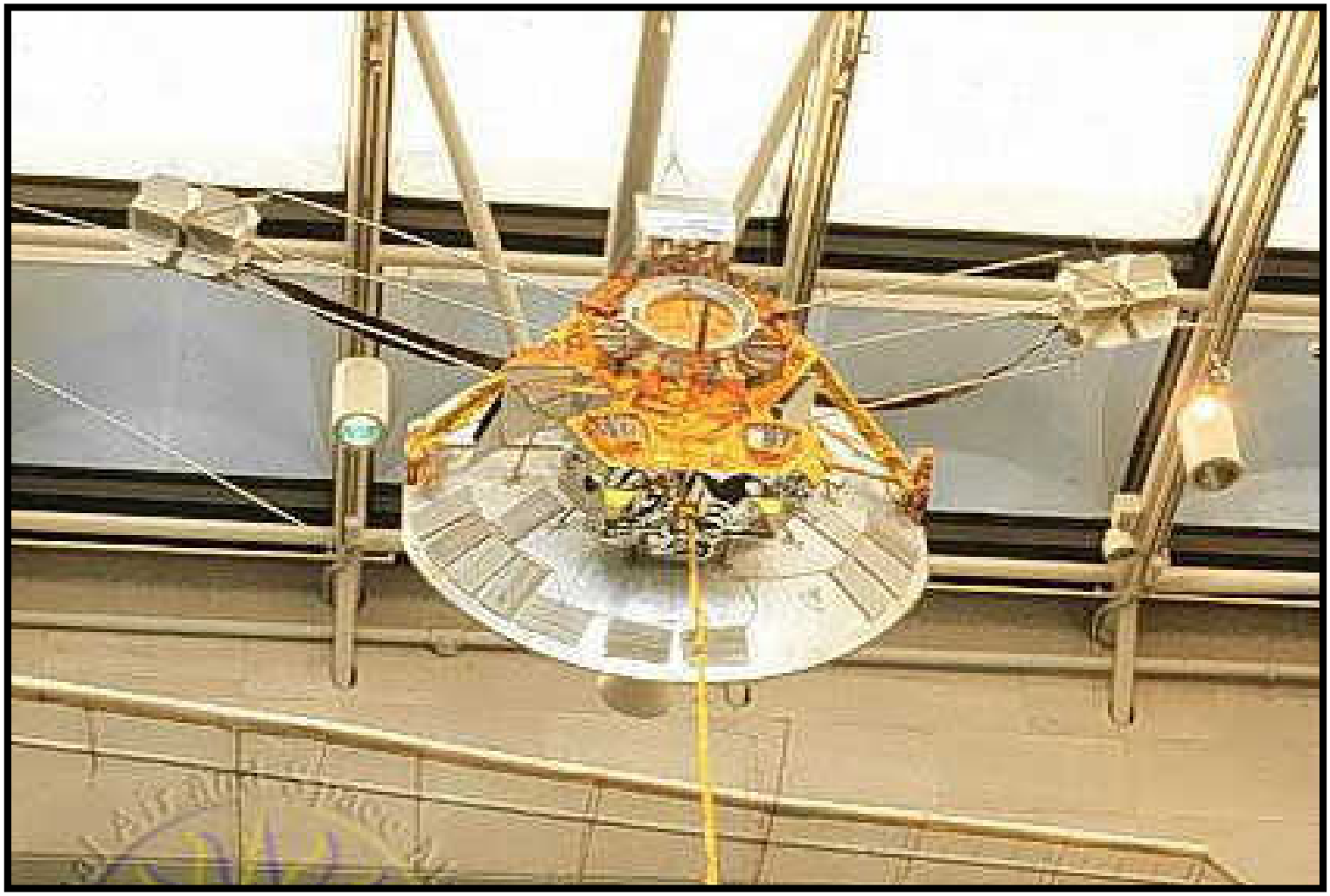
- For the unplanned Pioneer 11 extended mission to Saturn, SNAP 19 RTG power was approximately 30% above the power goal at encounter.

- Pioneer 10 was the first spacecraft to take close-up images of Jupiter and was still sending back signals after 29 years in space at a distance of 7 billion miles.

- Pioneer 11 was the first spacecraft to take close-up images of Saturn and continued to send back signals for more than 22 years in space before communication was lost with the spacecraft in 1995.

- Both Pioneer 10 and Pioneer 11 have exited the solar system. Pioneer 10 was the first man-made object to leave our solar system.

Pioneer 10 Spacecraft Replica at Smithsonian Institute



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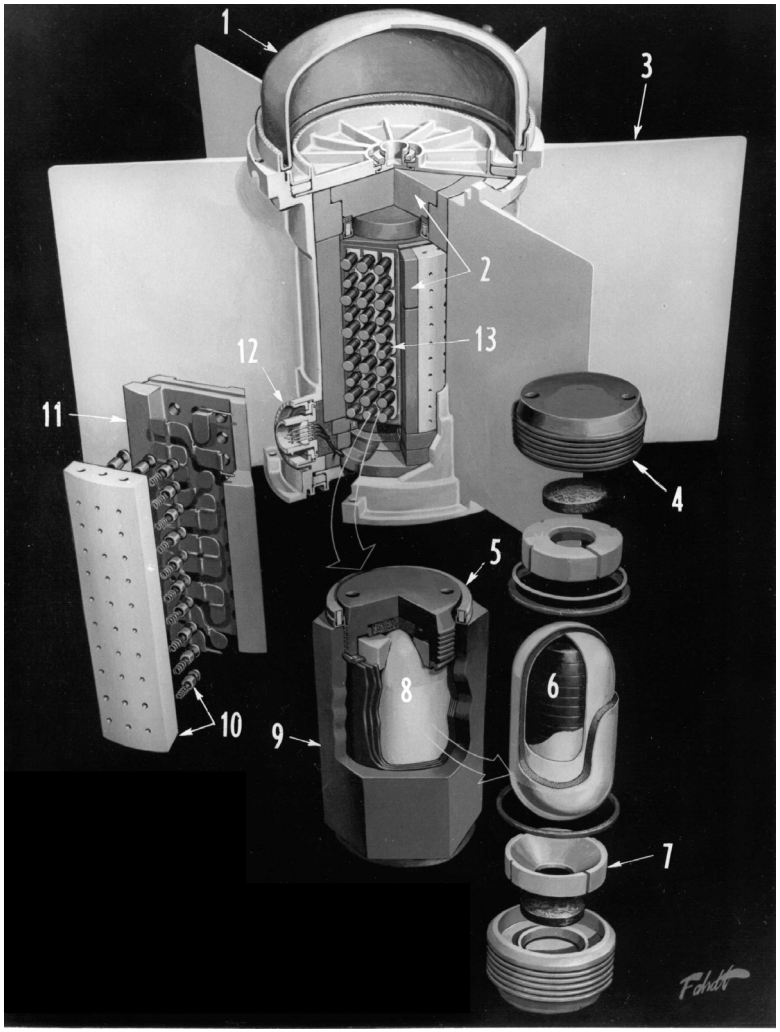
SNAP 19 Viking RTG Components

Legend:

1. Gas management reservoir
2. Min-K thermal insulation
3. Heat rejection fins (6)
4. Heat shield end cap (2)
5. Getter ring (2)
6. Plutonia radioisotope fuel
7. Split capsule support ring (2)
8. Radioisotope fuel capsule
9. Re-entry heat shield
10. Cold end hardware assy (6)
11. Module Min-K thermal insulation
12. Power output receptacle
13. Thermoelectric couple (90)



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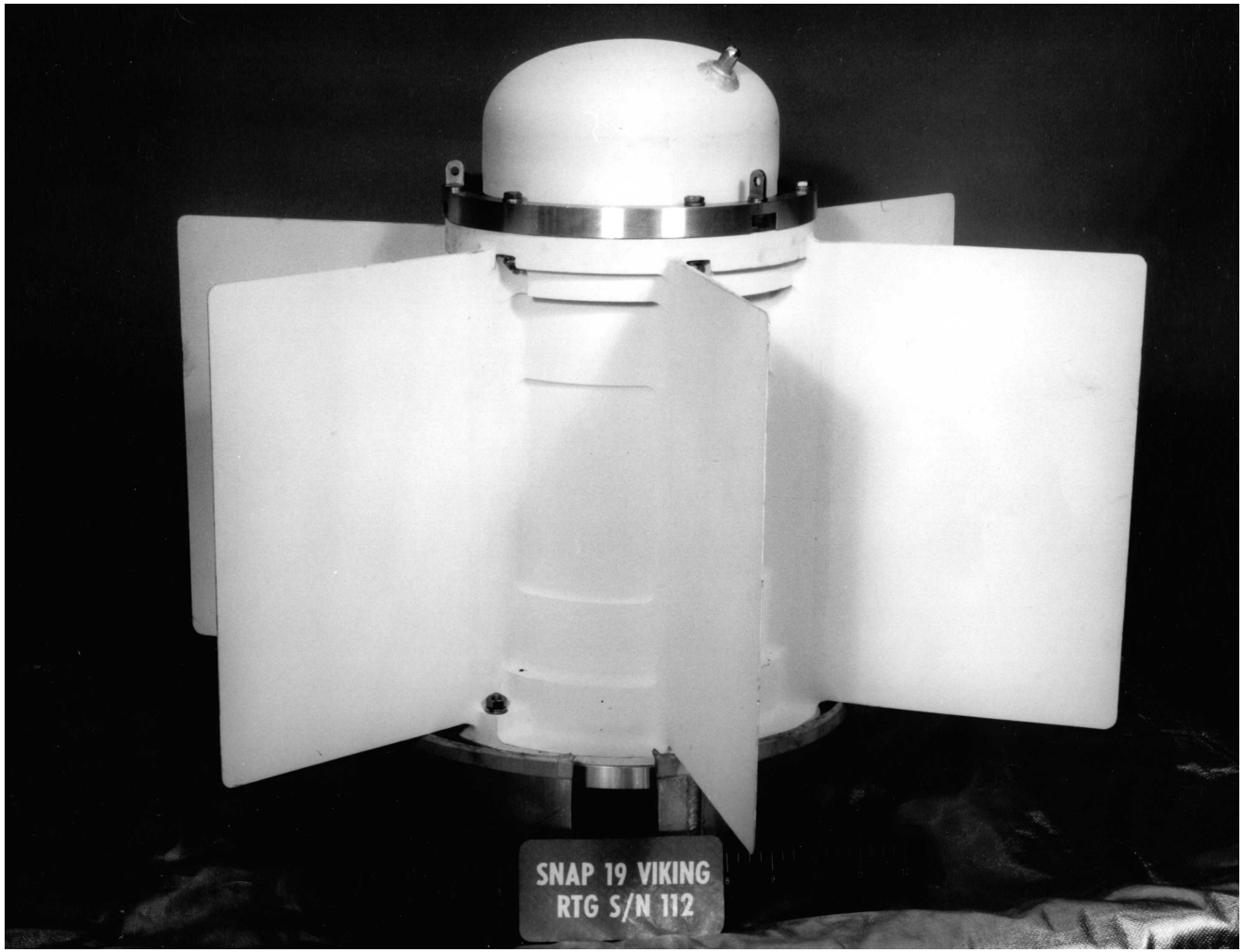
SNAP 19 Viking RTG S/N 112



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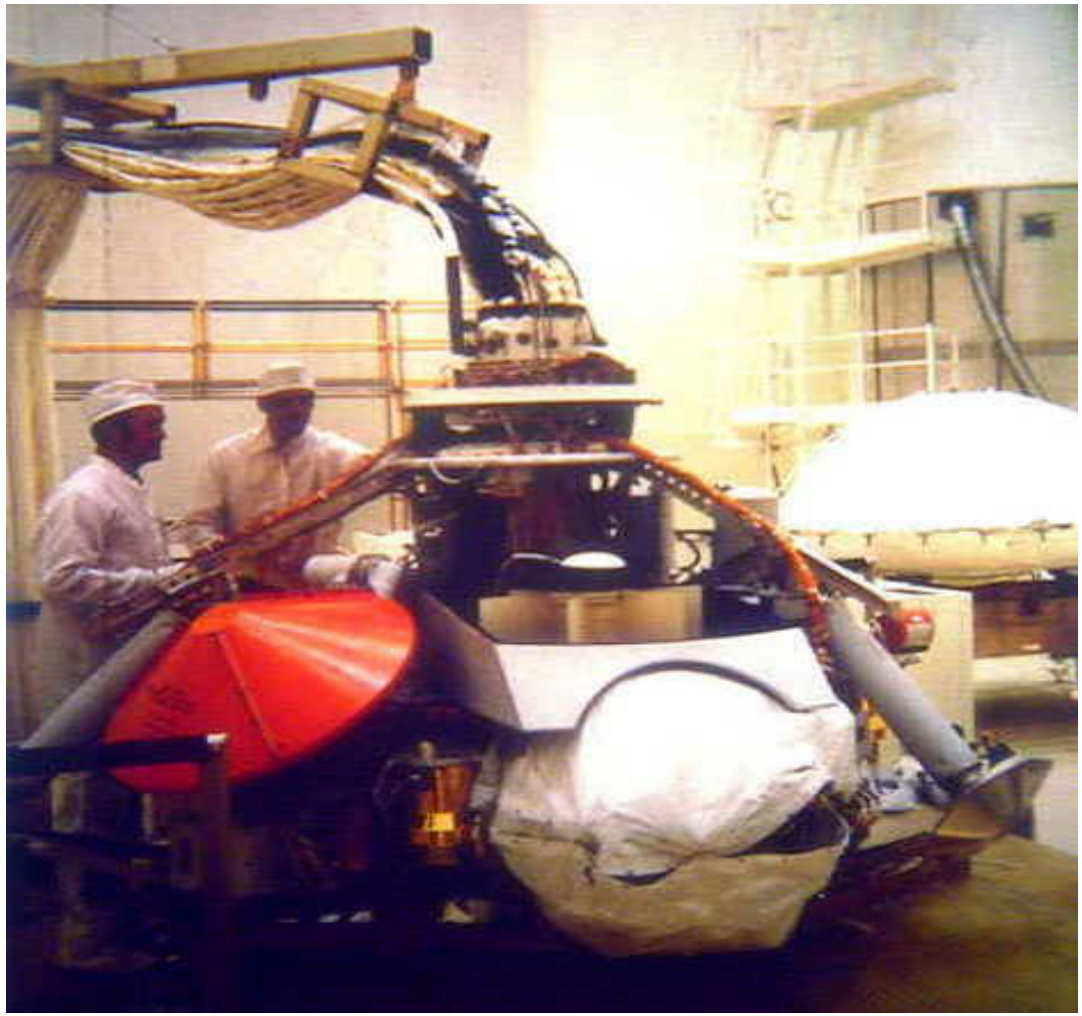
Viking Lander Assembly at Kennedy Space Center



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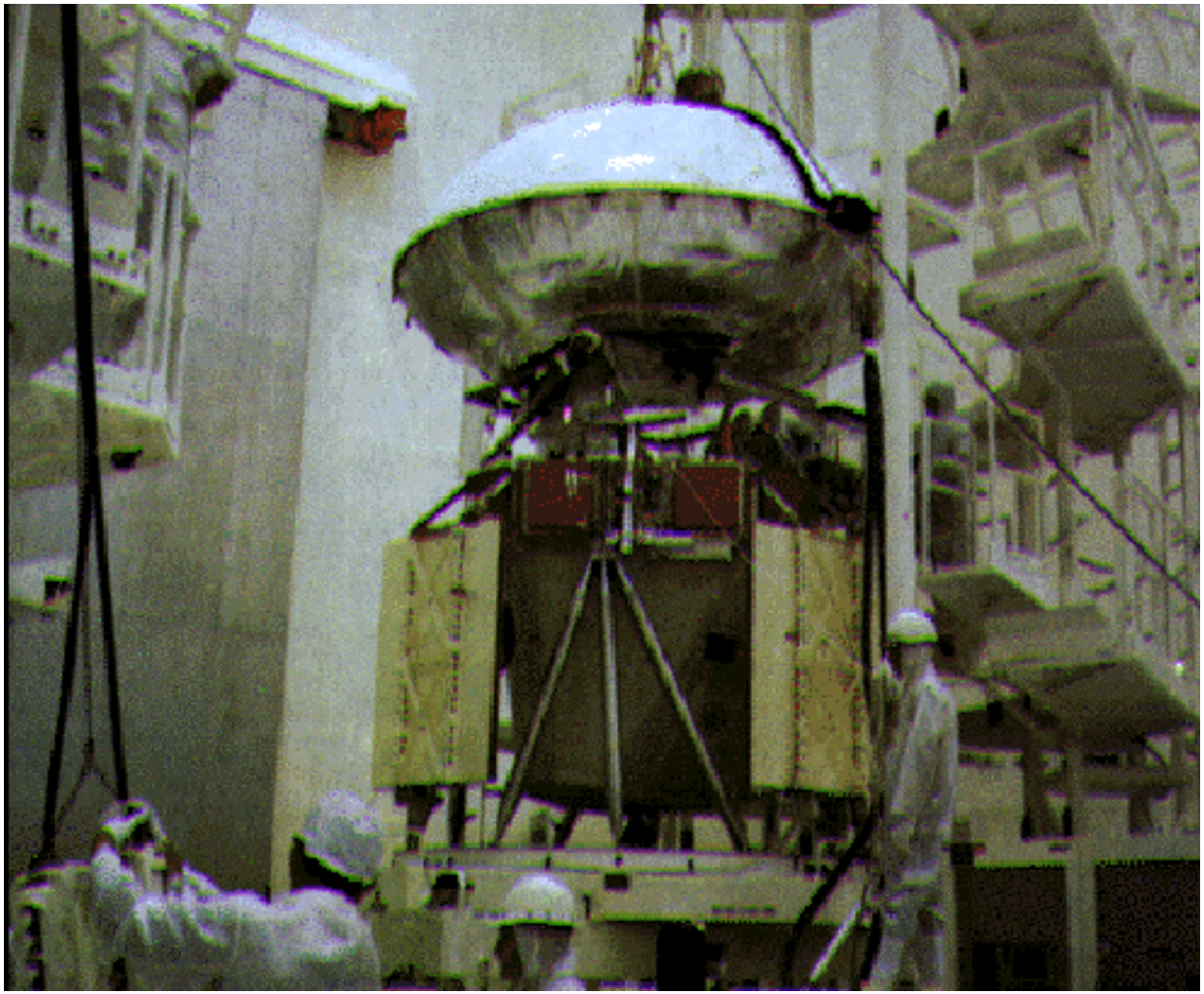
Viking Lander Mounting on Orbiter at Kennedy Space Center



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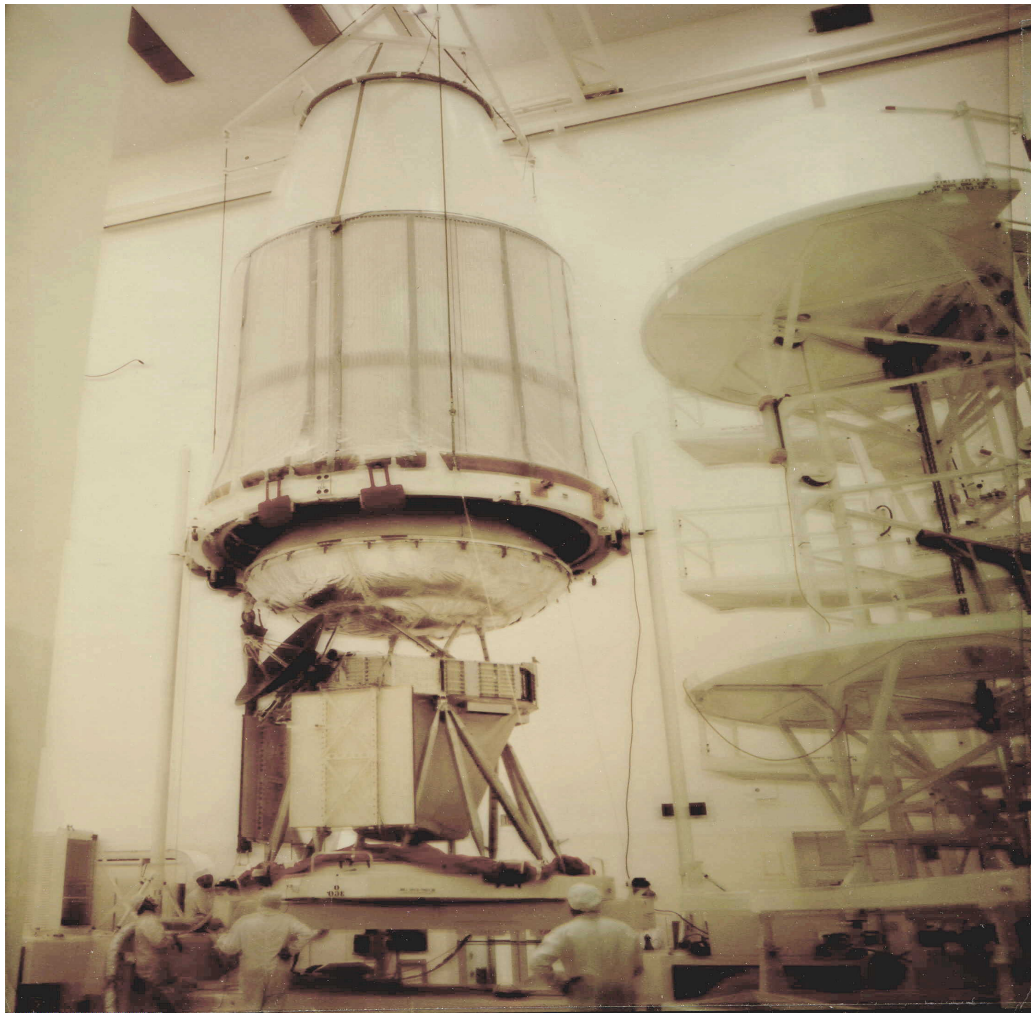
Assembly of Viking Spacecraft with Nose Cone at KSC



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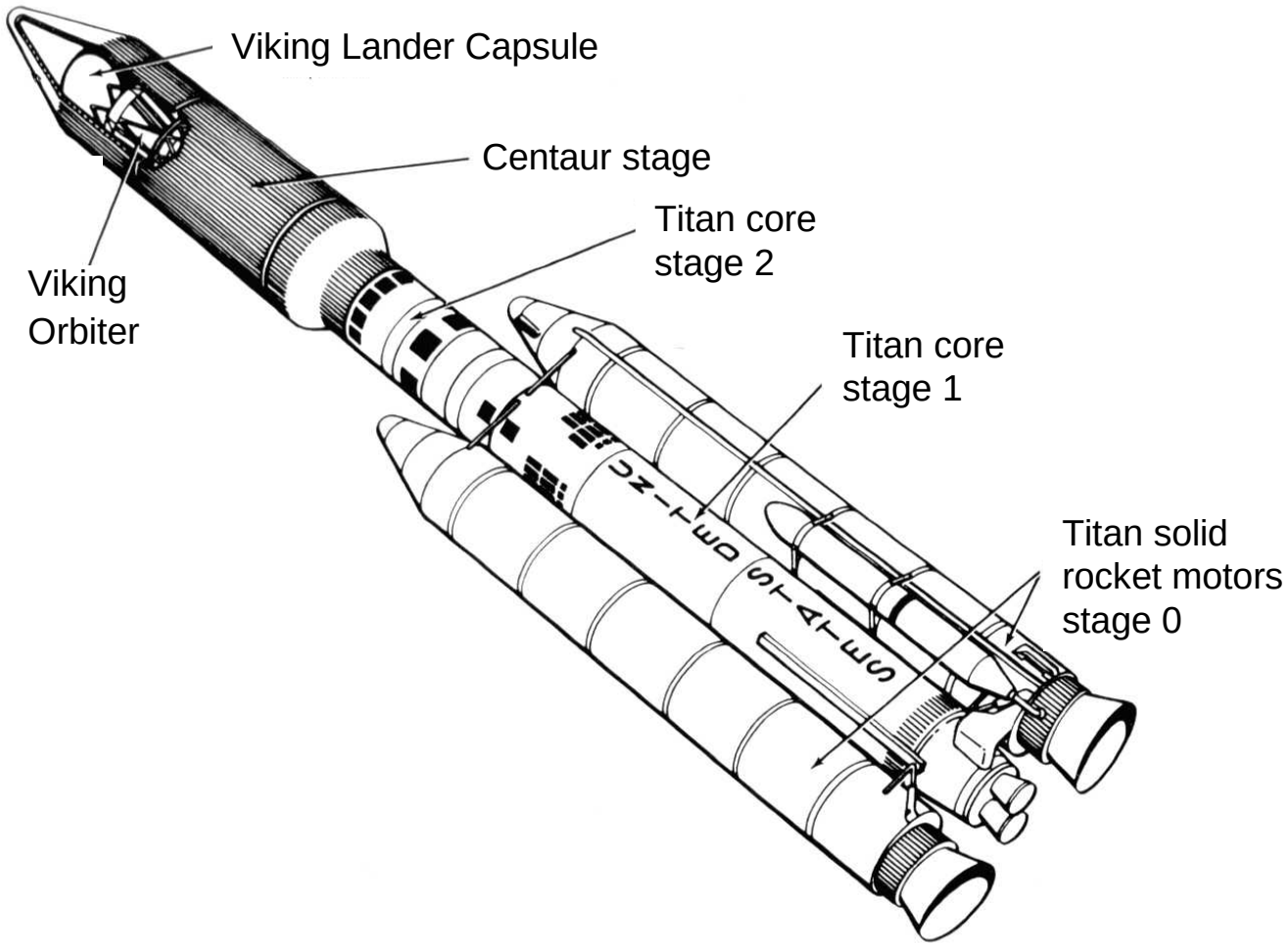
Viking Space Vehicle Configuration



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Viking 2 Launch from Kennedy Space Center

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Interplanetary Cruise, Mars Orbit, Descent and Entry

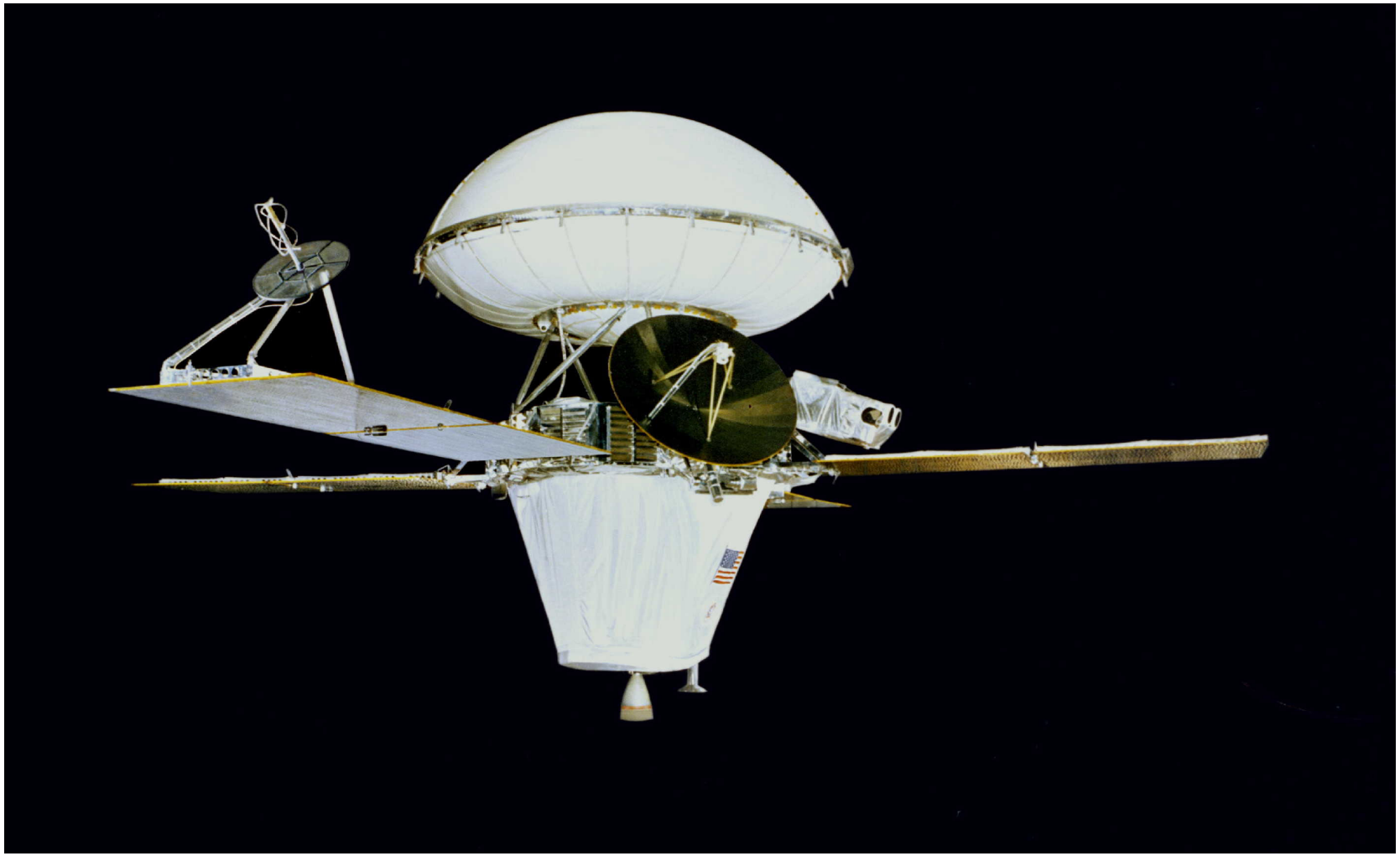
- During cruise, power was available from the orbiter for checkout of the Lander and battery charging - RTGs were operated on short circuit to minimize Lander and hot junction temperatures.

- In Mars orbit, the RTGs were placed on-load about 40 hours prior to entry for Lander checkout and battery charging. The RTGs remained on load for all subsequent mission phases.

- Prior to entry, the biocanister was ejected and the heat shield on the Lander oriented for entry.

- During descent and entry, the RTGs provided power for the entry science instruments.

Concept of Viking Interplanetary Cruise Configuration



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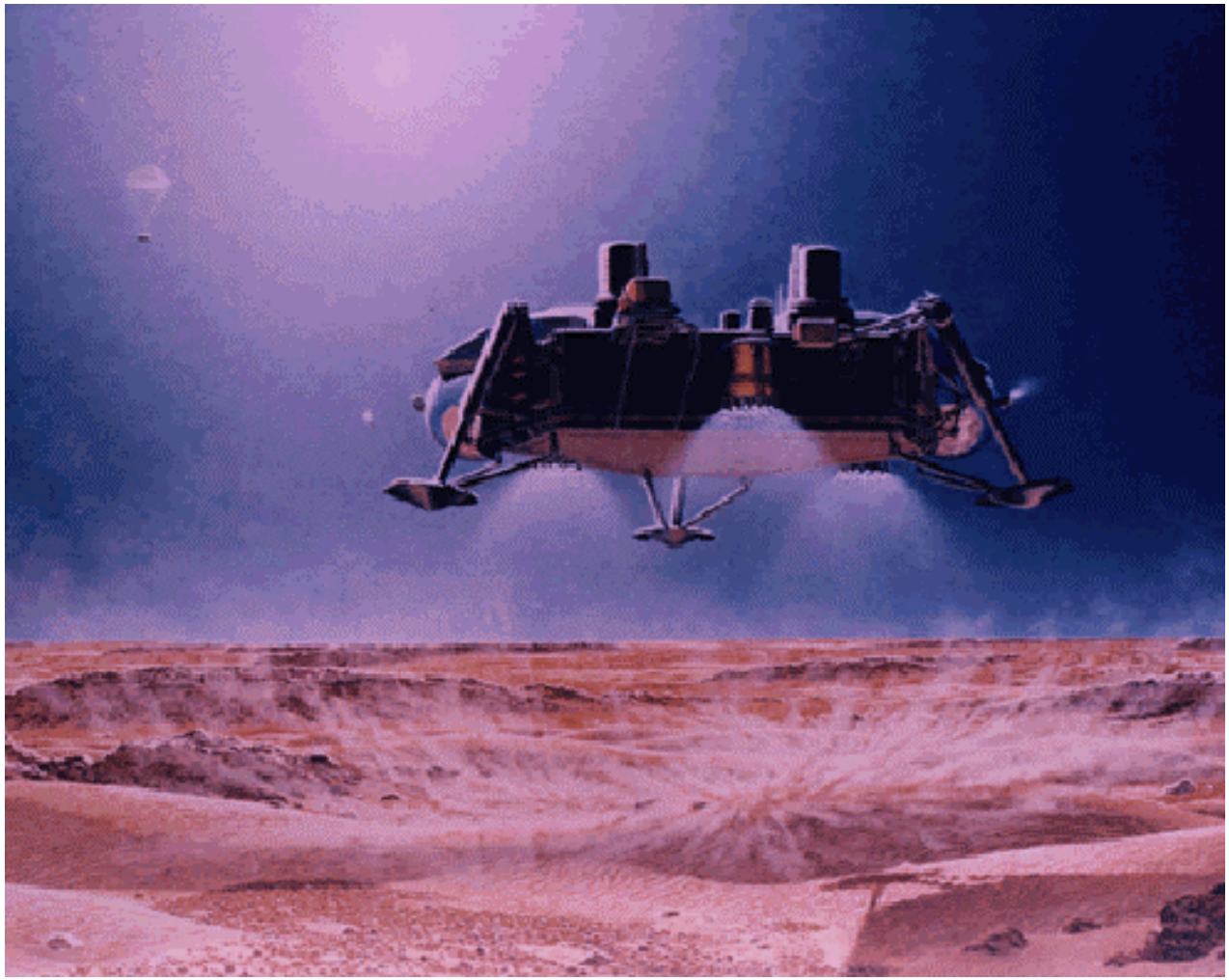
Concept of Viking Lander Powered Descent



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Mars Surface Operation

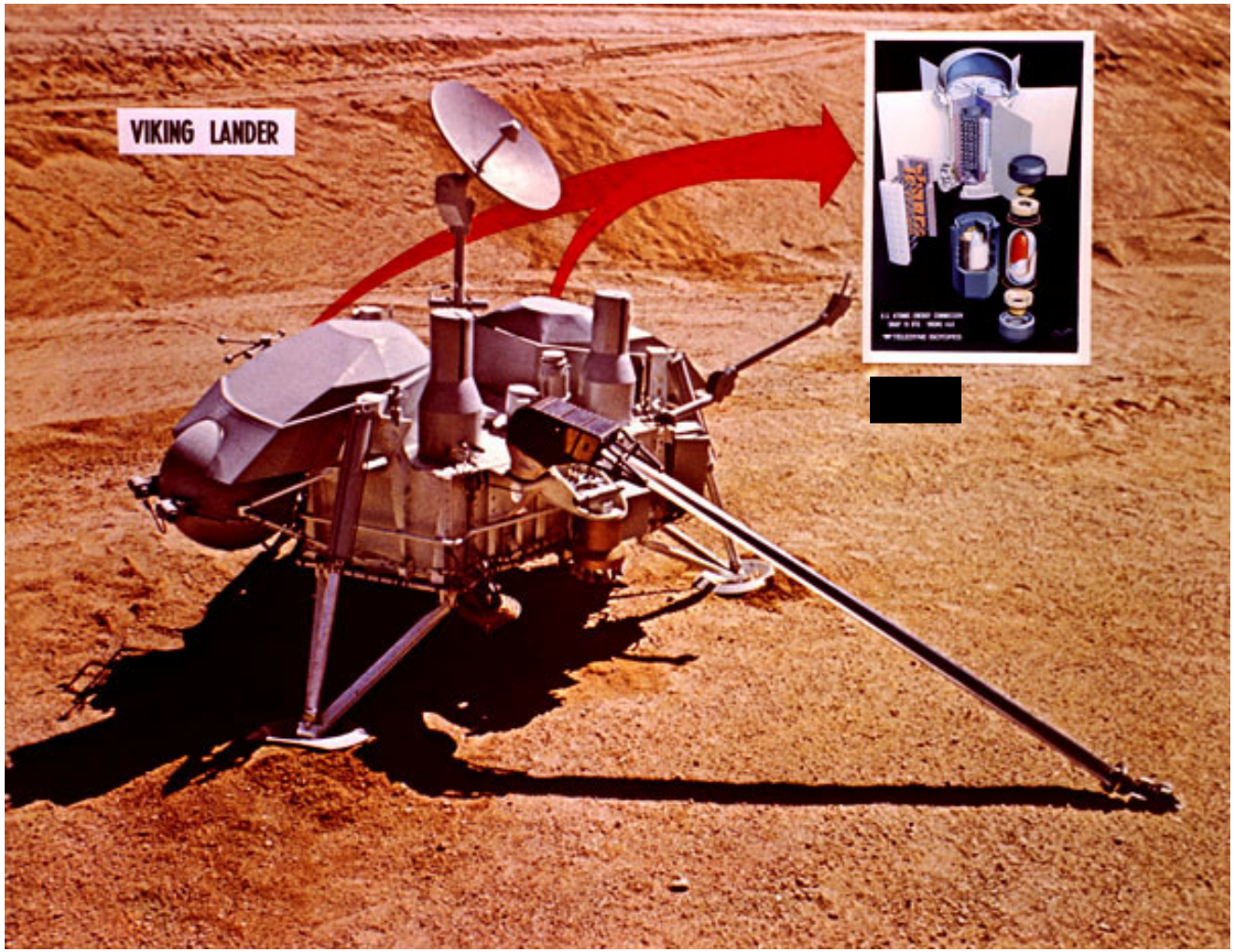
- After landing, the RTGs provided 70W minimum power at 8.8V for Lander operation.

- The Lander was exposed to the Martian 24.5-hour diurnal cycle with “hot day” temperatures ranging between -125ºF and +90ºF, and “cold day” values between -185ºF and -60ºF.

- Reject heat from the RTGs was used for thermal control of the Lander. A thermal switch under each RTG provided a heat conduction path from the RTGs into the Lander. Freon reservoirs sensed the Lander internal temperatures and opened or closed the switches to maintain the Lander within temperature limits.

- A wind cover was provided over each RTG to assure that the RTG housing temperature remained high enough for sufficient heat conduction into the Lander in the event of high velocity Martian winds.

Model of Viking Lander on Mars



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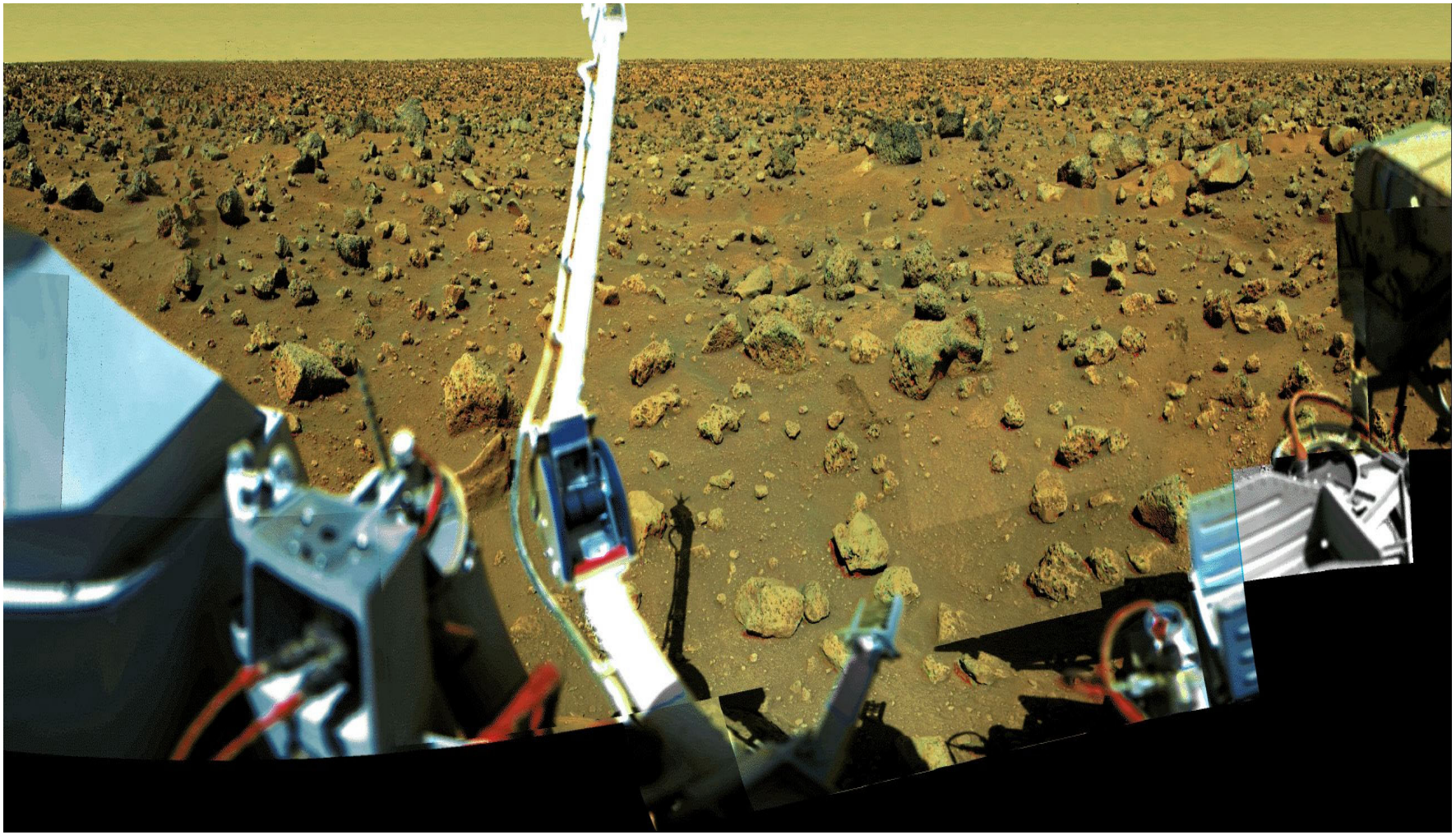
Panoramic View of Martian Horizon from Lander



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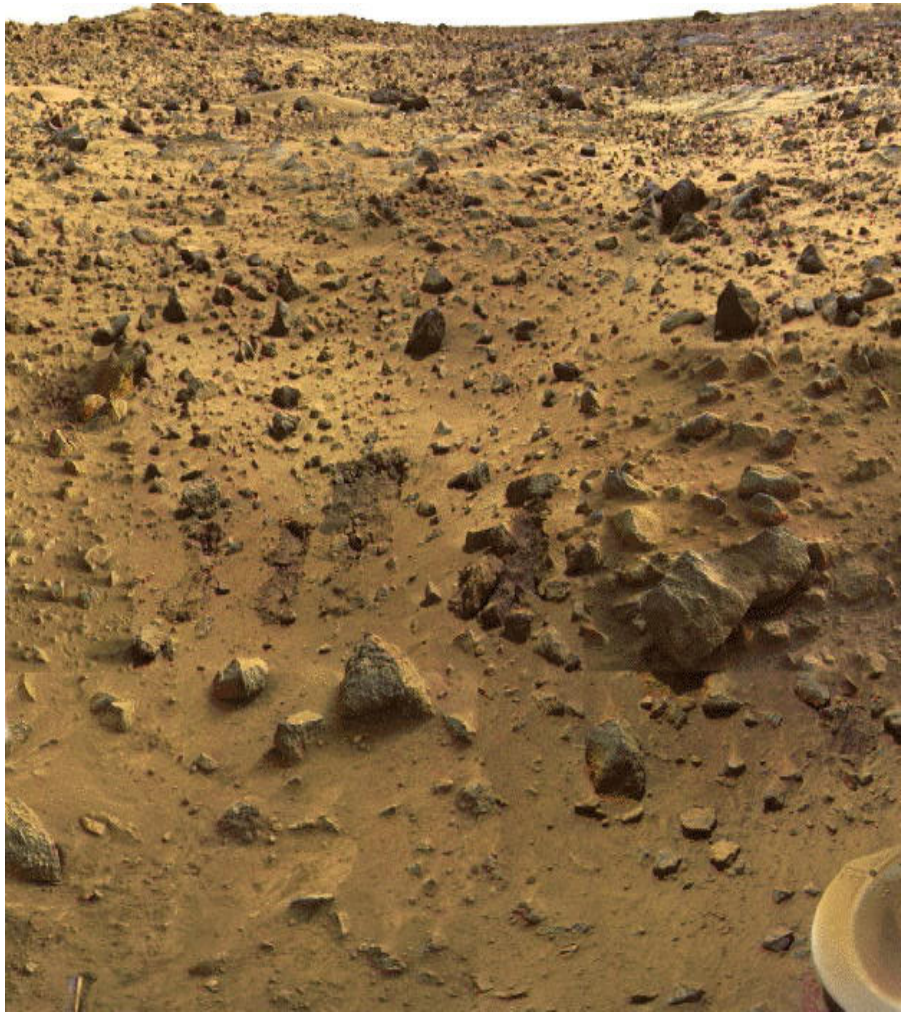
Pictures of the Martian Landscape



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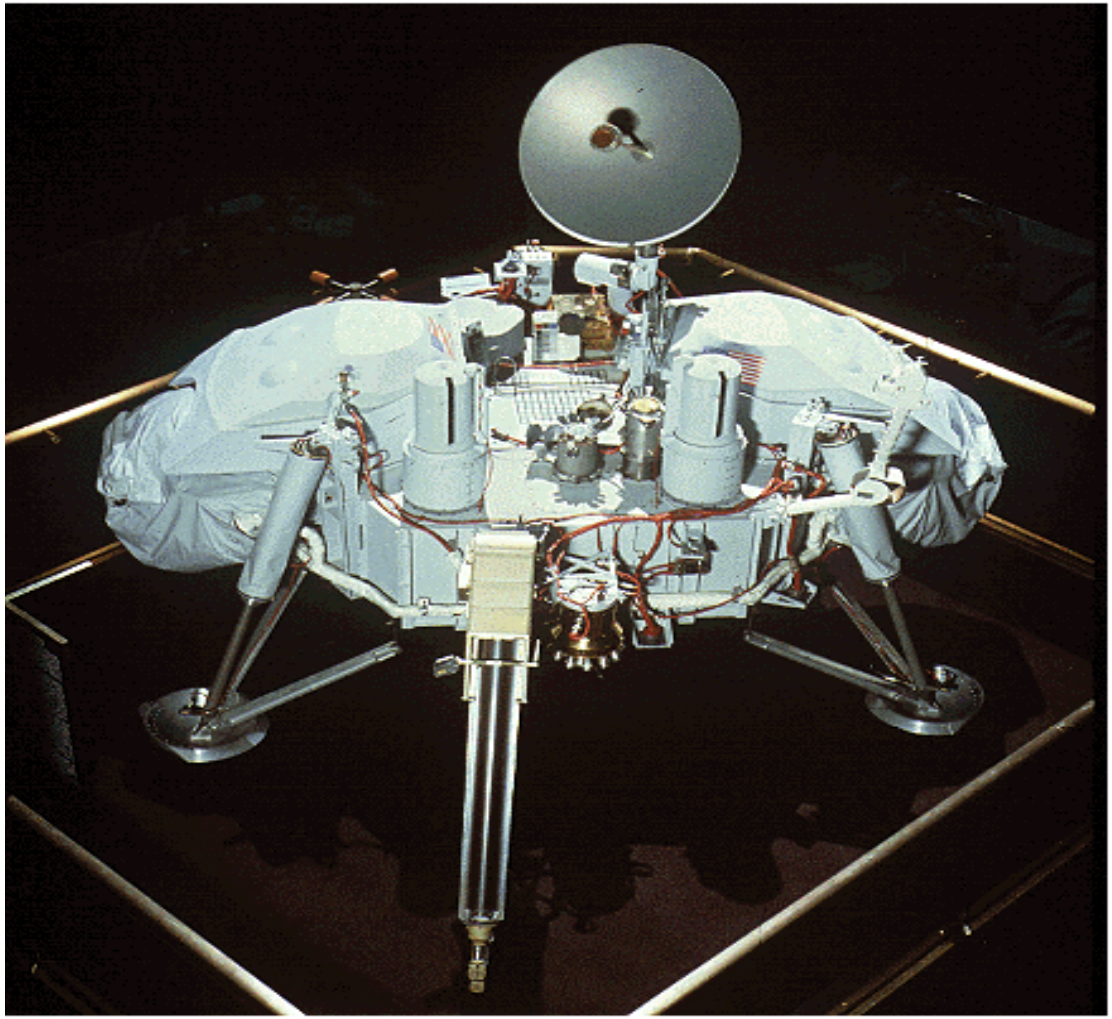
Viking Lander Replica at Smithsonian Institute



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Thermoelectric Analysis and Design

- TES routinely uses the analytical tools necessary to design T/E solutions for RTG applications-both Government-owned and TESI proprietary codes
- Considerations for Thermoelectric Converter design
  - User requirements (voltage, power, redundancy, etc)
  - T/E properties versus temperature
  - Maximum material operating temperatures
  - Mission environmental profile
  - Available isotopic heat source options
- TESI codes account for all TE effects
  - Seebeck, Peltier, Thompson.
  - Non-linearity of alpha (Seebeck), rho (resistivity), and k (thermal conductivity) as functions of temperature.

T/E Materials Options

- N type materials
  - Bismuth Telluride (< 600 F)
    - **Bridgeman grown**
    - **Hot pressed**
    - Cold pressed and sintered
  - Lead Telluride (<1100 F)
    - **Cold pressed and sintered**
    - Cast
  - Silicon Germanium (<2000 F)
    - Hot pressed

NOTE: **Bold** indicates most commonly used materials at TES

T/E Materials Options

- P type materials
  - Bismuth Telluride (< 600 F)
    - **Bridgeman grown**
    - **Hot pressed**
    - Cold pressed and sintered
  - TAGS (<1000 F)
    - **Cast**
    - Hot pressed
  - Tin Telluride (<1100 F)
    - **Cast in place**
  - Lead Tin Telluride (<1100 F)
    - **Cold pressed and sintered**
  - Silicon Germanium (<2000 F)
    - Hot pressed

NOTE: **Bold** indicates most commonly used materials at TES

T/E Couple and Module Choices

- Couples
  - Sizes produced range from 0.067 inch square to 0.6 inch diameter cross sections and 0.125 inch to 0.6 inch long legs
- Modules
  - Close packed array
  - Mini-couple close packed array
  - Assembly of discrete couples with interconnecting straps and fibrous insulation
- T/E converter (array of modules)

Figure of Merit P-leg Material

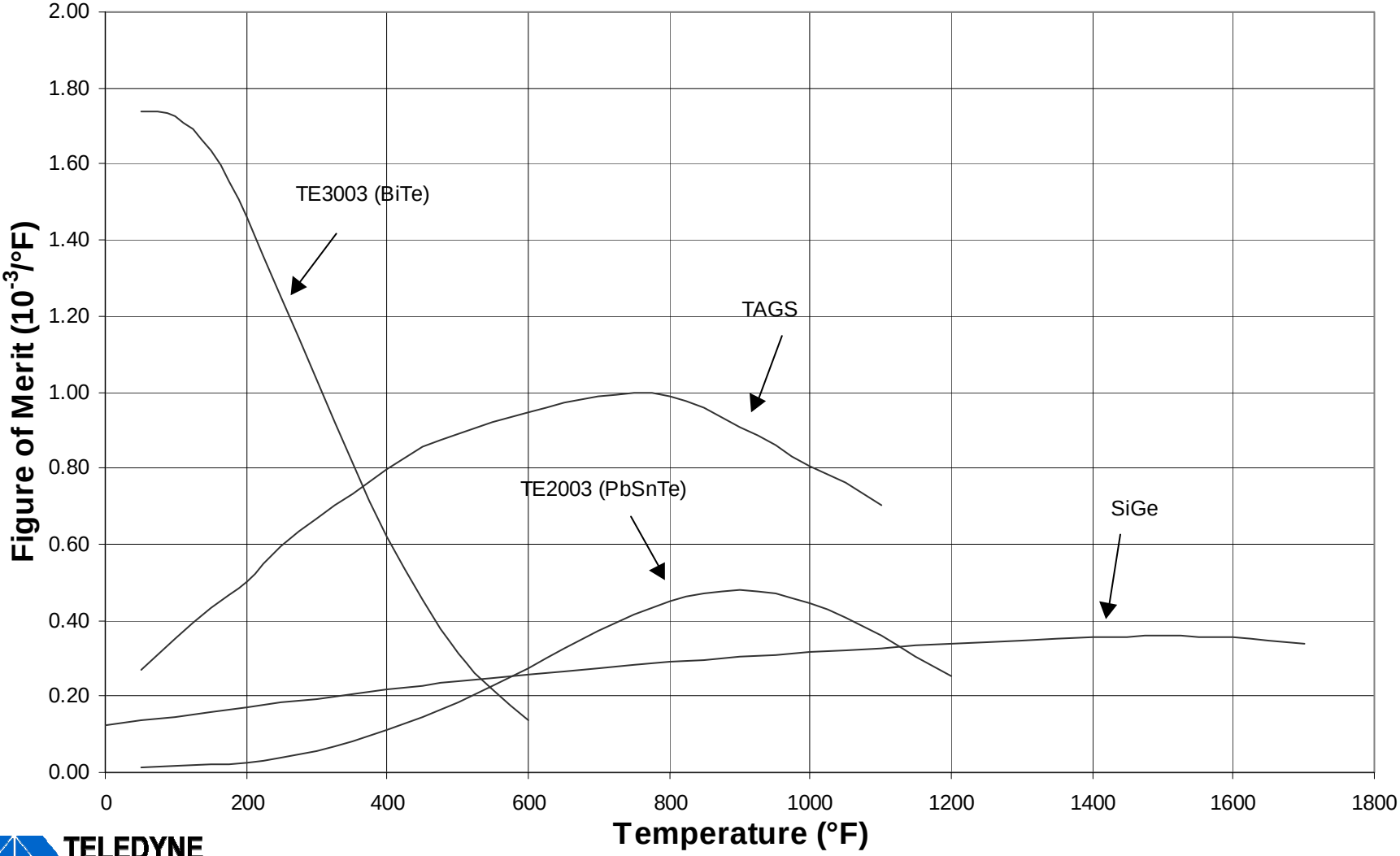

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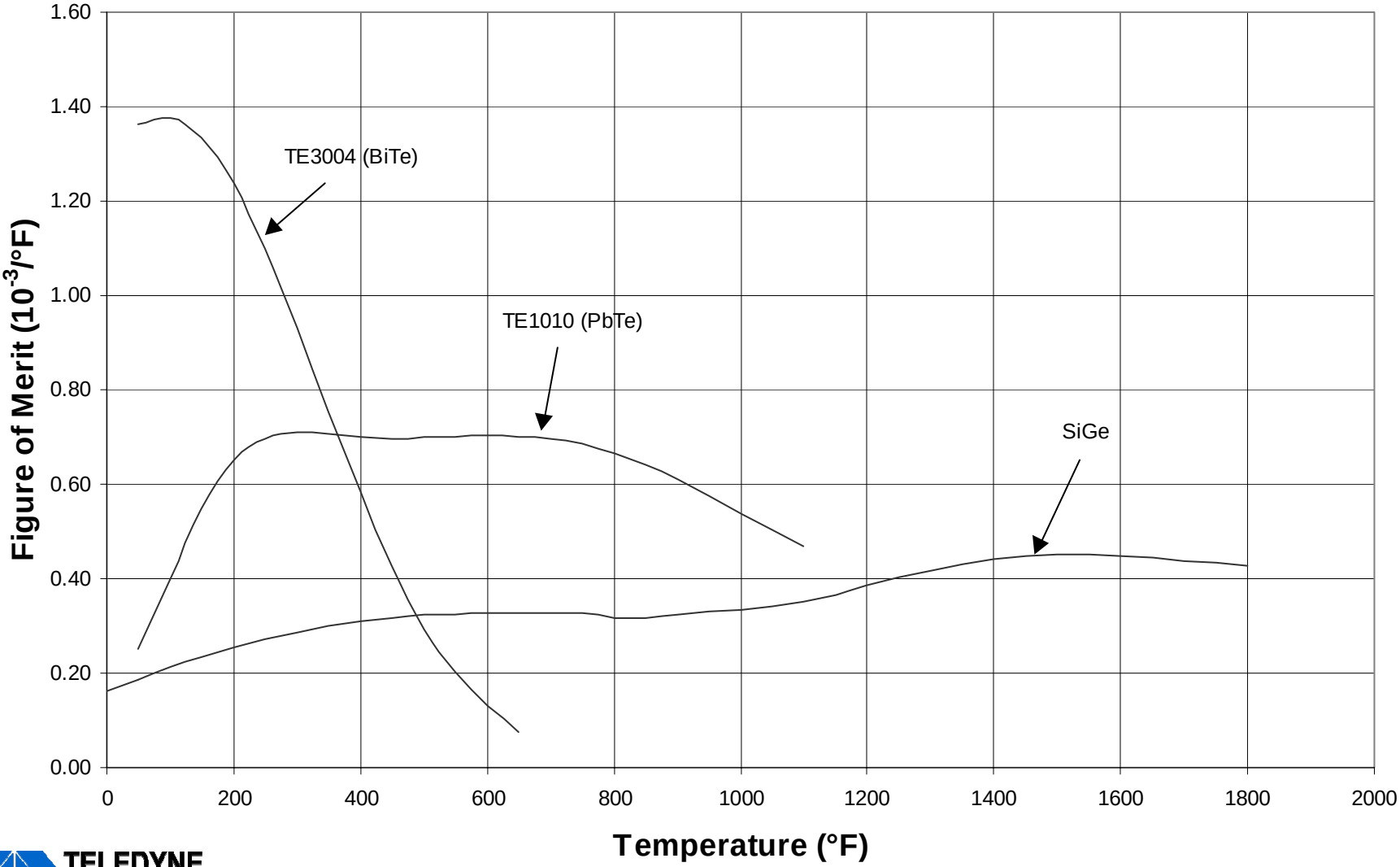
Figure of Merit N-leg Material



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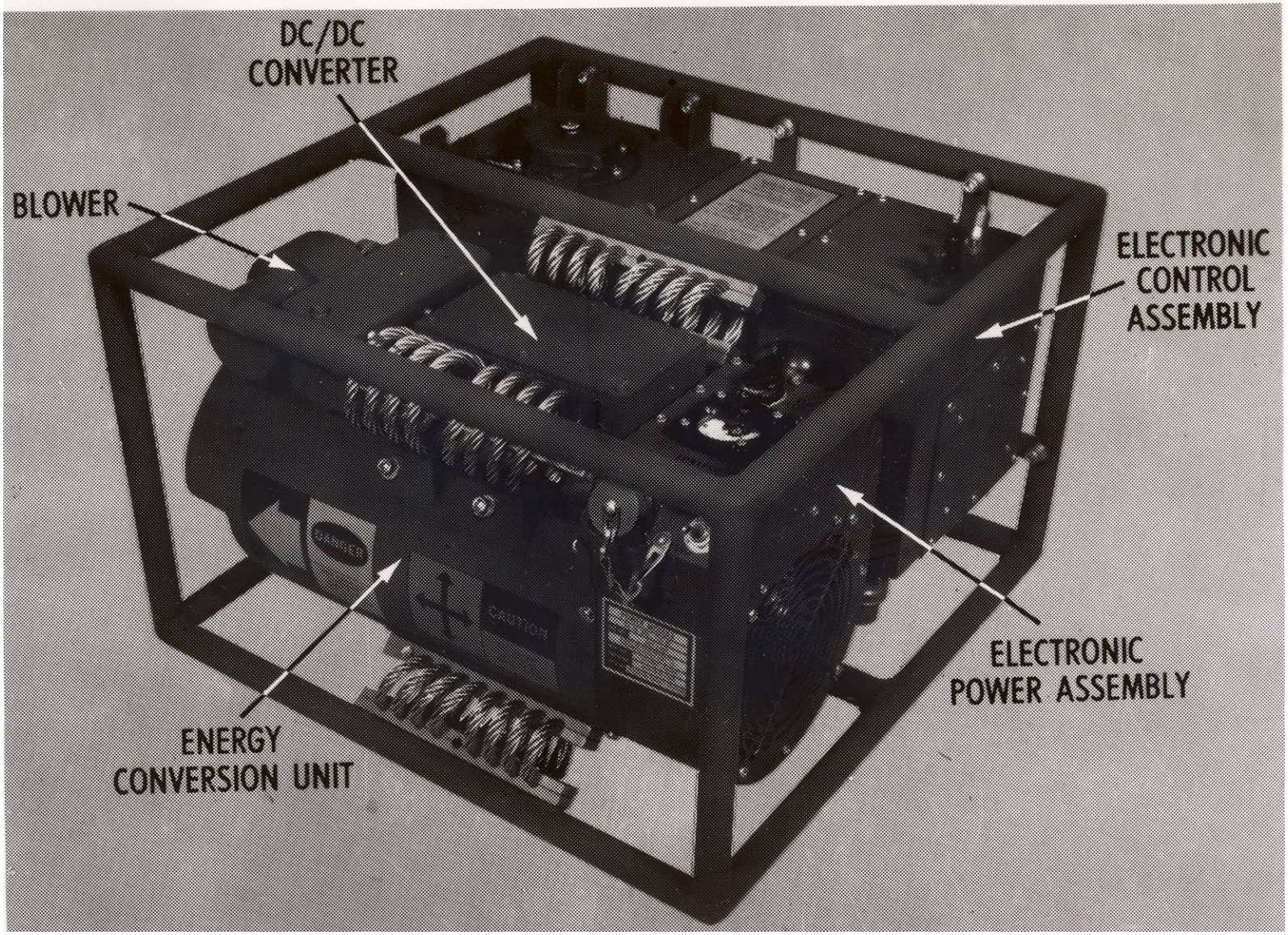
0.1kW THERMOELECTRIC POWER GENERATOR



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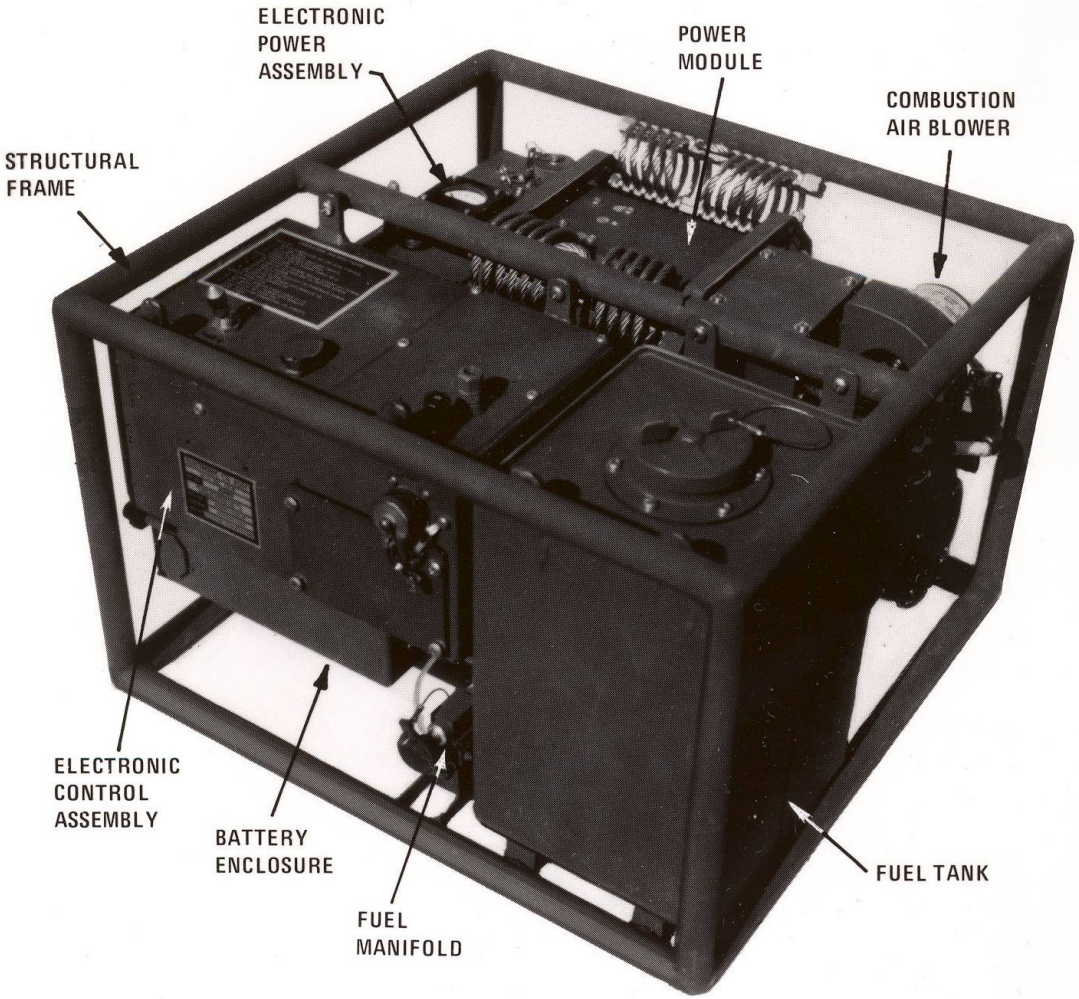

ARMY 120-WATT LIQUID FUELED THERMOELECTRIC GENERATOR

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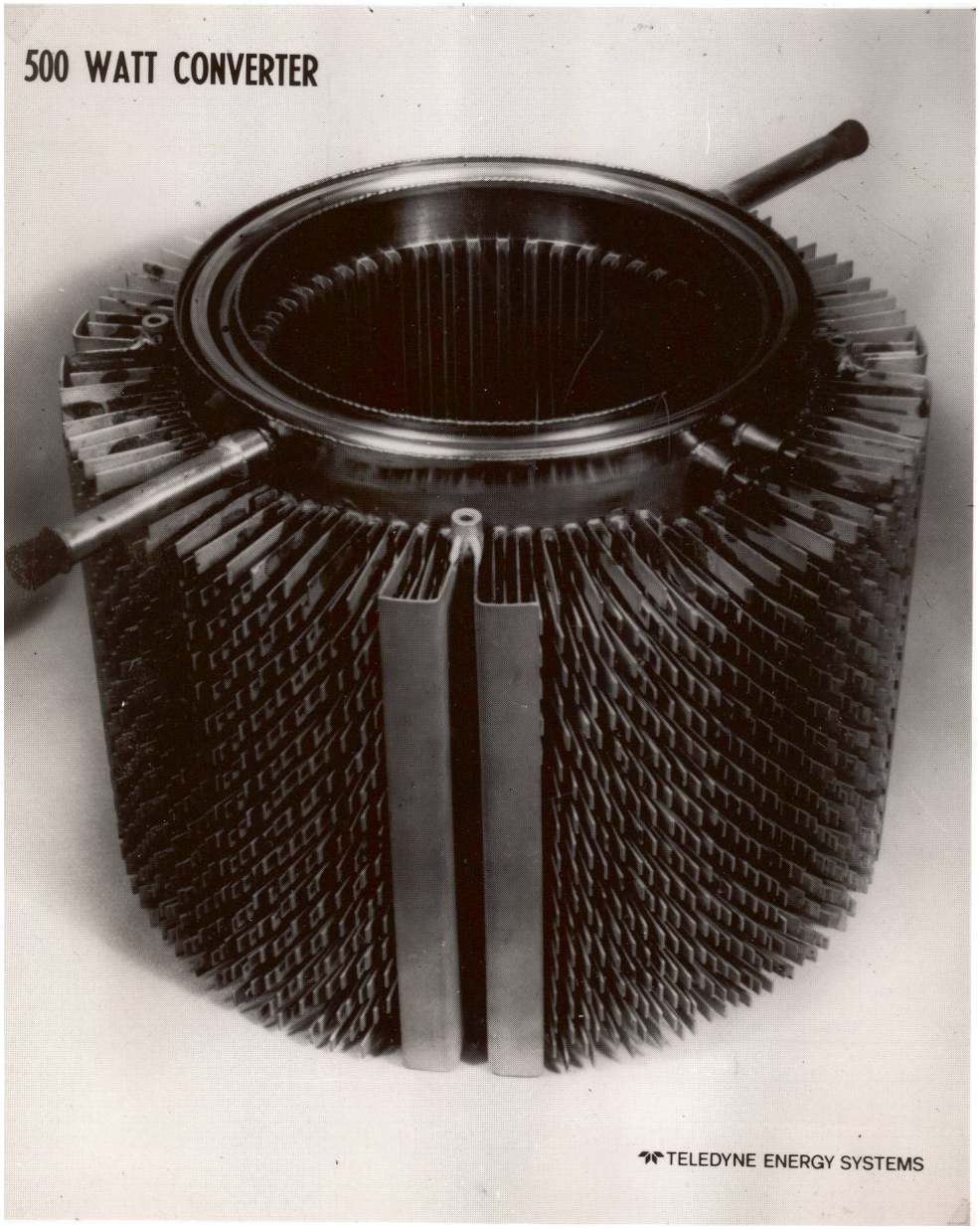

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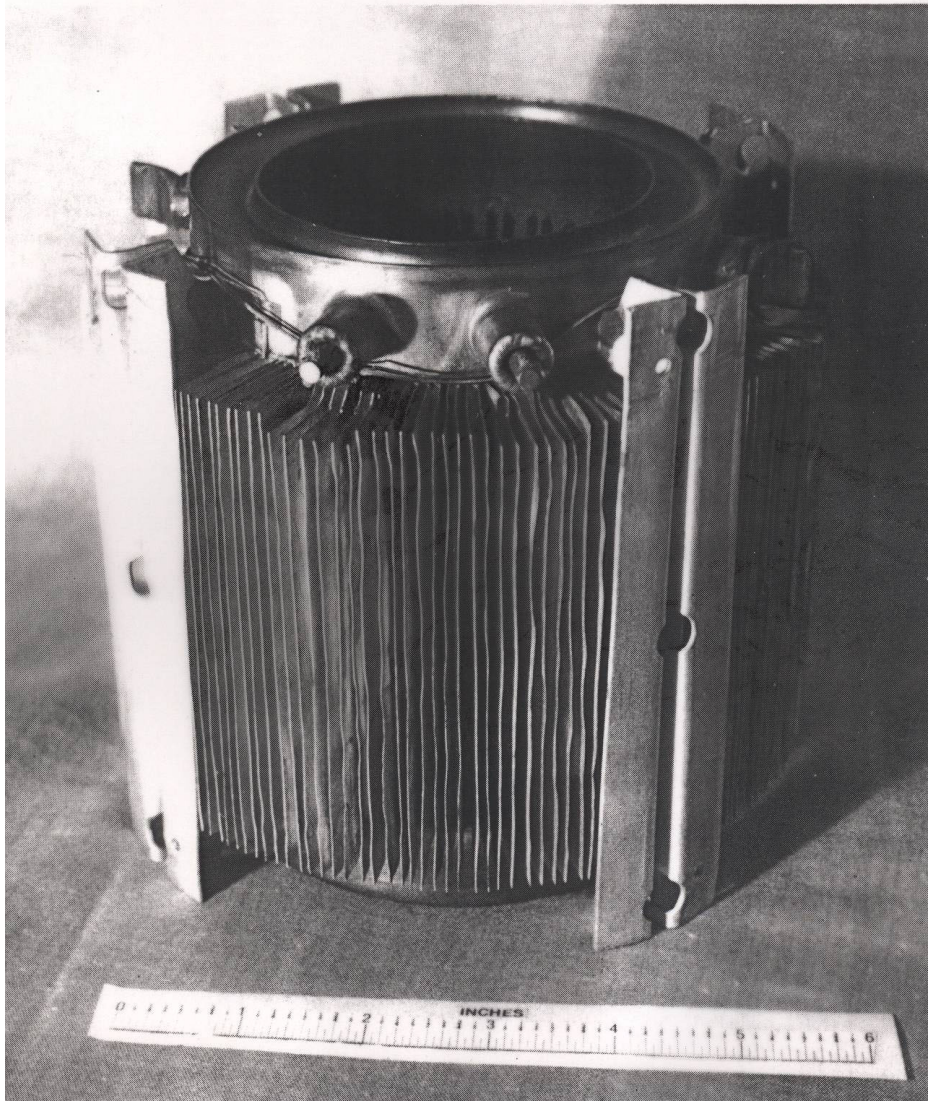
170 WATT AIR COOLED THERMOELECTRIC CONVERTER



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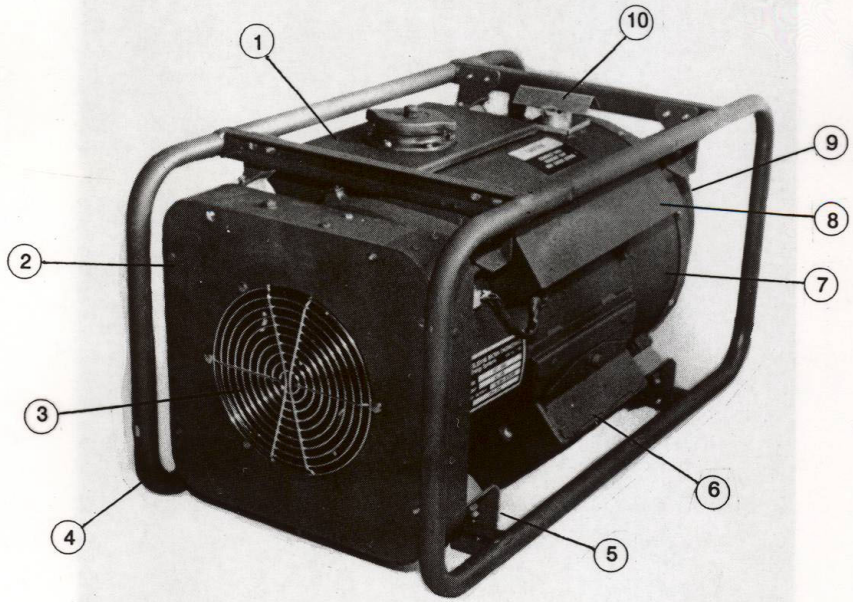
10,000 BTU/HR SELF-POWERED HEAT SOURCE
MODEL HDT10-1



LEGEND

1. SADDLE TYPE FUEL TANK
2. HOUSING FOR FAN, FUEL PUMP, FILTER AND ACCUMULATOR
3. AIR INLET
4. PROTECTIVE FRAME
5. SHOCK ISOLATOR
6. BATTERY HOUSING
7. MAIN HOUSING. CONTAINING BURNER, THERMOELECTRIC MODULE AND HEAT EXCHANGERS
8. ELECTRICAL COMPONENTS
9. 6 INCH DIAMETER HEATED AIR OUTLET
10. COMBUSTION EXHAUST

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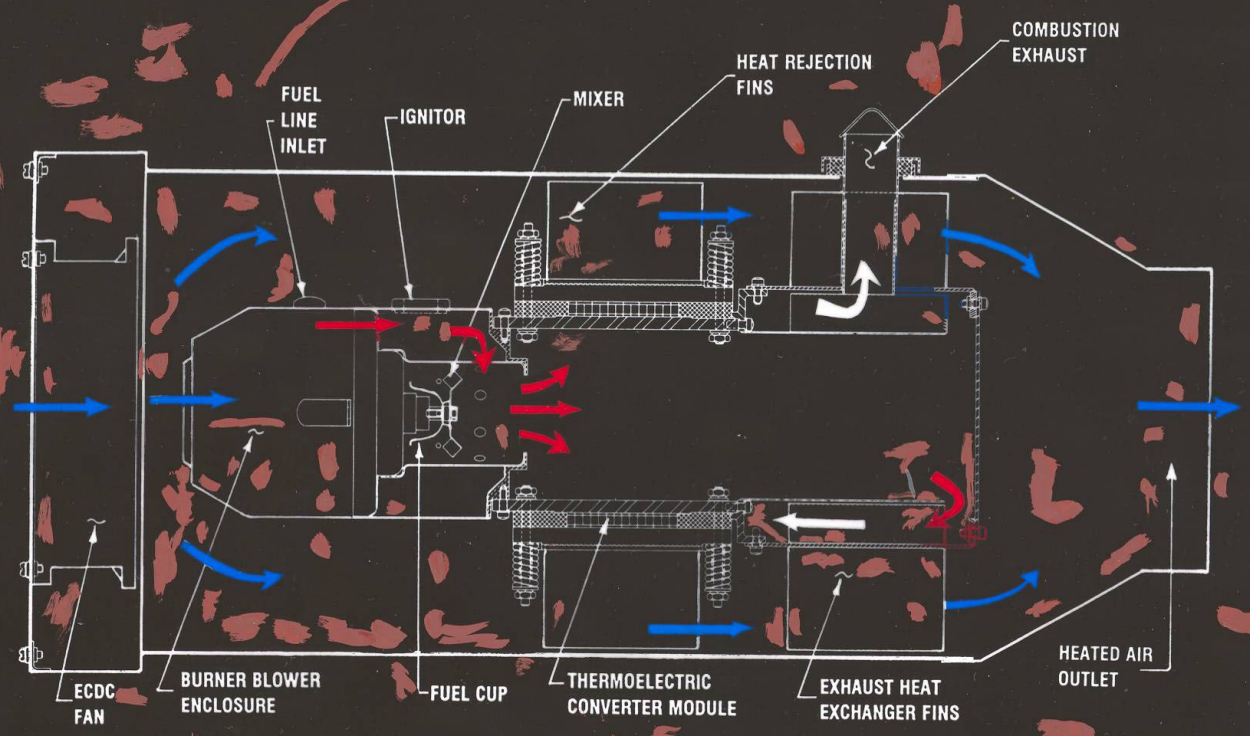
HEATER OPERATION



LEGEND:

HTD CLEAN AIRFLOW

COMBUSTION FLOW PATH

TELEDYNE BROWN ENGINEERING
Energy Systems

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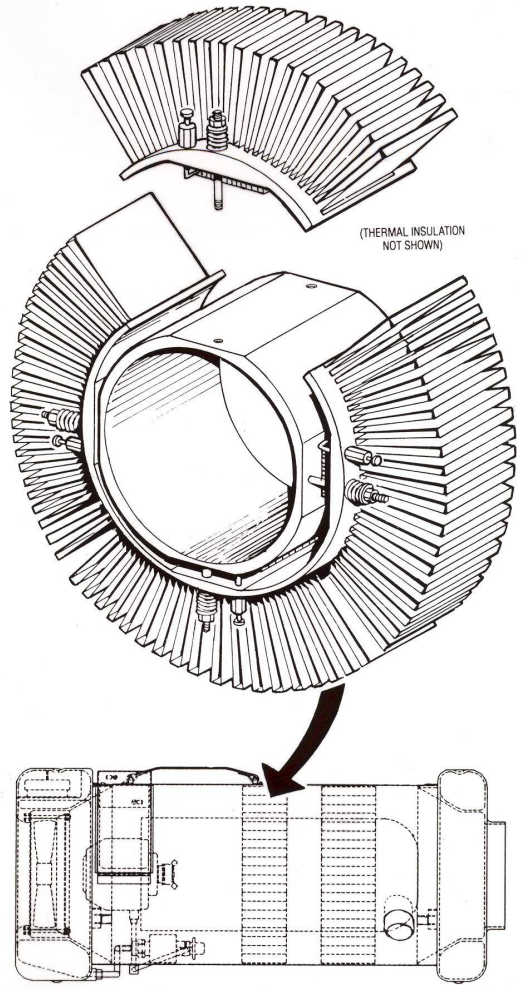
THERMOELECTRIC MODULE ASSEMBLY



TELEDYNE ENERGY SYSTEMS

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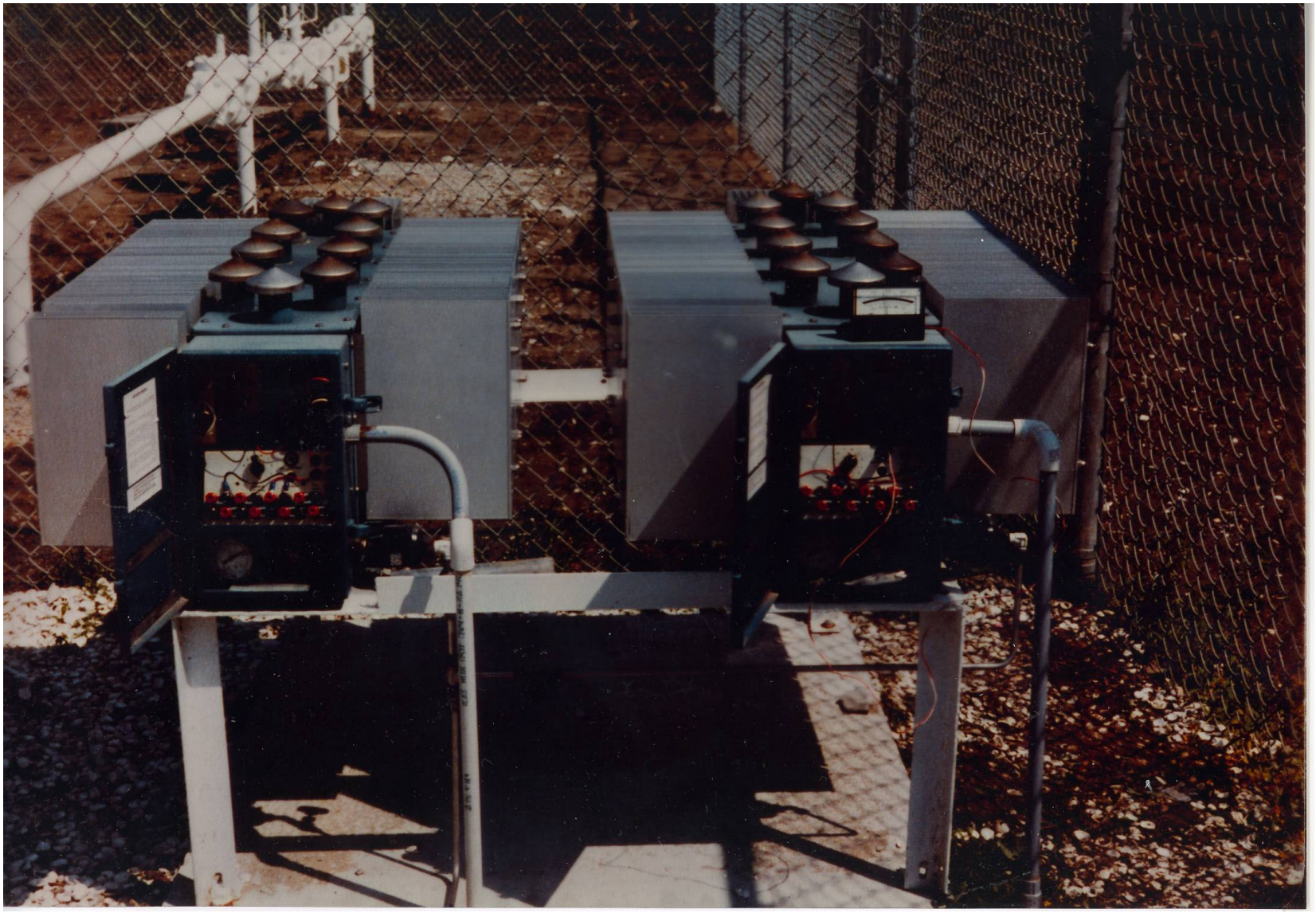

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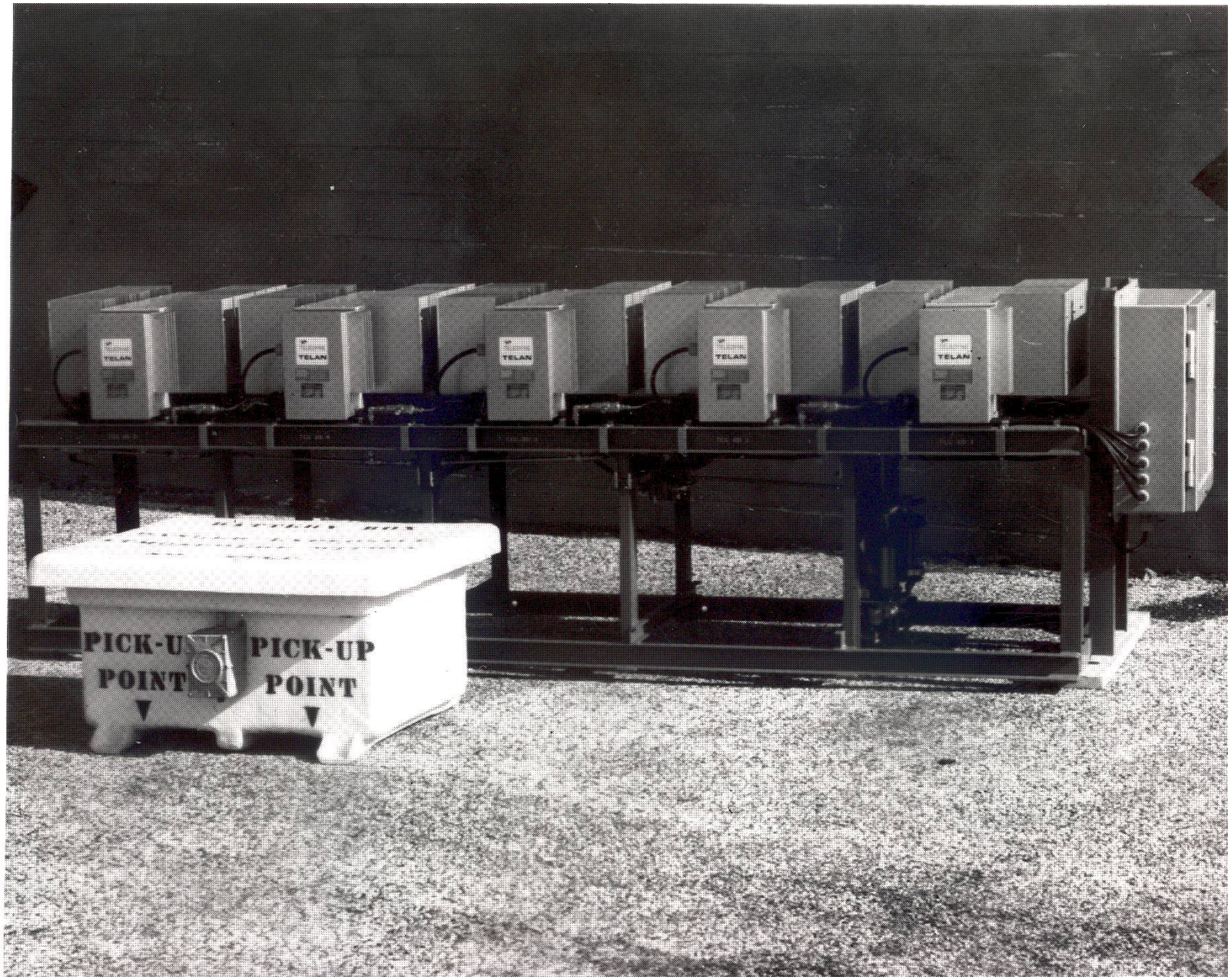

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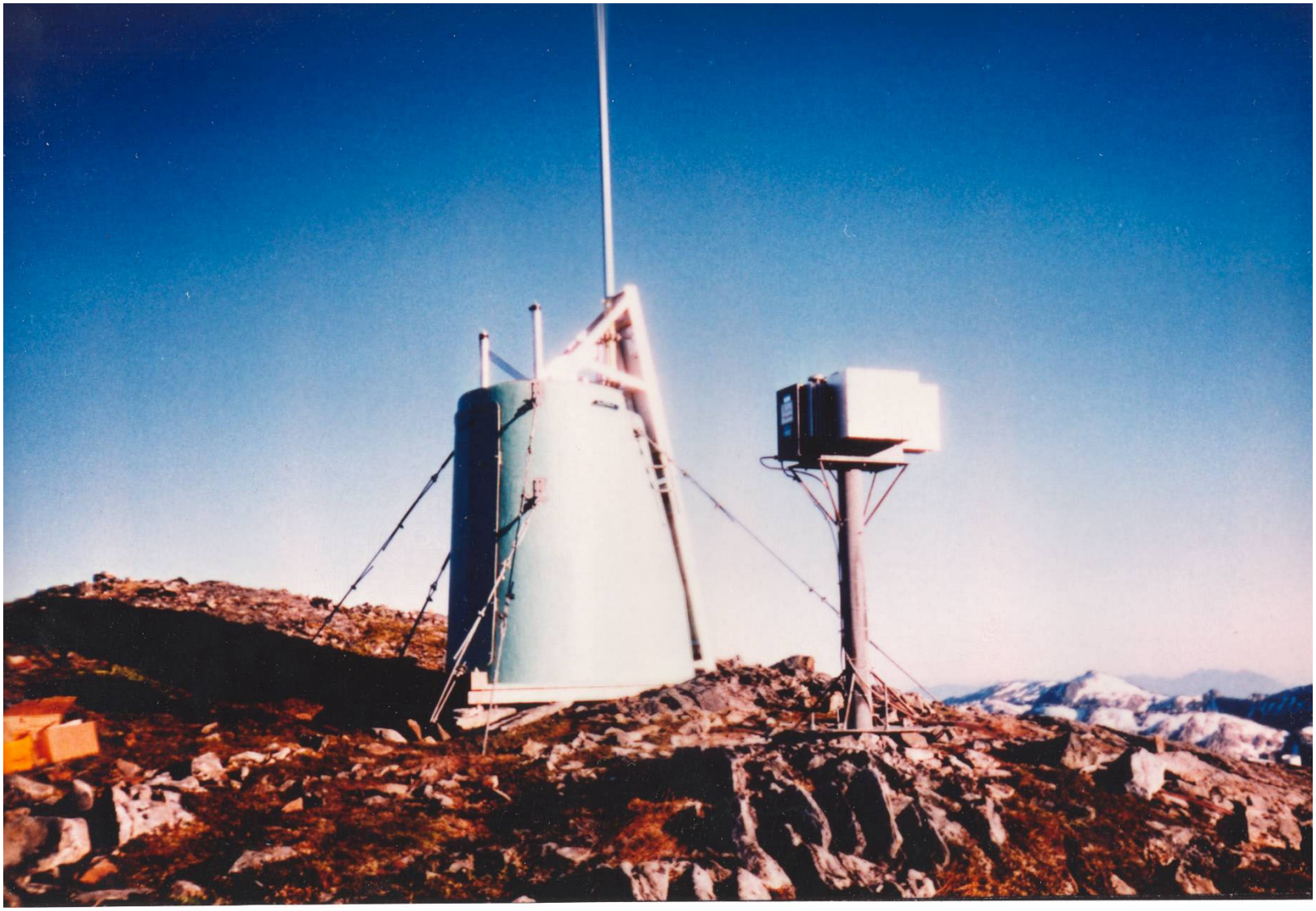

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TELAN 3W

Thermoelectric Generator

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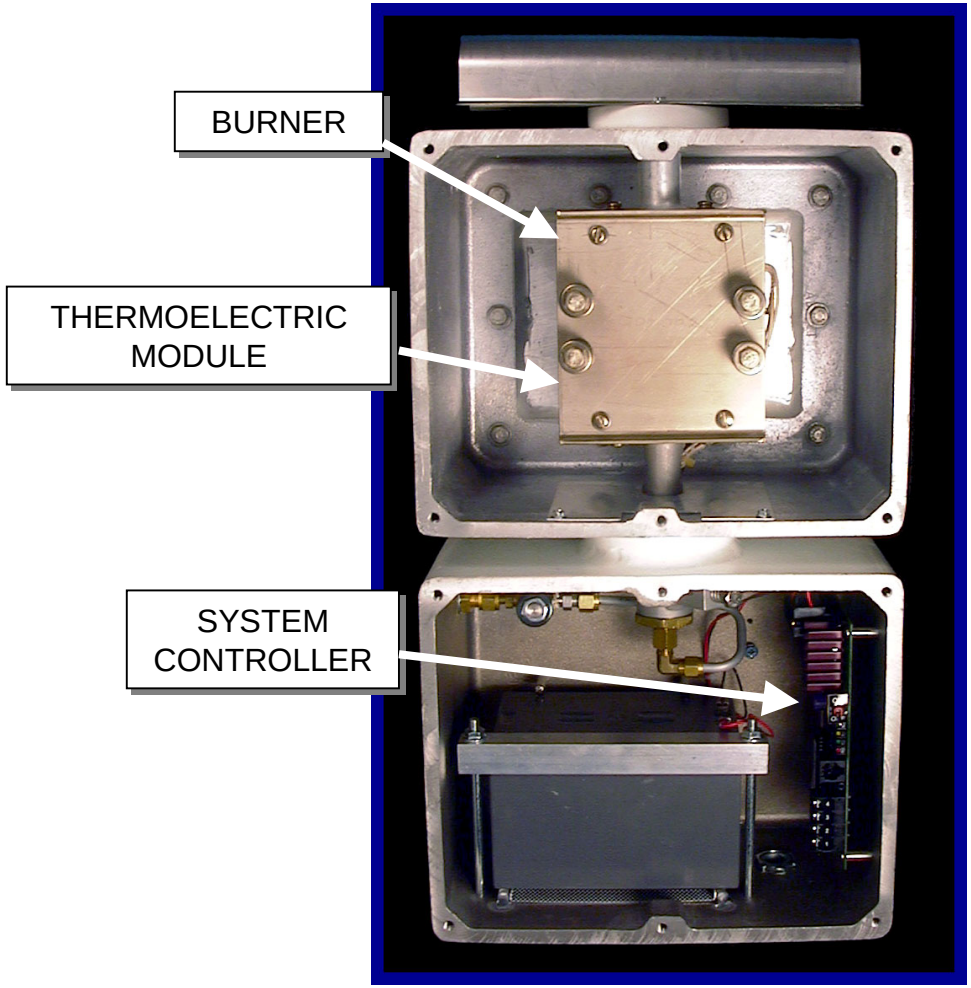
TELAN 3W

THERMOELECTRIC GENERATOR



Front View (Covers Off)

TELEDYNE
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- ***Specifications***
  - **20 year design life**
  - **At least 2 watts power after 10 years**
  - **12 volts DC (nom.)**
  - **30 lbs.**
  - **-40°F to 160°F operating range,**
  - **Outdoor applications**
  - **1/4 in. female NPT fittings for natural gas**
  - **14 AWG power terminals**

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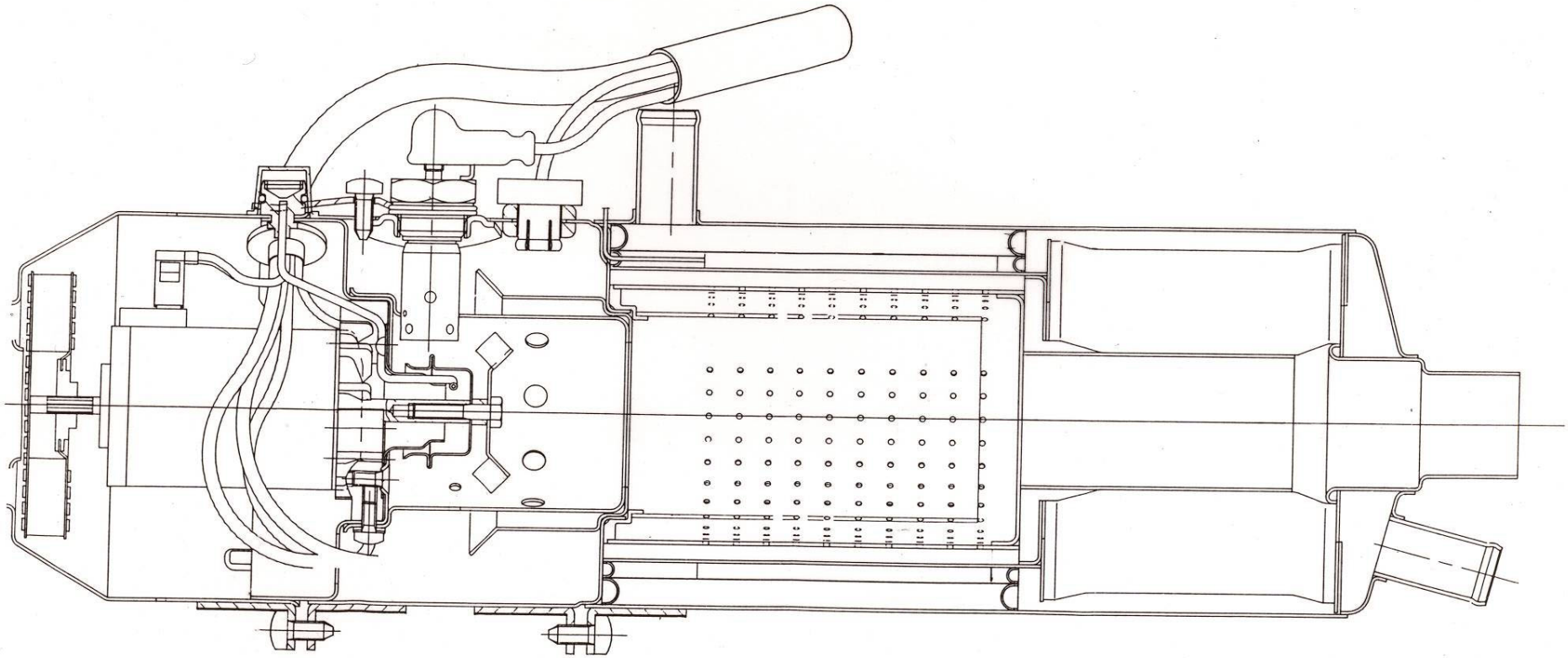
TELAN 3W

- *Features*
  - Approved for NEC Class I, Divisions 2 areas
  - Microprocessor controlled start-up and operation - just flip a switch
  - Flameless - clean catalytic burning
  - On board battery handles cyclical loads greater than 3 watts

TELAN 3W

- *Features*
  - RS 232 data port
  - Fault notification
  - Low / no maintenance
  - 20 micron external fuel filter
  - Weathertight enclosure
  - Brackets for pole or wall mount
  - 250 psig pressure regulator
    (25 psig min. recommended pressure)

SELF-POWERED VEHICLE HEATER CONCEPT



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Recovery of Waste Heat

- Oak Ridge National Lab sponsored TES to analyze the technical and economic feasibilities of using TE to increase efficiency of over-the-road diesel trucks
- Idea was to obtain power from exhaust heat and convert to dc to augment.
- TES looked at a 1kW TE converter and optimized the design including heat transfer into and out of the TEC.
- Technically feasible
- Economically marginal.

Multi-Mission Radioisotope Thermoelectric Generator Program Overview

Richard Rovang – Boeing, Rocketdyne Division
Robert Wiley – DOE, Space and Defense Power Systems, HQ
Dave Moul – Teledyne Energy Systems

February 9, 2004

BOEING

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MMRTG Program

- Objective
  - To develop, qualify and field the next generation RTG for NASA with multi-mission capability, i.e., operation in deep space or on the surface of planetary bodies such as Mars
- Status
  - System integration contract signed on June 24 with Boeing Company, Rocketdyne Propulsion and Power Division
    - Major subcontract to Teledyne for converter design and fabrication
  - System level multi-mission design requirements identified
  - Trade studies and design progress
  - Ongoing interface with Mars Science Laboratory (MSL) planning team at JPL

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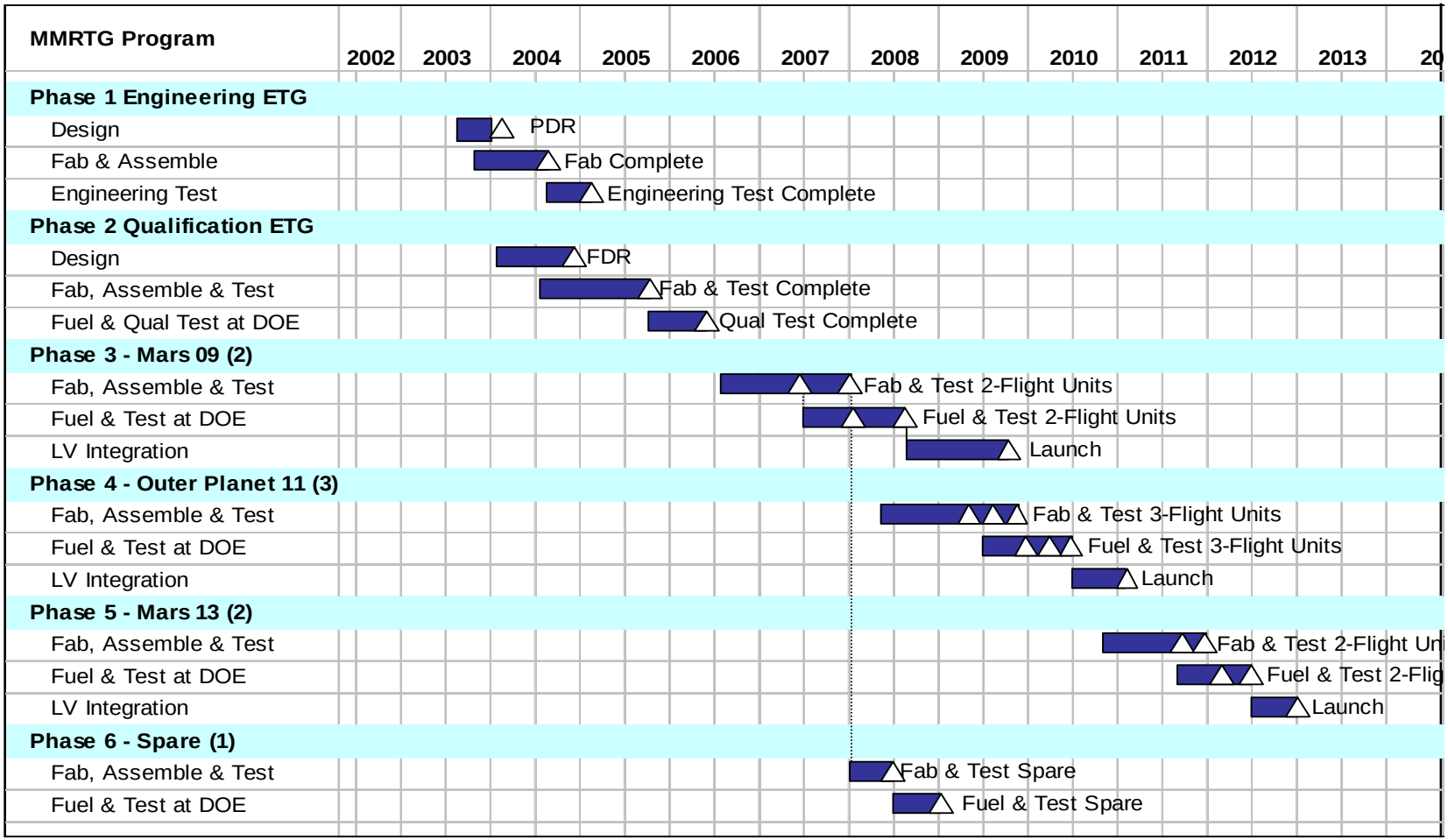
Program Schedule – All Phases



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TE ENERGY SYSTEMS, INC.
A Teledyne Technologies Company

Requirements Summary

- Power >110 watts @ BOM
  - 28 volts
  - Thermal environment, 60K (deep space) to 270K (Mars hot)
- 14 years design life
  - Launch loads include Atlas 5 and Delta IV
- 8 GPHS, (step 2, enhanced)
  - 600 g Pu_{238} each
  - 244 W minimum; 252 W maximum
  - Free and clear release
- Minimize mass
  - Goal = 38 kg
  - NTE = 45 kg
- Minimize volume
  - NTE length = 69 cm
  - NTE diameter (with fins) = 65 cm
- Minimize degradation
  - Goal <22% over 14 years
- Nuclear Safety
  - Comply with Presidential Directive/NSC 25
  - Comply with National Environmental Policy Act (NEPA)

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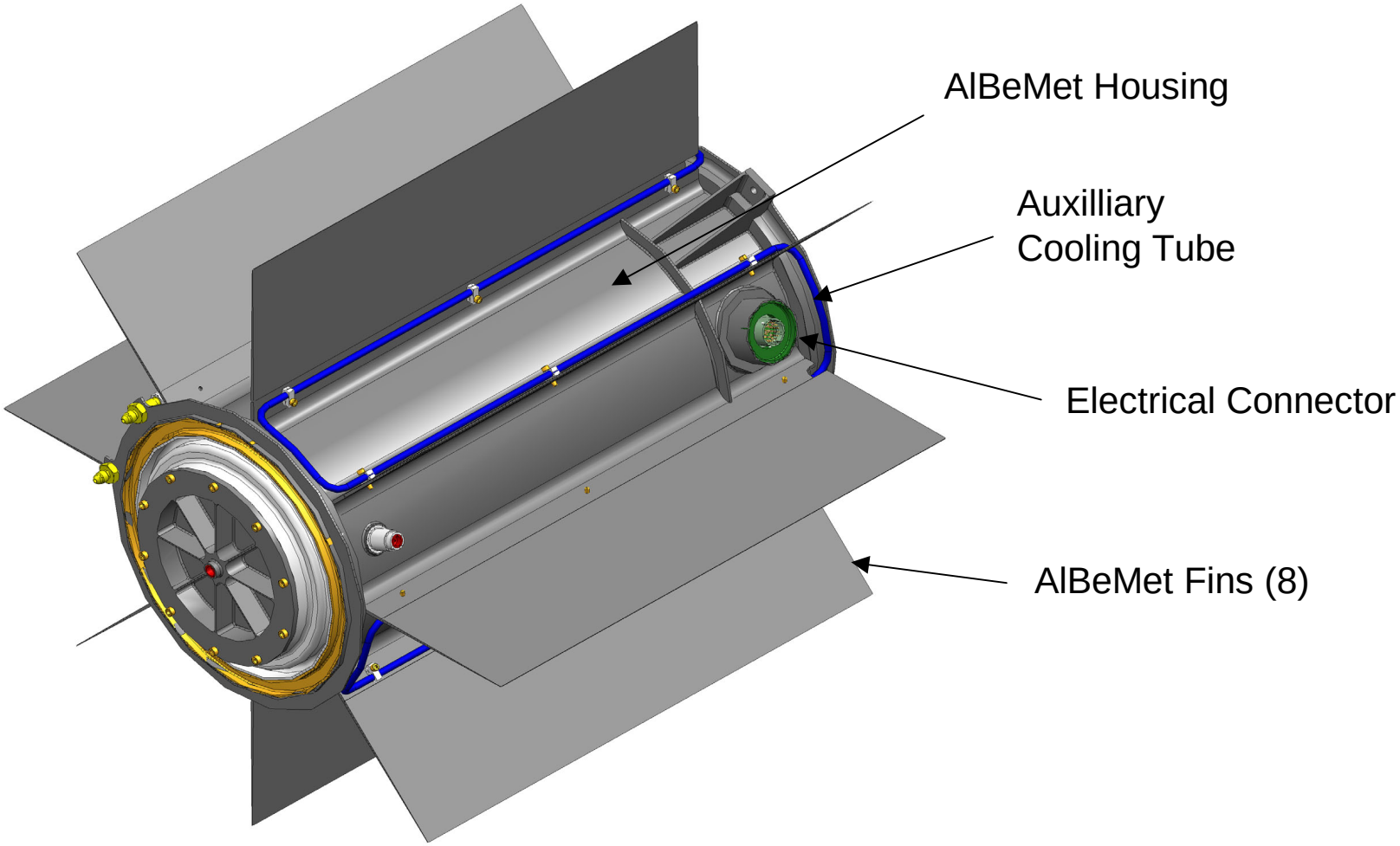
TELEDYNE ENERGY SYSTEMS, INC.
A Teledyne Technologies Company

MMRTG Converter, Isometric View



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ENERGY SYSTEMS, INC.
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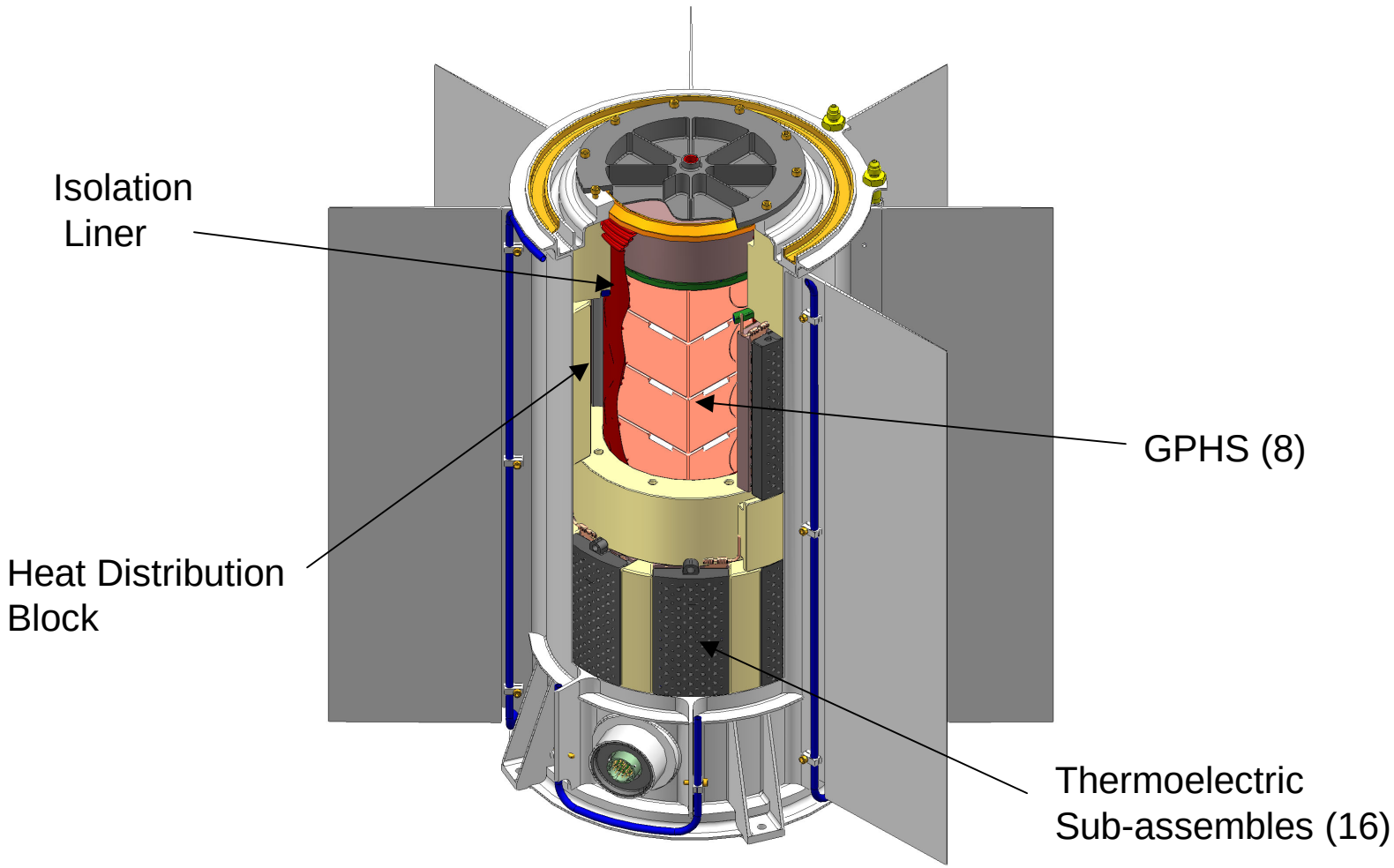
MMRTG Converter, Cut-away View



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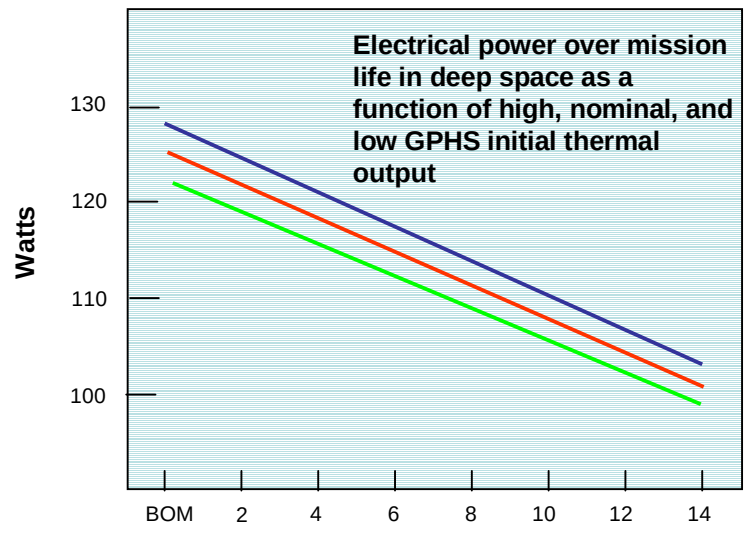
Current MMRTG Performance

	Mars (Hot Condition)		Mars (Cold Condition)		Deep Space	
Q_{in} (Watts)	BOM (Watts)	14 Years (Watts)	BOM (Watts)	14 Years (Watts)	BOM (Watts)	14 Years (Watts)
Nominal	123.5	98.7	125.2	100.8	125.3	101.0

Physical Characteristics
- Length: 64.7 cm
- Diameter: 60.2 cm (with fins)
- Mass: 39 kg



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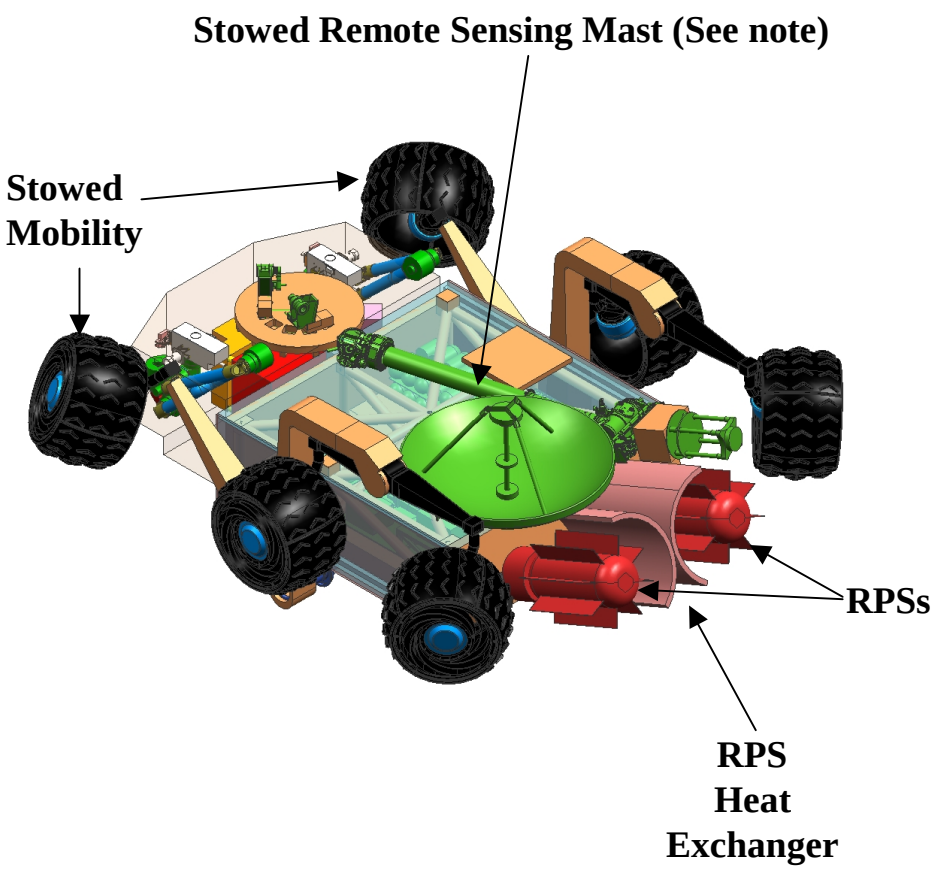
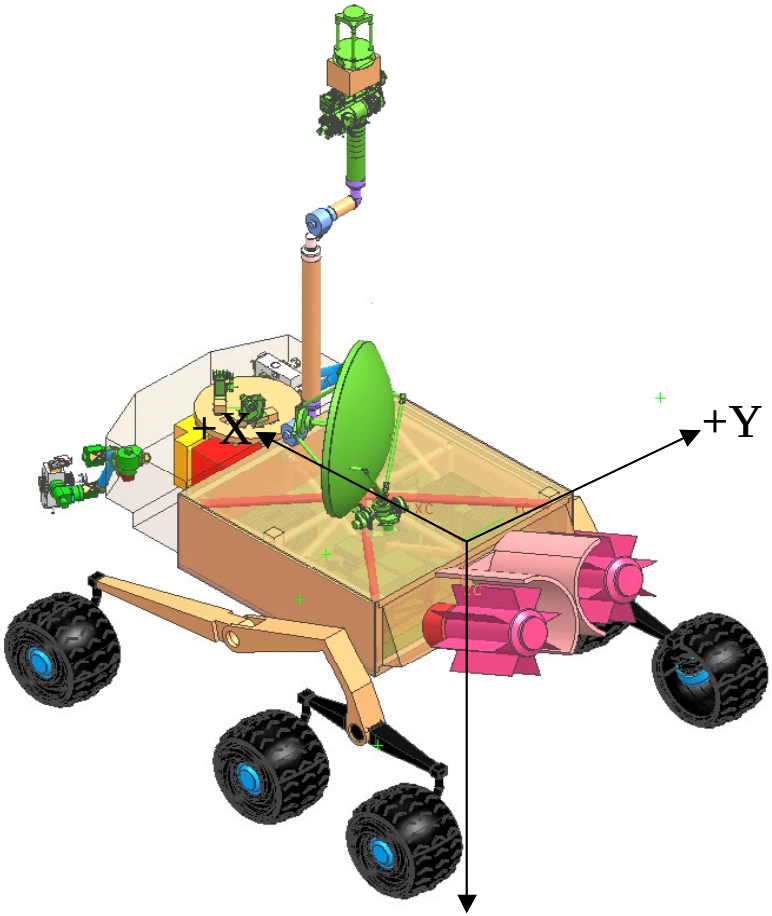
Potential MMRTG Mission Integration

Stowed Configuration



Deployed Configuration



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ADVANCED SUPERLATTICE BiTe PbTe/TAGS/PbSnTe MILLIWATT RADIOISOTOPE POWER SYSTEMS

Radioisotope Power Conversion Technology NRA
Project Prometheus

PI: Ben Heshmatpour
Phone: 410-891-2291 FAX: 410-771-8619
Company: Teledyne Energy Systems, Inc. Email: ben.heshmatpour@teledynees.com

TELEDYNE ENERGY SYSTEMS, INC.
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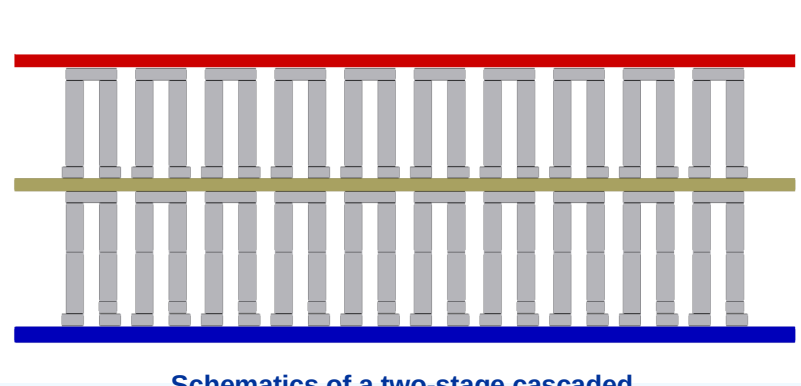
Advanced RPS NRA Selection: Superlattice Power Systems

Tech Area: Milliwatt TE (Research) **Contractor: Teledyne Energy Systems, Inc.**



Schematics of a two-stage cascaded BiTe/PbTe-BiTe/TAGS/PbSnTe-Superlattice BiTe Thermoelectric Module

Goals

- Develop cascaded PbTe/TAGS-superlattice BiTe based module for milliwatt RPS
- Specified performance goals: 8% or higher efficiency with a power output range of 50 to several hundred mW

Objectives/Approach

- Design, develop and produce superlattice BiTe multi-couple devices for high efficiency energy conversion
- Design, develop and produce monolithic PbTe (n-type)/TAGS (p-type) multi-couple devices
- Fabricate cascaded thermoelectric module - PbTe/TAGS hot stage, BiTe cold stage
- Test and optimize the cascaded device for performance

Schedule/Resources

Task/Milestone	Yr. 1	Yr. 2	Yr. 3
Superlattice Fab & Test Cascaded Fab & Test Ph 2 Cascaded Design&Fab Device Test & Eval Optimize Module Designs Ph 3 Cascaded Fab & Test Final Device Fab, Test, and Qual			
Resources	$.38M	$.58M	$.74M

Technical Challenges

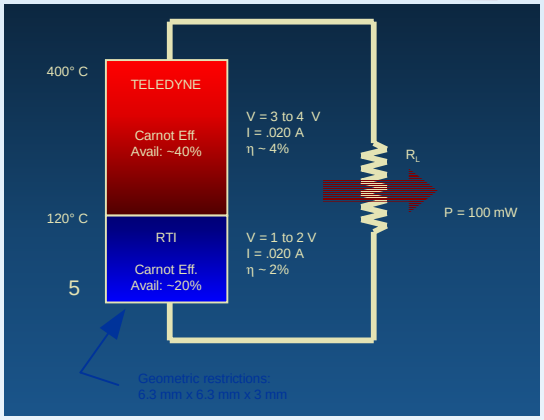
- Development of a high efficiency superlattice device with large TE element L/A ratio
- Development and fabrication of a close packed array, glass bonded, monolithic, miniature PbTe/TAGS device

Participants

- **Teledyne Energy Systems** - PI, Ben Heshmatpour
- **Research Triangle Institute** – CoI, Rama Venkatasubramanian

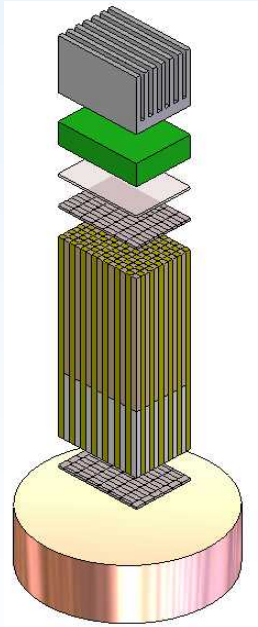
Project Prometheus

Project Overview



Focus of development

- Design a high efficiency (≥ 8%) two stage cascaded thermoelectric device (to TRL level 2-3) which meets the desired performance requirements
  - Superlattice BiTe (n-type and p-type) cold stage multi-couple device
  - Segmented PbTe (n-type)/TAGS (p-type). PbSnTe (p-type) hot stage close-packed array device
  - Two stage cascaded superlattice BiTe-PbTe/TAGS/PbSnTe device
- Develop materials, processes and fabrication methods to produce cold stage, hot stage and cascaded devices

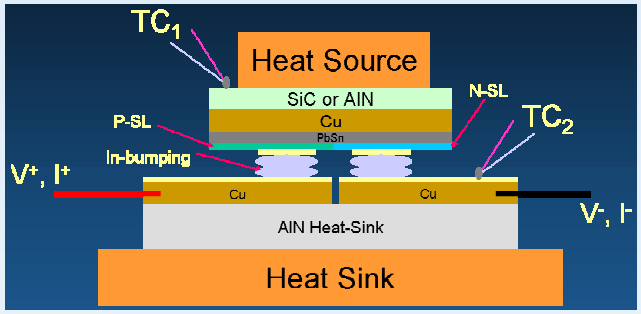


Advantages of the Proposed Technology

- Teledyne's Segmented TE Couple Technology
  - High reliability/long life-proven through several NASA space missions
  - High efficiency, mass/volume efficient
  - Compatible with RHU, scalable
  - Static system, no EMI/vibration to effect science experiments
- RTI's Superlattice BiTe TE device technology
  - High efficiency: >5% @ T = 100° K, material ZT>>1 (over twice that of bulk BiTe)
  - High power density: 1.3 W/cm2 @ T = 77° K (over 40% high than bulk BiTe)
  - High specific power: 1.65 W/g (an order of magnitude larger than bulk BiTe)

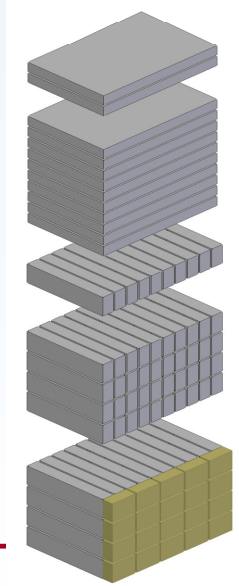
Technical Challenges

Technical issues to be addressed



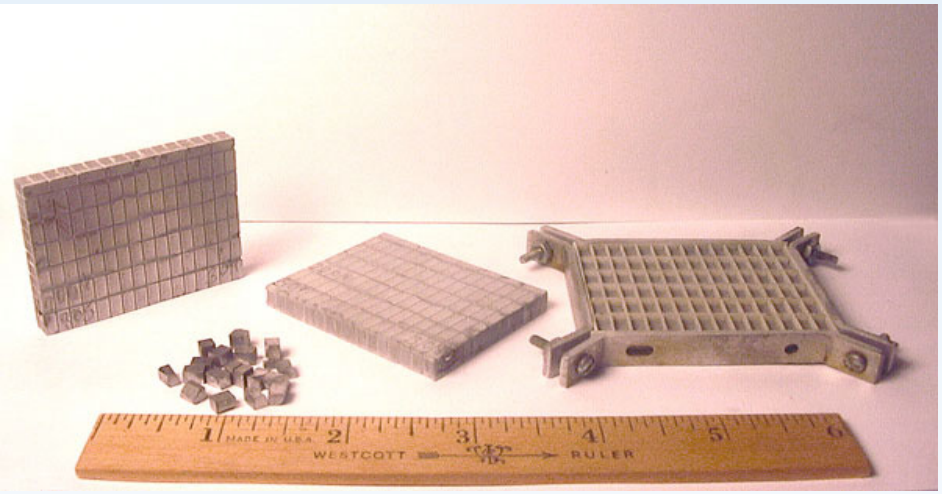
- Superlattice device:
  - Achieving large TE element length (thin film thickness), L, to cross sectional area (thin film active area), A, ratio to enhance device efficiency and optimize power output characteristics (current vs. voltage)
  - Achieving large energy conversion efficiency (ZT) by reducing internal thermal and electrical resistances

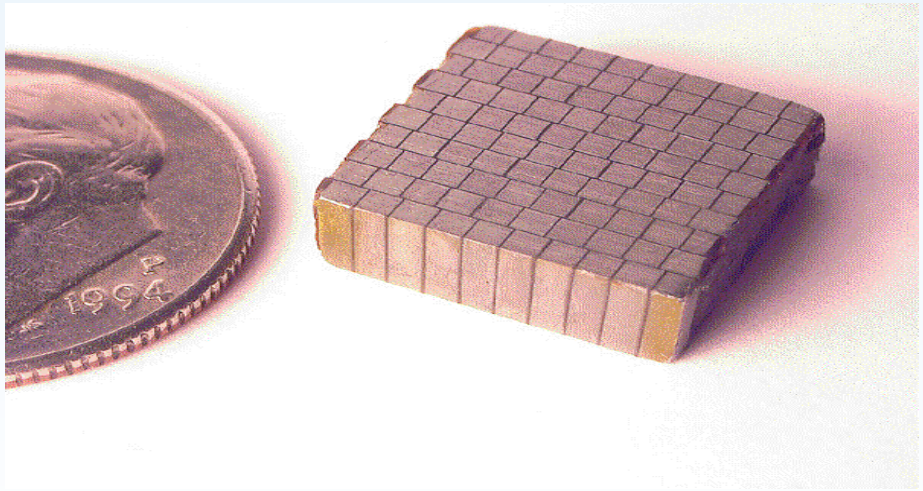
- Segmented PbTe-TAGS/PbSnTe close-packed array device:
  - Identifying/selecting a low temperature glass or an inorganic adhesive to successfully bond TE material slices into a monolithic multi-couple
  - Developing materials and methods to successfully form the hot and cold end electrodes to the glass bonded multi-couple



Previous Work

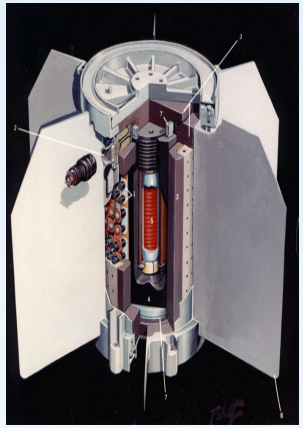
- Teledyne has designed and built close-packed array TE devices for many Applications

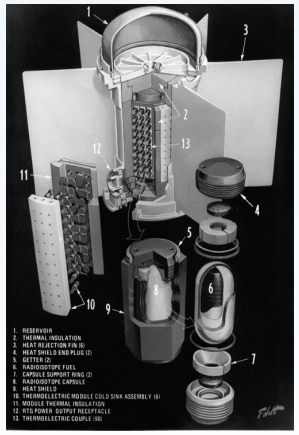


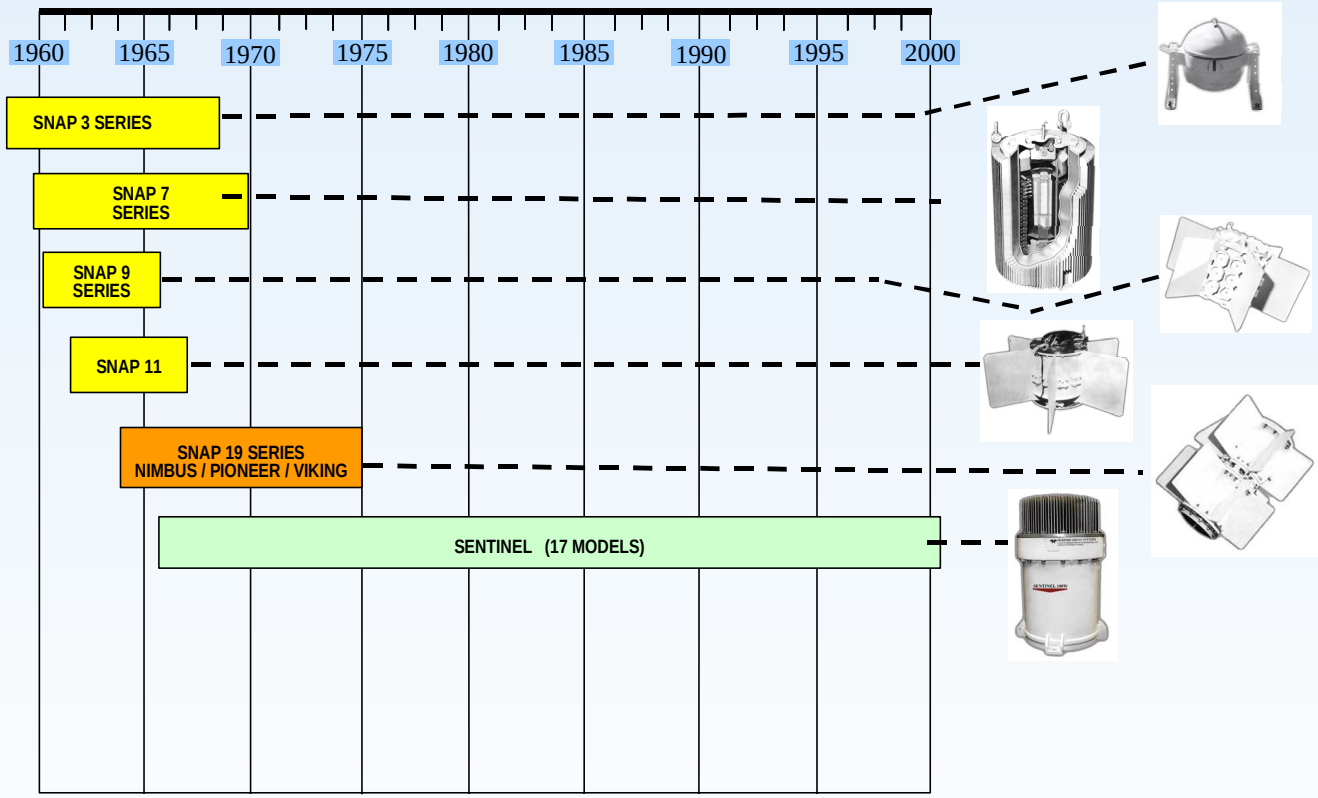


Previous Work

- Teledyne has designed and built over 80 RTGs from 500mW to 2KW power output





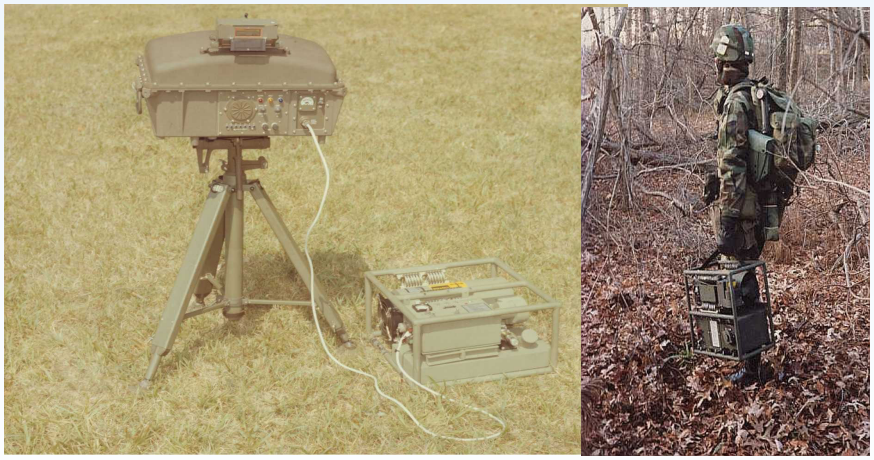


Project Prometheus

Previous Work

600- and 120-Watt Thermoelectric Generators

120-Watt Thermoelectric Generator in Field Use by U.S. Army



Previous Work

RTI Pioneering Work:

- Thin-film superlattice materials
- Micro- and opto-electronic hot spot cooling and temperature control
- Portable power generation systems

Planned Efforts/Approach

Plans - Year 1:

- **Design hot/cold stage devices to deliver high energy conversion efficiencies**
  - Hot Stage: Segmented PbTe-TAGS/PbSnTe (720° K-440° K)
  - Cold Stage: Superlattice BiTe (400° K-300° K)
  - Cascaded device: PbSnTe/TAGS/PbTe-Superlattice BiTe (720° K-300° K)
  - End of mission net power output: 100 mW @ 5 V, 20 mA
- **Define/develop materials, methods and processes to fabricate the hot/cold stage proof-of-concept devices**
  - Close-packed array segmented PbTe-TAGS/PbSnTe multi-couple
  - Superlattice multi-couple having large L/A ratio
- **Build several proof-of-concept hot and cold stages devices**
- **Assemble the hot and cold stage devices into a single cascaded TE device**
- **Evaluate the cascaded device performance**

Planned Efforts/Approach

Plans - Years 2 and 3:

- Optimize the design, materials, methods and processes for the proof-of-concept cascaded device
  - Maximize energy conversion efficiency
  - Improve device integrity
- Establish device performance testing capabilities
- Evaluate/determine hot stage, cold stage and cascaded device performance
- Qualify the cascaded device

Technical Progress

- Designs for the Phase1 hot and cold stage proof-of-concept devices have been completed

RTI Device Cascaded With TESI Device					
Inputs		Outputs			
Heat flow (W)	No. of couples	L/A (1/cm)	Current (A)	Max Power (W)	Efficiency (%)
0.798	32	85.1	0.022	0.125	3.2

RTI Device Electrically Independent of TESI Device					
Inputs		Outputs			
Heat flow (W)	No. of couples	L/A (1/cm)	Current (A)	Max Power (W)	Efficiency (%)
0.800	4	14.7	0.458	0.046	5.8

Technical Progress

PbTe-PbSnTe-TAGS Module				
To be cascaded with RTI superlattice module				
Heat flow into module (W)	1			°K
Strap efficiency	0.935		Hot junction temperature	720
T/E degradation (1%/yr for 15 yrs)	0.85		Cold junction temperature	438
Thermal efficiency	0.85			
Load voltage per couple (V)	0.0637			
Percentage of length of N-leg:			Percentage of length of P-leg:	
PbTe	100.0		PbSnTe	17.8
			TAGS	82.2
INPUT			OUTPUT	
Module cross-diagonal (in)	0.32		Number of couples	80
Module area (in^2)	0.0512		Couple length (in)	0.86
Output power (W)	0.101		Couple area (in^2)	0.00115
Voltage per module (V)	5.1		N-leg area (in^2)	0.00070
Current through module (mA)	19.7		P-leg area (in^2)	0.00045
Load resistance (ohm)	258.4		N-leg bit width (in)	0.02644
T/E efficiency (%)	6.6		P-leg bit width (in)	0.02133
System efficiency (%)	5.6			
Notes:				
1. T_{CJ} is 50°F higher than the 410 K, the specified T_{HJ} for the RTI BiTe module.				
2. Current through each module = Gross power output per module / Gross voltage per module				
3. System efficiency = Net power output / Total heat input				
4. Calculations assume 1% T/E degradation per year for 15 years.				

Technical Progress

- Several types of bonding glass and inorganic adhesive formulations have been identified/obtained for use in assembling the PbTe and TAGS/PbSnTe slices
- Glass bonding fixtures and TE materials powder compaction tooling have been fabricated
- Large rectangular shape PbTe, TAGS and PbSnTe compacts are being produced
- Maximum acceptable parasitic resistance as a function of thermoelectric superlattice element aspect ratio has been determined
- Precision tooling for bonding of thin film superlattice material is being improved.
- Thin film BiTe/SbTe thermoelectric couple prototypes with increased L/A ratio have been manufactured and characterized.
- BiTe/SbTe superlattice prototype couples have been ZT tested, and efficiency and power projections has been derived, for RT to 75 ºC.

TELEDYNE
ENERGY SYSTEMS, INC.
A Teledyne Technologies Company

SEGMENTED BiTe/PbTe-BiTe/TAGS/PbSnTe THERMOELECTRIC GENERATORS

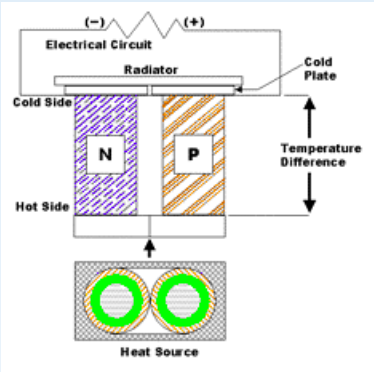
Radioisotope Power Conversion Technology
Project Prometheus

PI: Dave Moul
Phone: 410-891-2372 FAX: 410-771-8619
Company: Teledyne Energy Systems, Inc. Email: david.moul@teledynees.com

TELEDYNE ENERGY SYSTEMS, INC.
A Teledyne Technologies Company

Advanced RPS NRA Selection: Segmented Thermoelectric Generators

Tech Area: Segmented Thermoelectrics (Development) **Contractor: Teledyne and Boeing**



Validate new TE materials to develop more efficient RTGs

Goals

- Validate the advantages of segmenting "n" and "p" type BiTe material with standard PbTe and TAGS thermoelectric materials for space applications.
- Mass optimize the space design for nominal space-background and planetary temperatures.
- Ruggedize metallurgical bonds for launch qualification.
- Improve conductivity of interface with heat rejection subsystem

Objectives/Approach

- Phase-I: Develop system requirements and conceptual designs
- Phase-II: Material testing and test module development
- Phase-III: Module testing and generator design

Schedule/Resources

Task/Milestone	CY03	CY04	CY05	CY06
•Couple Design Review				
•Heat Source Dsgn Rvw				
•Module Design Review				
•Boeing Concept Design Rvw on Cold-end H/W				
•Test Module PDR				
•Generator Concept Rvw				
•Fab Readiness Review				
•Workmanship Testing				
•Thermal Perf. Testng				
Resources ($K)	788	1,616	1,609	832

Technical Challenges

- BiTe is currently segmented for terrestrial applications. This effort shall optimize for space applications and facilitate integration into spacecraft systems.

Participants

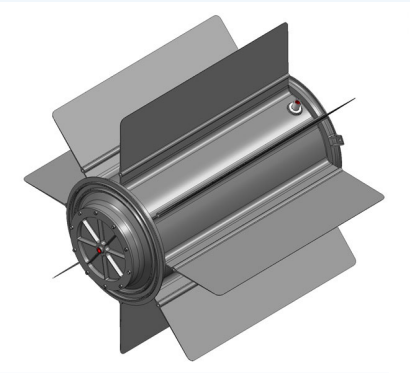
- Teledyne Energy Systems – Lead, Converter
- The Boeing Company – Sub, Integration Issues

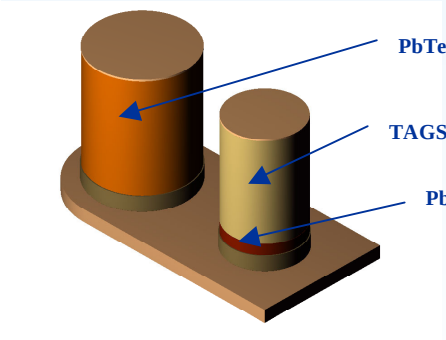
Project Prometheus

Project Overview

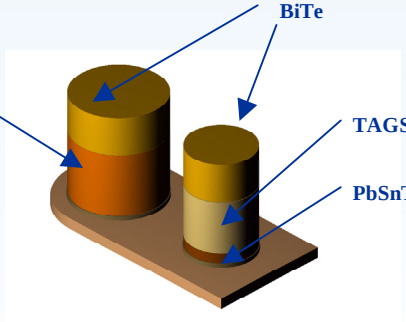
Focus of development or research

- Develop improved thermoelectric materials.
- Demonstrate improved thermoelectric couple structural capability for multi-mission environments.
- Develop heat rejection interface allowing integration to spacecraft thermal systems (fluid loops or heat pipes).

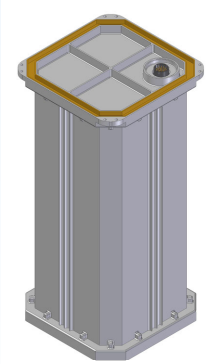




PbTe Couple



BiTe Couple



Technical Challenges

Technical Problem Trying to Solve

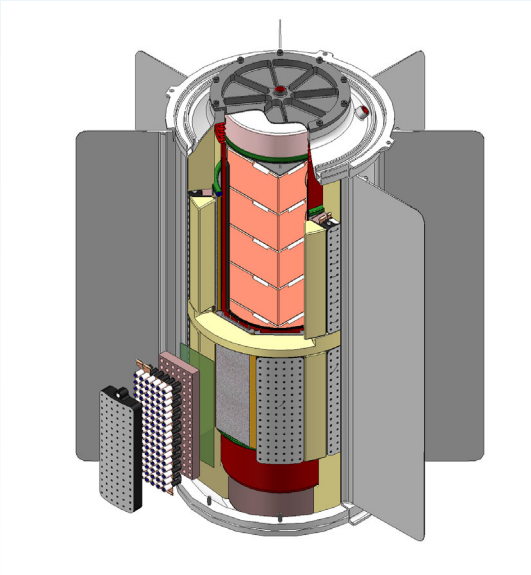
- Current BiTe materials provide potential of >8% system efficiency using NH3 heatpipes, improved materials provide potential of exceeding 10% efficiency.
- Terrestrial/commercial environments not as severe as space environments, materials and processes need evaluation for multi-mission loads and temperatures.
- Integration with spacecraft systems require conductive interface for fluid loops or heatpipes at 100C or less.

Previous Work

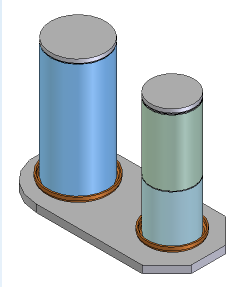
Summary of previous/related work/knowledge

- PbTe/TAGS couples used successfully in Viking and Pioneer missions (31 years on Pioneer 10).
- BiTe segmented couples under development since 1988 for terrestrial applications, with over 50M couple hours under test.

MMRTG program qualifying PbTe thermoelectric design for multimission environments.

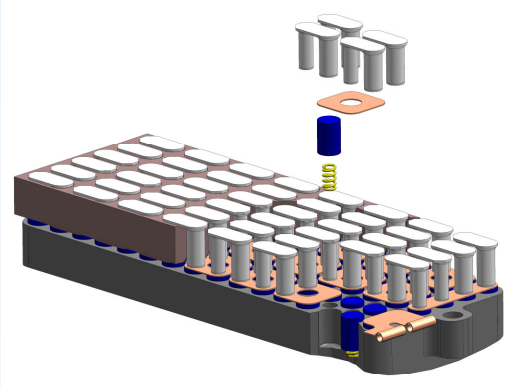


Planned Efforts/Approach



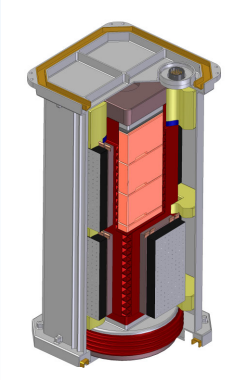
Plans Year 1:

- Incorporate material improvements to increase individual couple efficiency from 9% to 11%
- Optimize heat rejection for operation at fluid loop temperatures (100C or lower)



Plans Years 2 and 3:

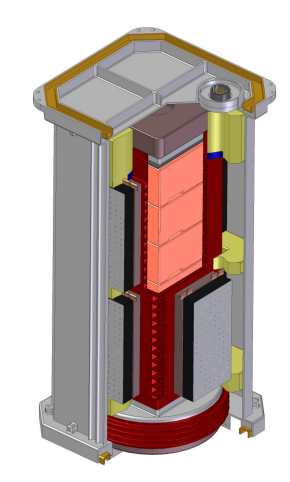
- Fabricate and test thermoelectric modules
- Demonstrate and test improved heat rejection interface
- Develop conceptual generator design.

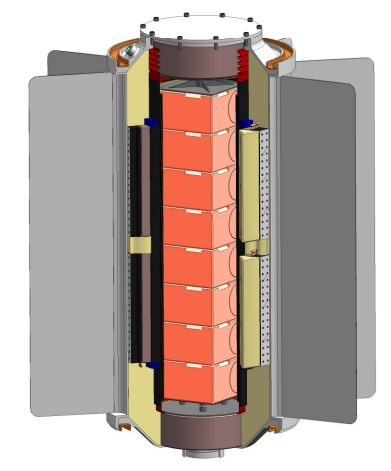


Technical Progress

Summary of any technical progress to date

Conceptual design study developed a 120W RTG using only 6 GPHS modules, at 8% efficiency and 5.4 W/kg specific power.





Preliminary analyses of a BiTe version of MMRTG provides 150W, specific power of 4-5 W/kg (depending on fins), and over 8.5% efficiency operating at 100C.