DESIGN AND ANALYSIS OF RTGs* FOR SOLAR AND MARTIAN EXPLORATION MISSIONS

*Radioisotope Thermoelectric Generators

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Summary

Key Words: Space Power, Space Nuclear Power, Radioisotope Power, Radioisotope Thermoelectric Generator, Solar Probe, Solar System Exploration, Solar Probe Power Supply, Solar Probe Thermal Management, Mars Lander, Mars Rover, Mars Sample Return, Mars Global Network, Penetrator

The paper describes the results of design, analysis and spacecraft integration studies of Radioisotope Thermoelectric Generators (RTGs) for three unmanned space exploration missions. The three missions, consisting of the Mars Rover and Sample Return (MRSR) mission, the Solar Probe mission, and the Mars Global Network (MGN) mission, are under study by the Jet Propulsion Laboratory (JPL) for the U.S. National Aeronautics and Space Administration (NASA). The NASA/JPL mission studies are supported by the U.S. Department of Energy's Office of Special Applications (DOE/OSA), which has commissioned Fairchild Space Company to carry out the required RTG design studies.

The MRSR mission is intended to permit robotic exploration of Mars by means of a largely autonomous Rover vehicle, for excursions up to 40 km from the lander. It will perform a variety of measurements and collect samples for return to Earth at the end of the mission. It requires RTGs supplying approximately 500 watts during the five-year mission, to power the mobility system and the computers that make the autonomous operations possible.

The Solar Probe mission is designed to explore and help resolve the fundamental nature of the solar corona, by performing in-situ measurements at distances as close as four solar radii or 0.02 AU from the sun. Gravity-assist flybys of both Earth and Jupiter will be used to lift the spacecraft into a polar sun orbit and to reach the 0.02 AU perihelion. RTGs supplying 430 watts during the nine-year mission are required.

The MGN mission is intended to create a network of ~24 small and relatively inexpensive landers spread over both low and high latitudes of the Martian globe. These landers will be protected by graphite entry shields, and will be slowed down by parachutes and, in some cases, by retrorockets. Either surface landers or penetrators, or combinations thereof, will be employed. They will be used to determine the structural, mineralogical, and chemical characteristics of the Martian soil, search for possible subsurface trapped ice, and collect long-term seismological and meteorological data. The data will be periodically transmitted to an orbiting spacecraft, for relay to Earth. The high-data-rate transmission bursts will be powered by batteries that are recharged by a small RTG. Each surface lander will require an RTG supplying 2 to 3 watts at ~ 5 volts for ten years.

Each of these three missions present special RTG design constraints which preclude the use of existing generators. The key problem on the MRSR RTG is how to vent the helium generated by the fuel's alpha decay to the outside without allowing the Martian atmosphere to enter into and build up harmful quantities within the RTG.

The key problems on the Solar Probe RTG are fitting the generators into the very limited space available within the solar umbra, and radiating the waste heat from the highly obstructed RTGs without excessive performance penalties due to higher and non-uniform cold-junction temperatures.

The key problem on the MGN RTG is how to make the generators able to tolerate higher G-loads than those encountered on previous RTG missions, in order to increase the lander's allowable impact velocity and to reduce the mass of its required retrorockets.

The paper describes promising solutions to these key problems, the resultant RTG designs for the three mission, and their performance characteristics. The results are presented in the form of word charts and self-explanatory figures.

INTRODUCTION

- NASA's Jet Propulsion Laboratory (JPL) is studying unmanned space exploration missions, including the:
    - Mars Rover and Sample Return Mission
    - Solar Probe Mission
    - Mars Global Network Mission

- JPL has tentatively baselined the use of RTGs for those missions

- Each of these missions has special requirements that preclude the use of existing RTG designs

- To support the JPL mission studies, the Office of Special Applications of the US Department of Energy has commissioned Fairchild Space Company to conduct RTG design, analysis, and integration studies for the three missions.

- Because of limited time and space, the paper will be confined to:
    - summarizing the principal mission goals and plans
    - identifying the principal RTG design problem for each
    - describing a promising solution to each problem
    - depicting a spacecraft-integrated RTG design for each
    - summarizing the performance of those RTGs

Mission No. 1:
MARS ROVER AND SAMPLE RETURN (MRSR) MISSION

- Principal Mission Goals:
  - Determine the geological, climatological, and biological history of Mars, and characterize its near-surface materials
  - Use Rover vehicle for exploratory trips up to 40 km from lander
  - Perform in-situ analyses, and return selected samples to Earth
  - Test key technologies for subsequent human exploration of Mars

- Principal RTG Design Problem:

  How to vent the helium generated by the fuel's alpha decay to the outside, without allowing the Martian atmosphere to enter into and build up harmful quantities within the RTG

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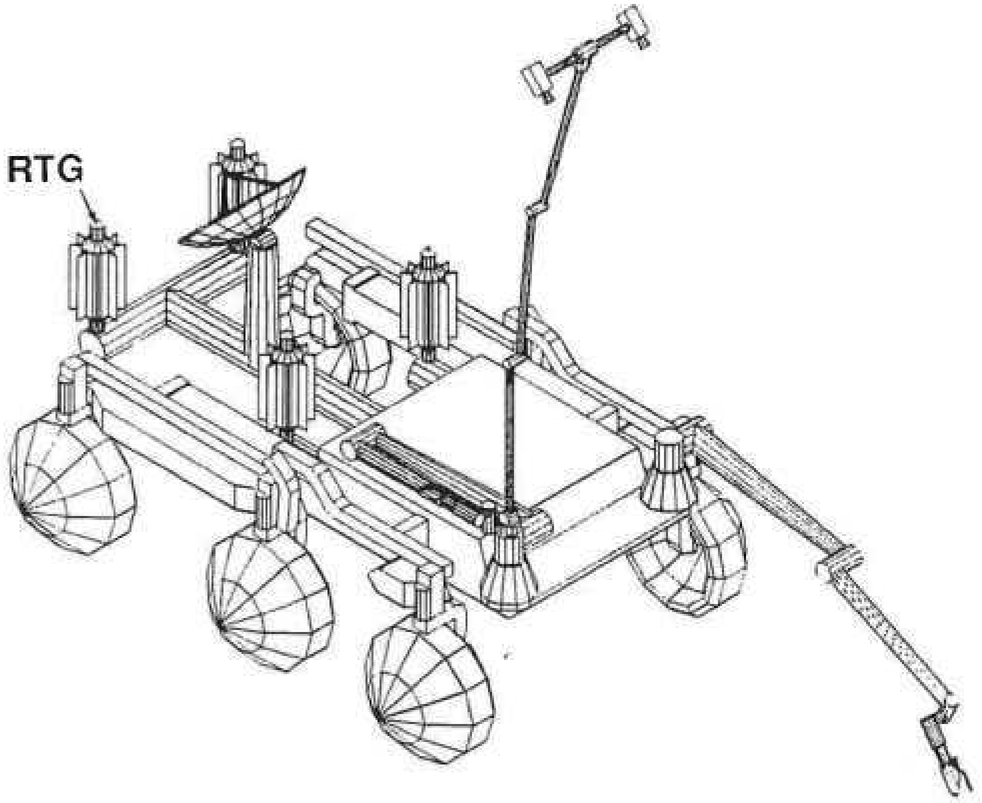
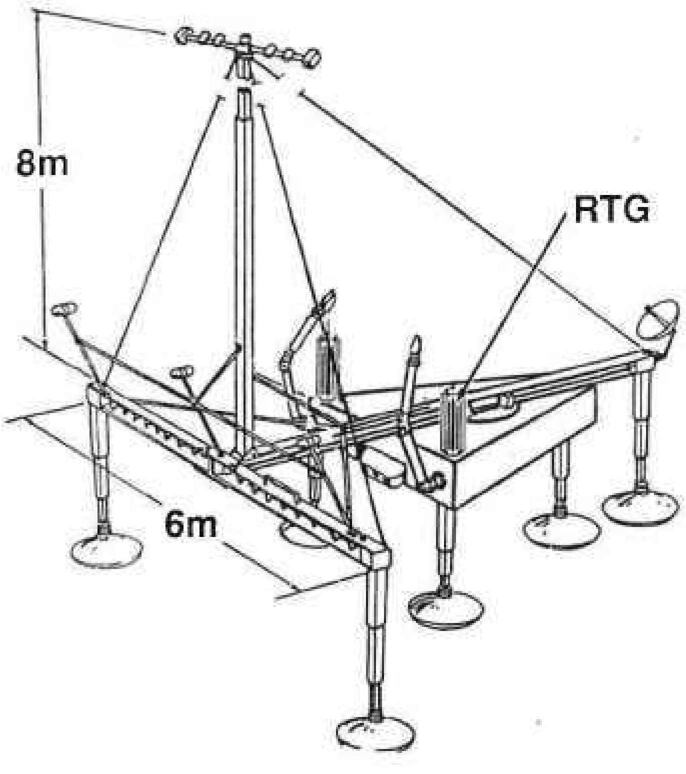
ILLUSTRATIVE ROVER DESIGN OPTIONS

Wheeled Vehicle with Four 125-Watt RTGs



Walking Beam Vehicle with Two 250-Watt RTGs

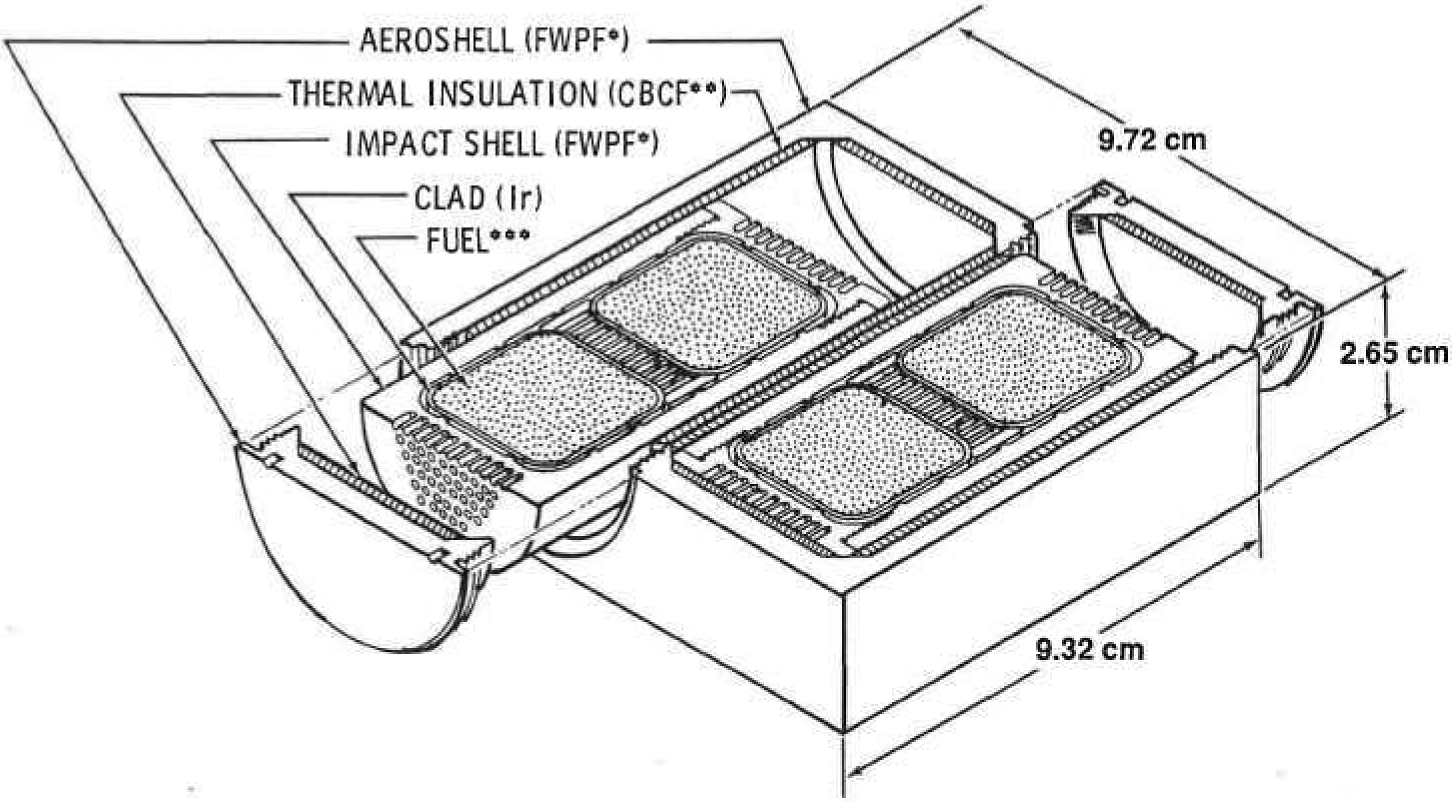


RTG Building Block:

GPHS

GENERAL-PURPOSE HEAT SOURCE MODULE (250 WATT)

Sectioned at Mid-Plane



*Fine-Weave Pierced Fabric, a 90%-dense 3D carbon-carbon composite

**Carbon-Bonded Carbon Fibers, a 10%-dense high-temperature insulator

***62.5-watt $^{238}PuO_2$ pellet

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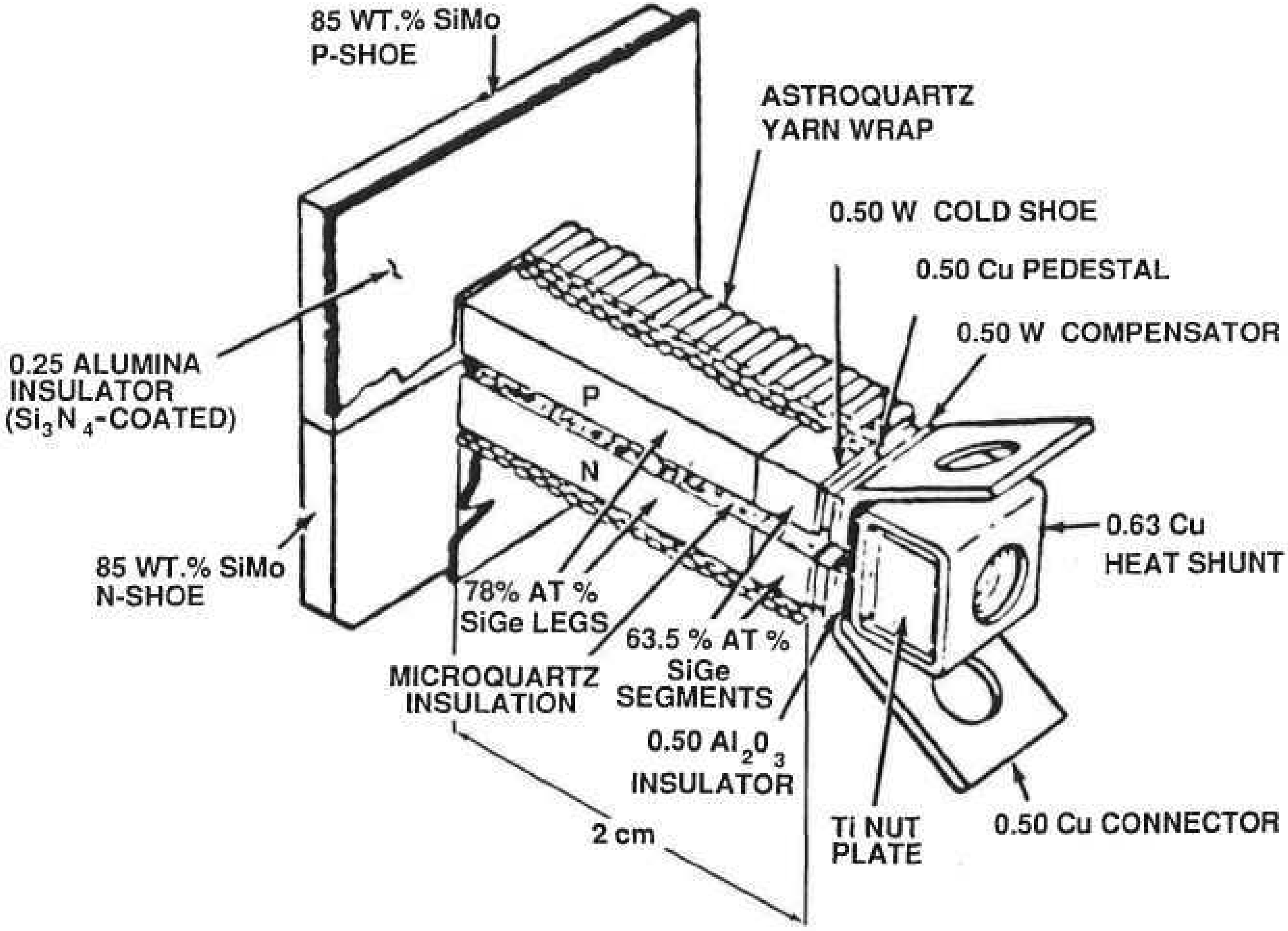
RTG Building Block:

THERMOELECTRIC UNICOUPLE

Dimensions in mm



- GPHS RTG CONTAINS 576 UNICOUPLES
- HOT SHOES HEATED BY RADIATION FROM HEAT SOURCE ACROSS VACUUM GAP
- UNICOUPLE'S COLD ENDS BOLTED TO RTG HOUSING
- THERMOCOUPLE LEGS EMBEDDED IN MULTIFOIL THERMAL INSULATION

KEY PROBLEM IN DESIGNING RTG FOR MARS

Cause:

- Radioisotope's alpha decay continuously generates helium
- Cannot allow helium buildup in thermoelectric converter, because thermal insulation only effective in vacuum
- RTGs operating in space vacuum are vented once they leave the Earth's atmosphere
- Converter of MRSR RTG cannot be vented because of external Martian atmosphere
- Even small quantities of atmospheric O_2 and CO could react with hot converter components and degrade performance
- Current RTGs contain hundreds of C-ring seals, which leak

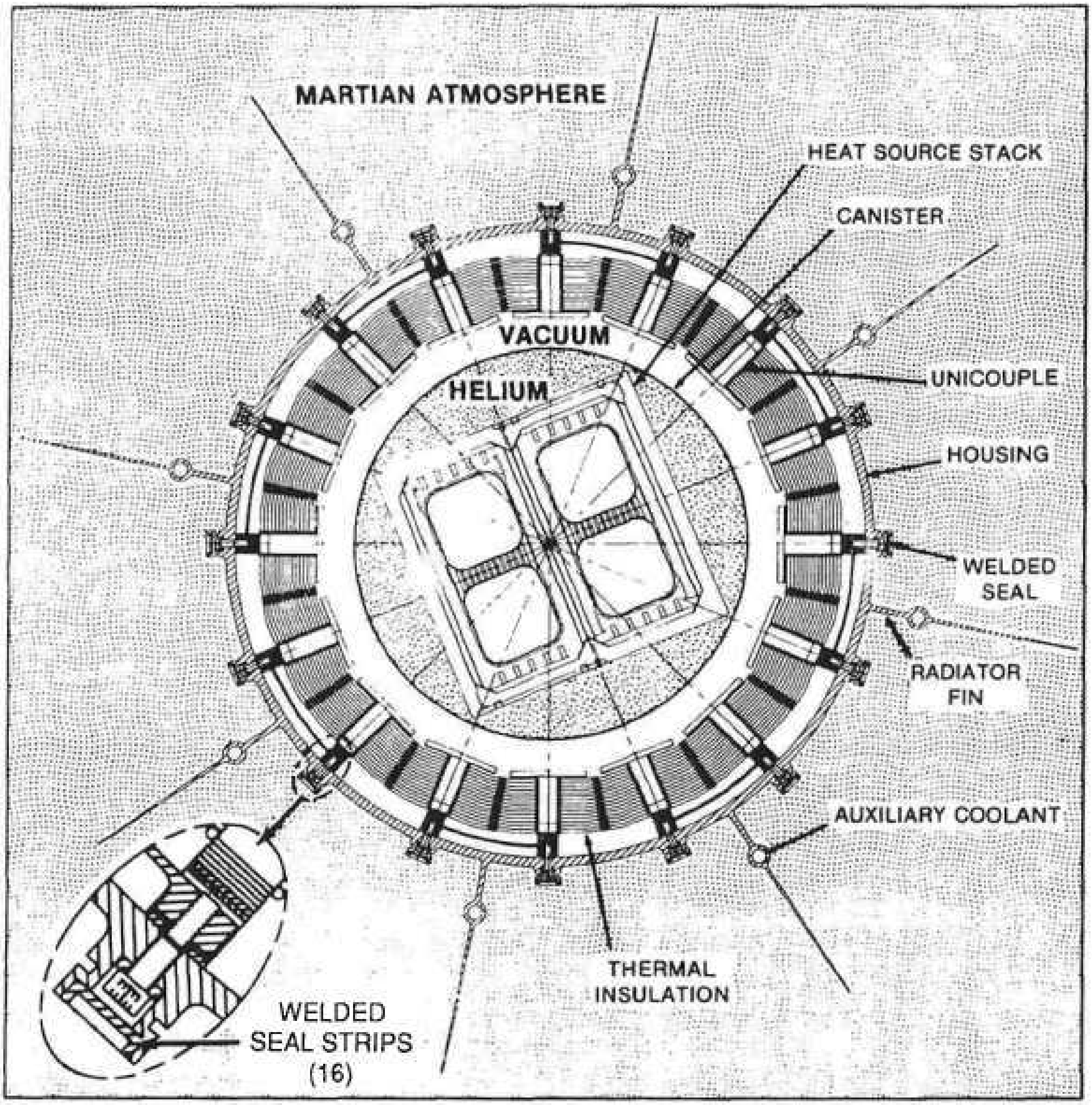
Pricipal RTG Design Problem:

- How to vent the Hellium generated by the fuel's alpha decay to the outside, without allowing the Martian atmosphere to enter into the RTG

Proposed Solution:

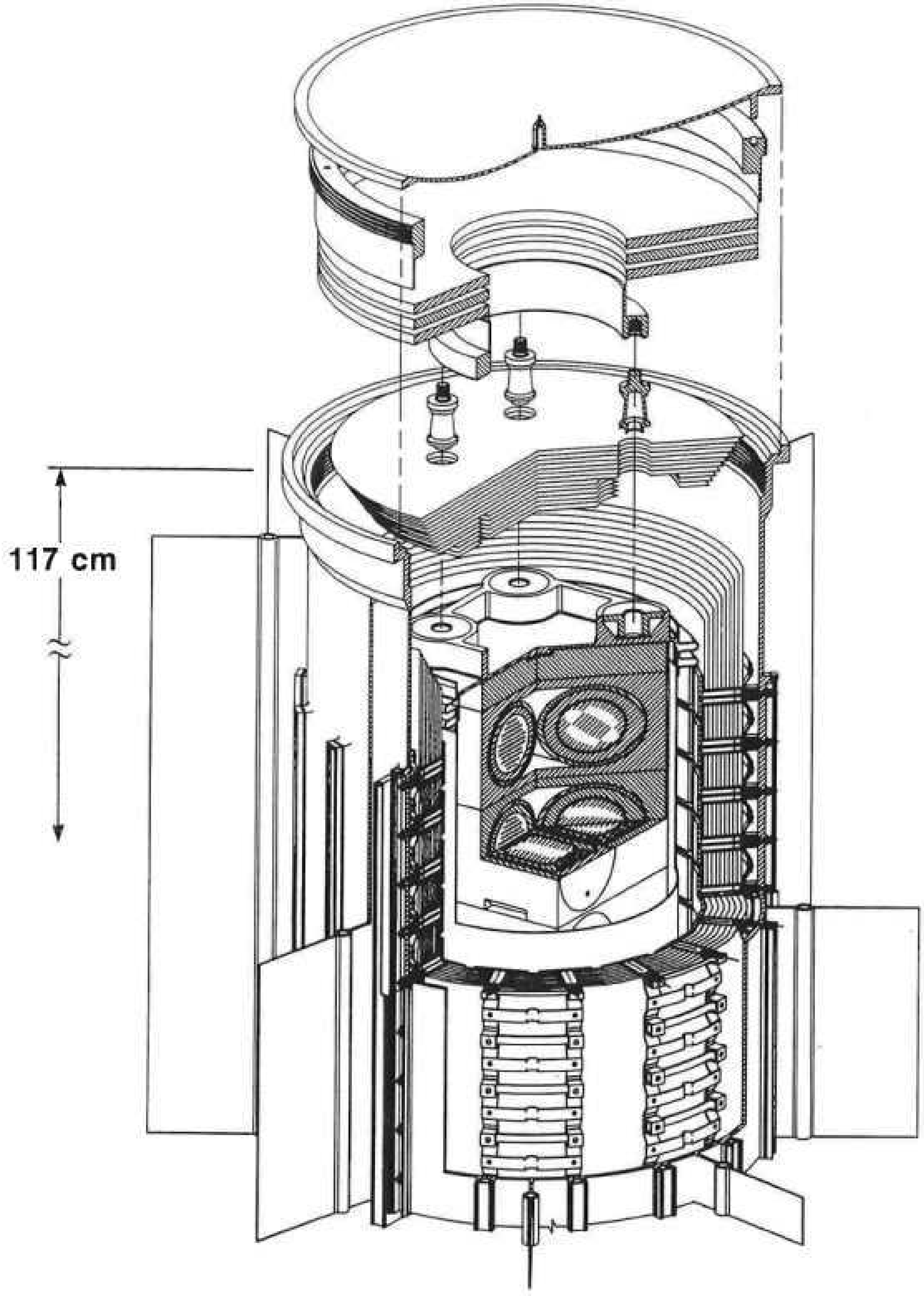
- Enclose heat source in canister, to separate helium from converter
- Vent canister to the outside through semi-permeable vent
- Weld seal covers over unicouple mounting bolts to prevent inleakage

HORIZONTAL CROSS-SECTION OF RTG
Illustrating Proposed Solution



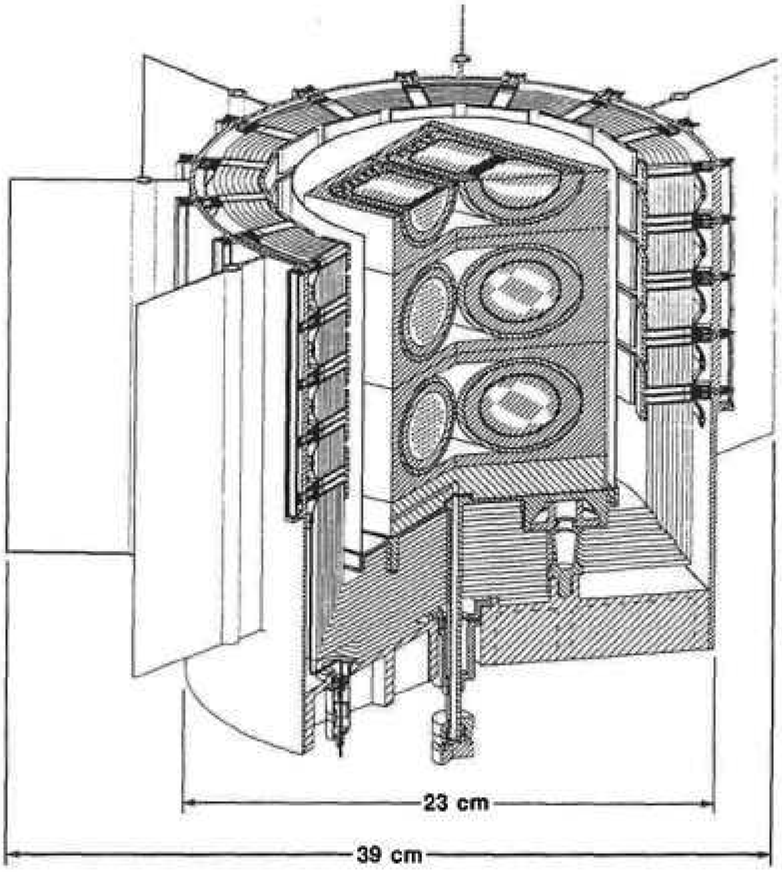
UPPER END OF MRSR RTG

Showing Heat Source Load Structure, Preload Springs, and Series-Parallel Leads



BOTTOM END OF MRSR RTG

Showing Heat Source in Canister, Helium Vent, 1 of 4 Heat Source Supports, Annular Converter, Seal Strips, Series Leads and Output Terminal



Mission No. 2:

SOLAR PROBE MISSION GOALS

- Explore and help resolve fundamental nature of solar corona
- Perform in-situ measurements (down to 4 solar radii or 0.02 AU) of:
  - density, velocity, and composition of solar wind plasma
  - magnetic fields
  - plasma waves
  - energetic particles

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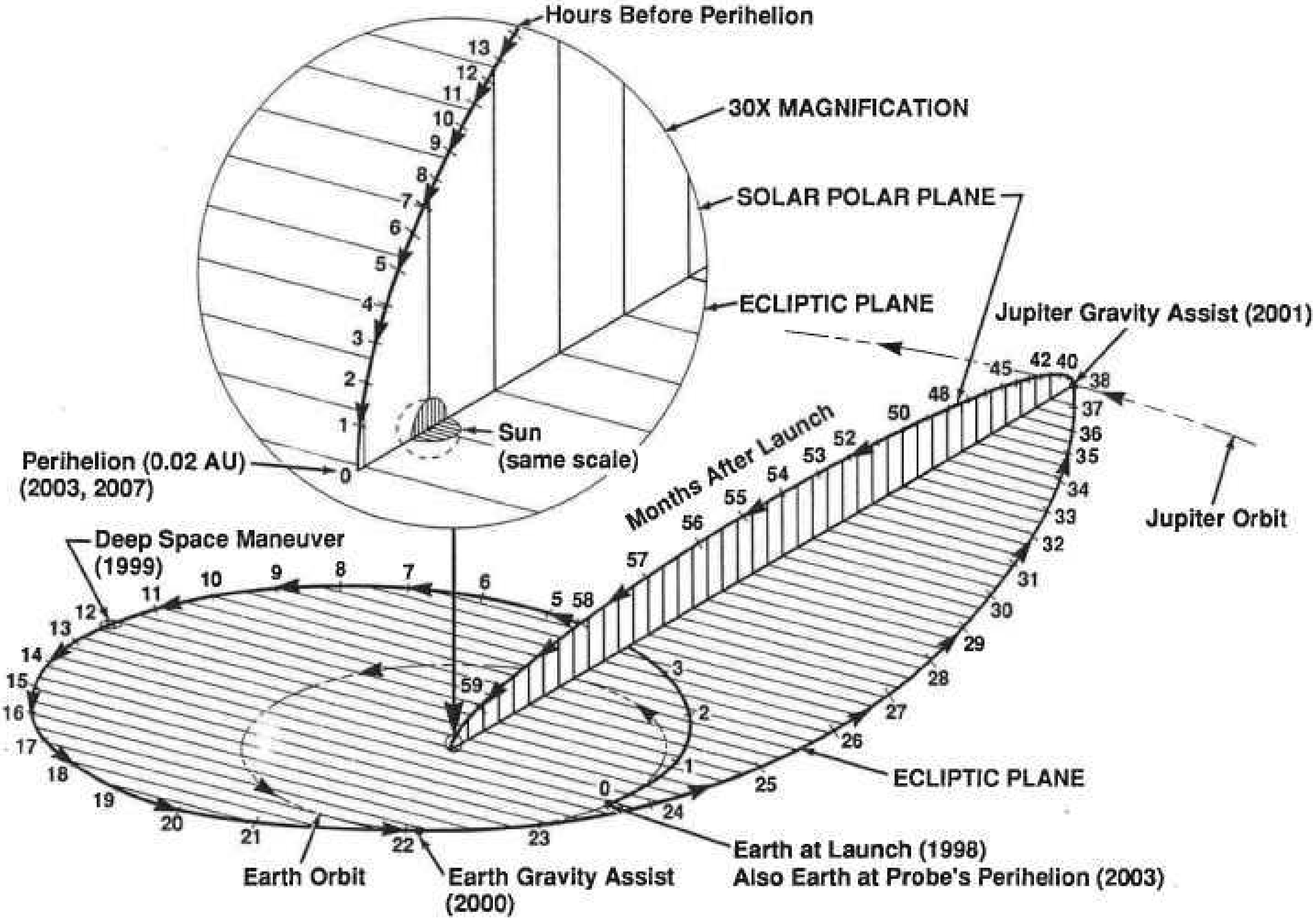
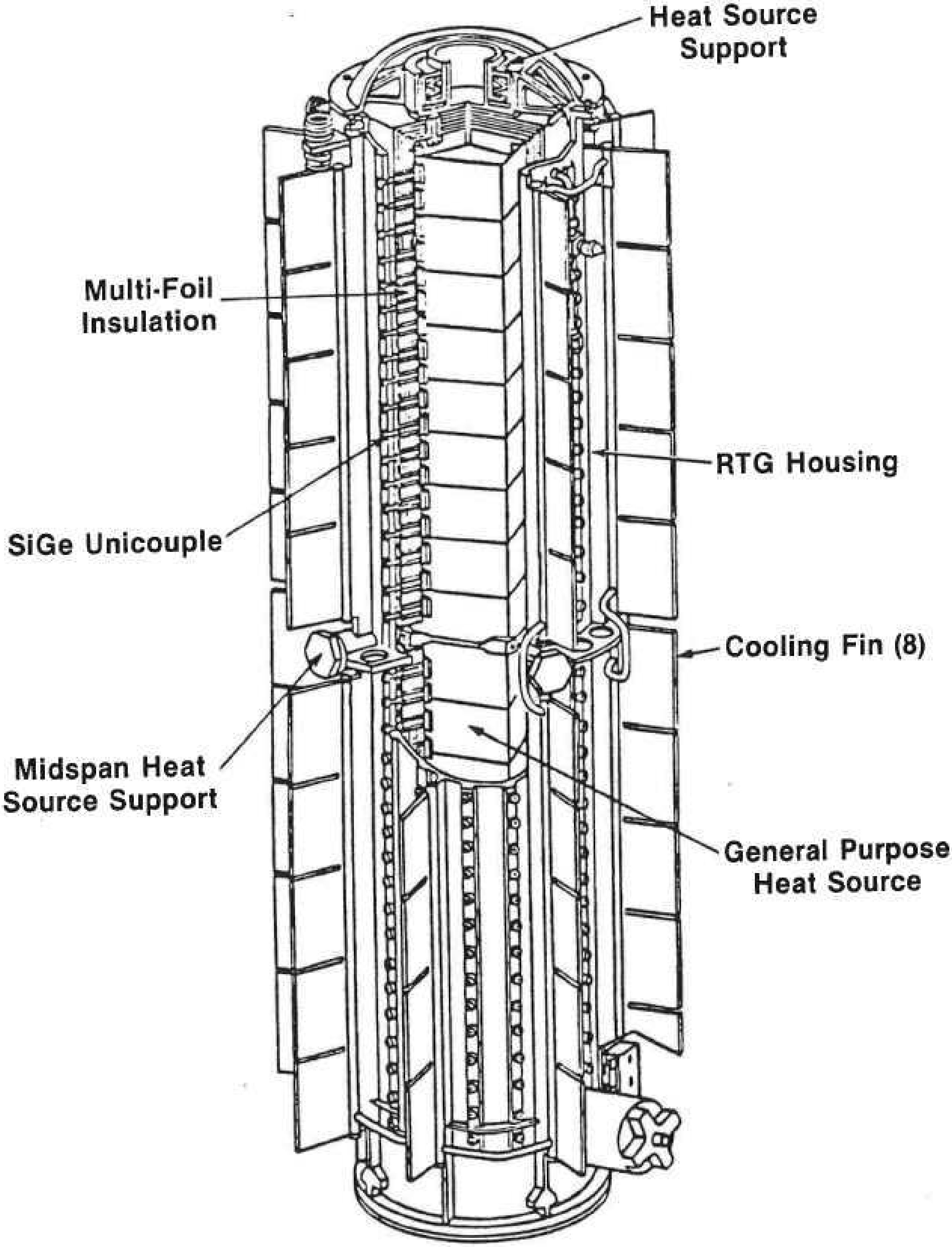
SOLAR PROBE TRAJECTORY AND SCHEDULE
Using Earth and Jupiter Gravity Assists

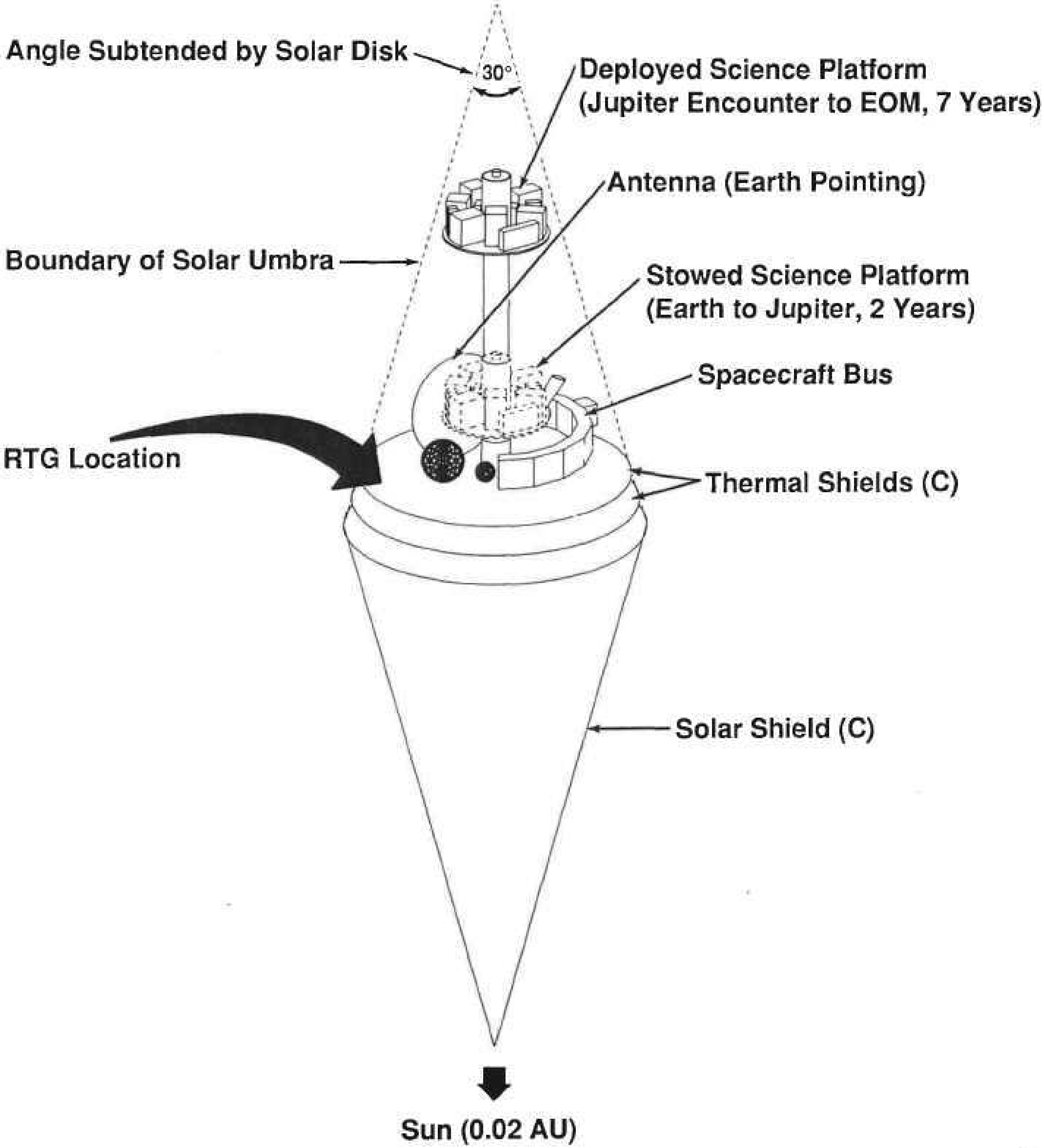


GPHS RTG



- 500-watt EOM output requires two 1.14m-long RTGs

JPL' s SOLAR PROBE DESIGN CONCEPT
Showing Limited Space Available For 500-watt RTGs



Solar Probe Mission:

PRINCIPAL RTG DESIGN PROBLEM

- To stay within the shaded umbra, RTGs cannot be boom-mounted but must be located close to the solar shield and the payload
- RTGs cannot reject heat in direction of hot solar shield
- To avoid overheating sensitive equipment, RTGs cannot reject heat in direction of spacecraft bus or of science platform
- Therefore, the RTGs have a highly obstructed heat rejection path
- Obstructed heat rejection path can result in higher and less uniform cold-junction temperatures, both of which lower the thermoelectric efficiency of the RTGs
- **KEY PROBLEM:** HOW TO COOL THE OBSTRUCTED RTGs

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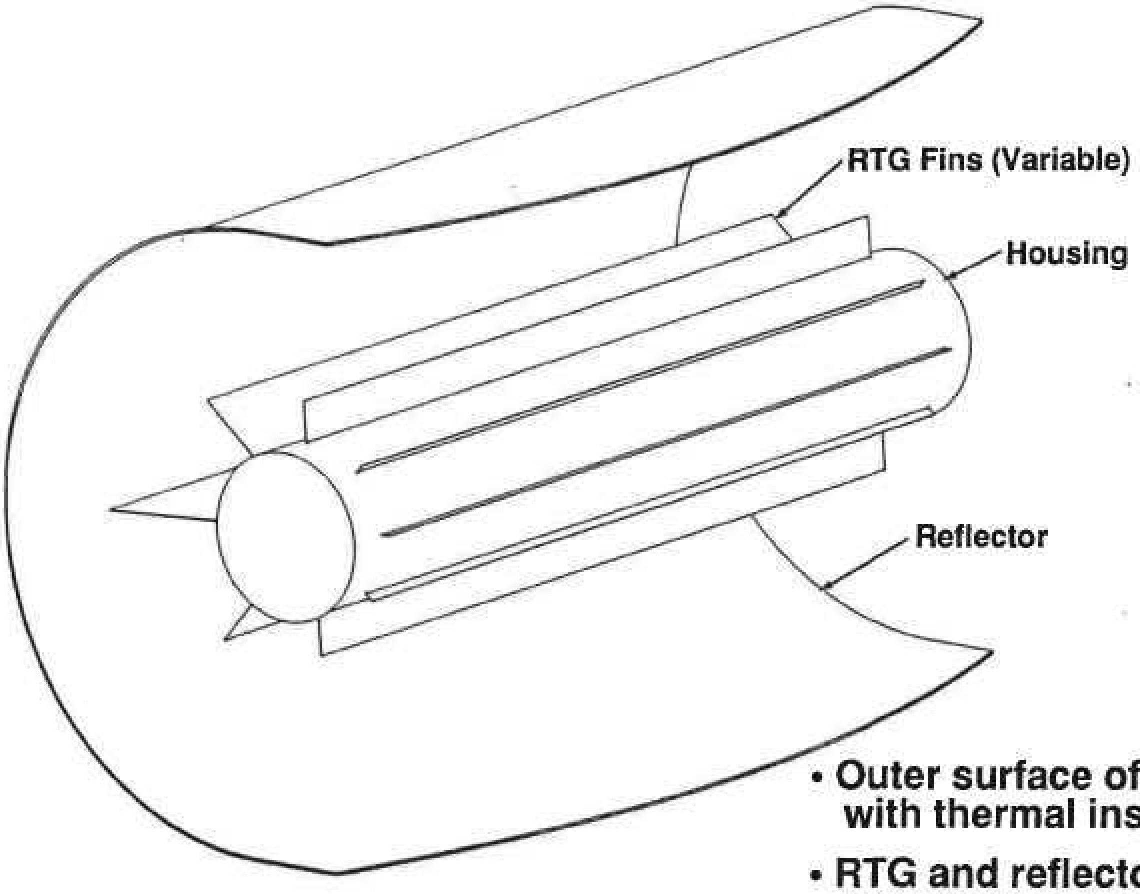
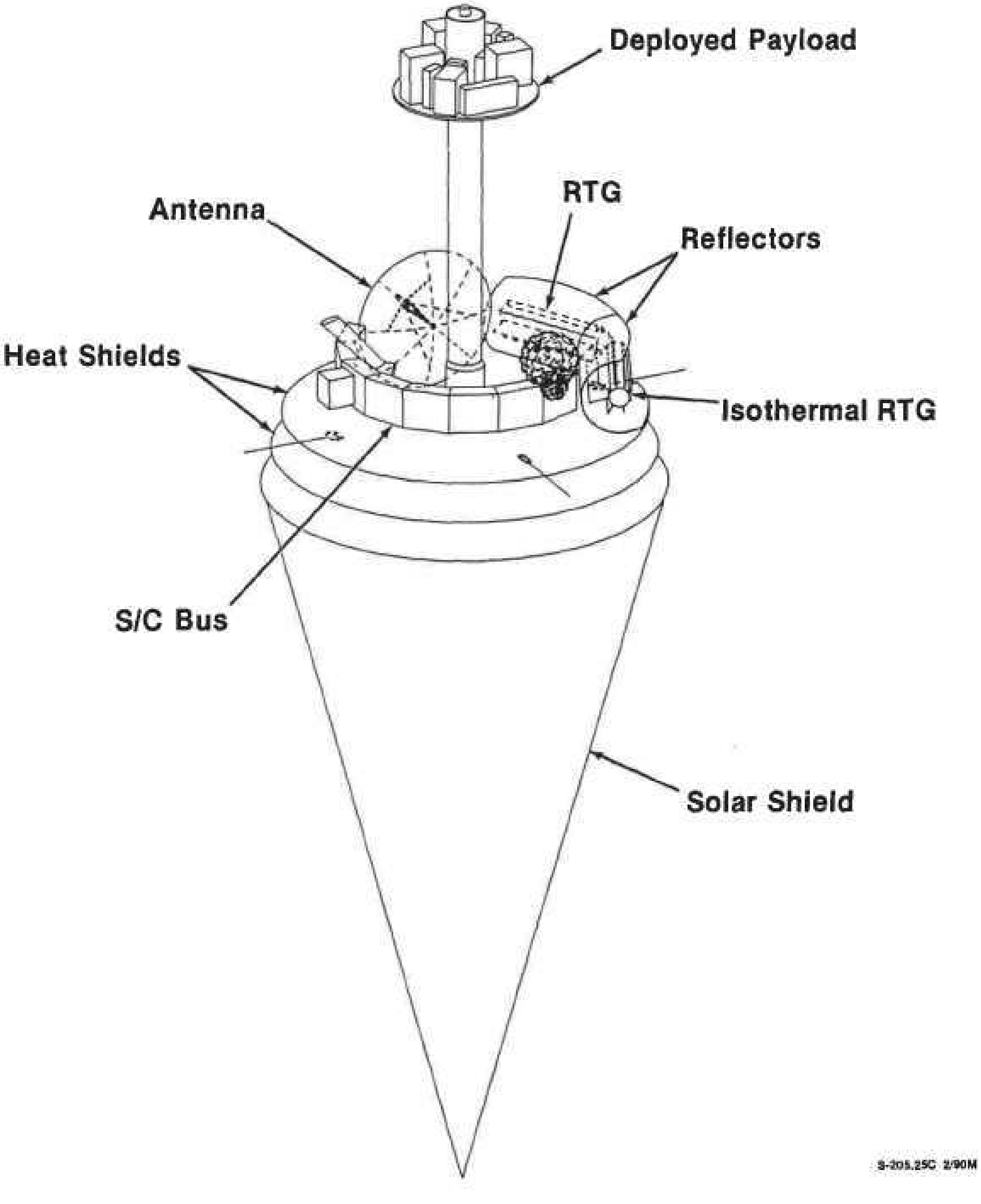
PROPOSED SOLUTION:
REFLECTOR-COOLED RTG WITH VARIABLE FINS

Fin Dimensions Adjusted to Yield Uniform Housing Temperature

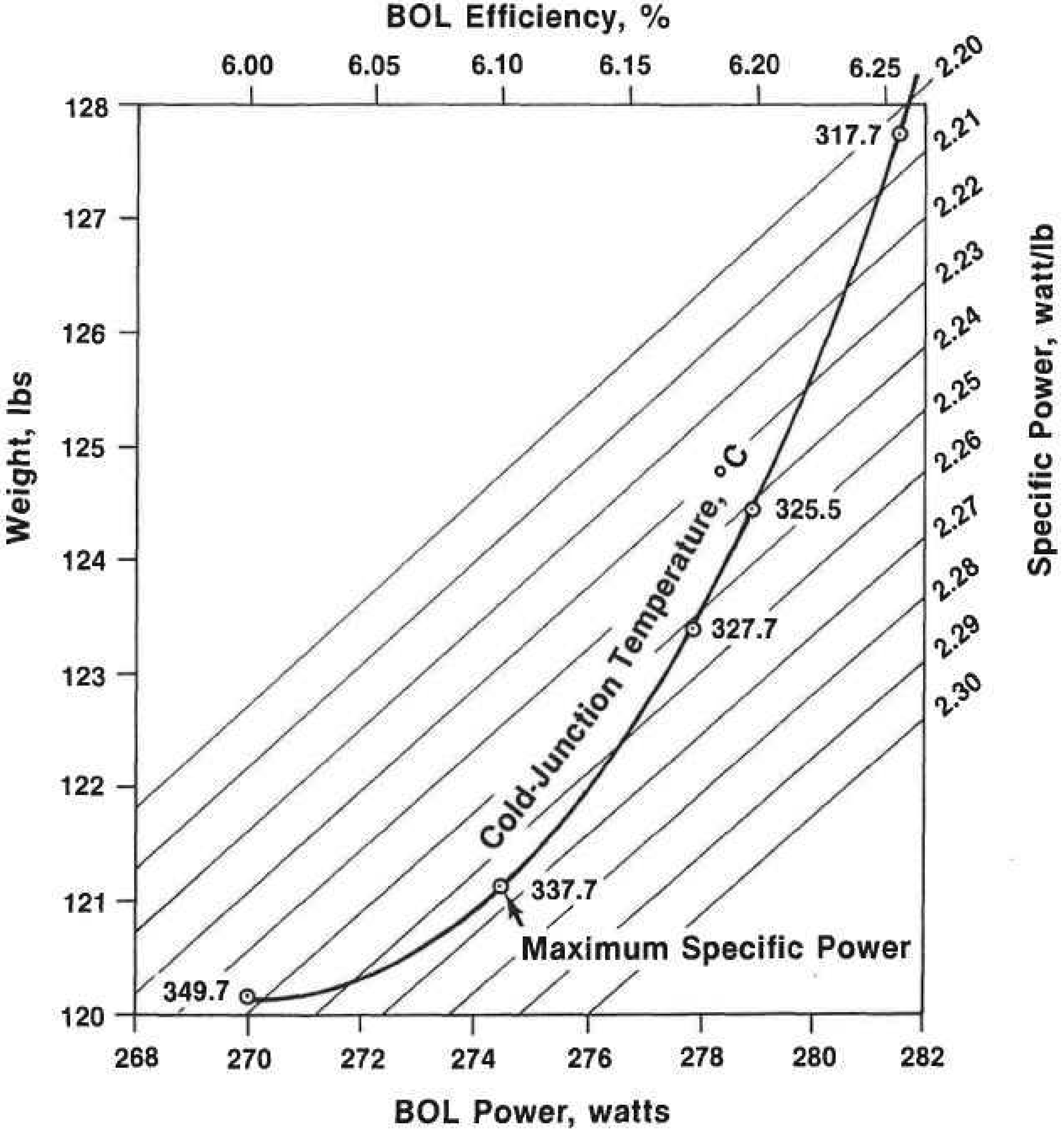


- Outer surface of reflector covered with thermal insulation
- RTG and reflector temperatures virtually independent of reflector reflectivity (specular or diffuse)

REFLECTOR-COOLED RTGs WITH VARIABLE FINS INTEGRATED WITH SOLAR PROBE



EFFECT OF COLD-JUNCTION TEMPERATURE ON BOL POWER, EFFICIENCY, MINIMUM WEIGHT, AND SPECIFIC POWER OF ISOTHERMAL RTG



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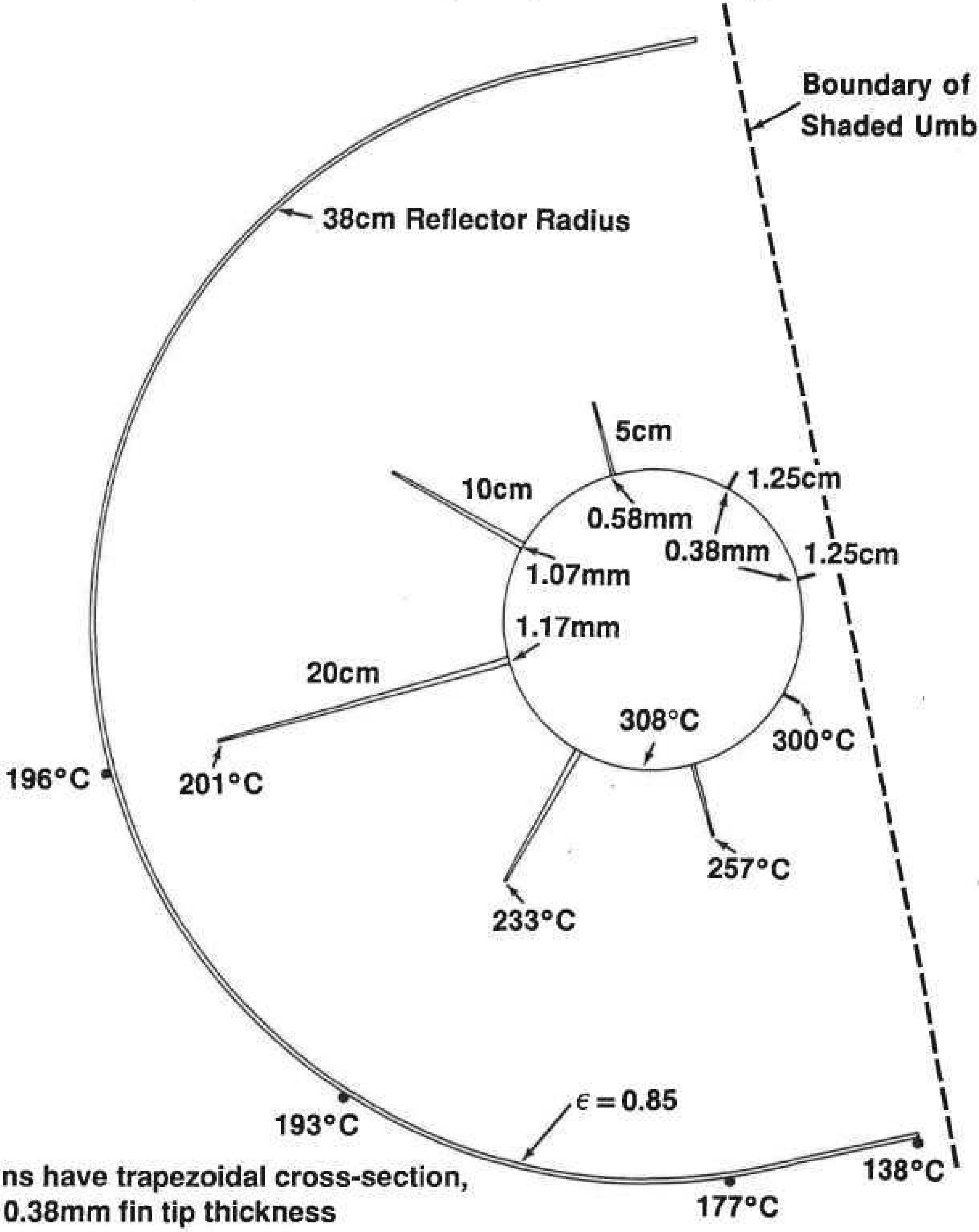
Solar Probe

OPTIMUM FIN DIMENSIONS AND RADIATOR TEMPERATURES FOR REFLECTOR-COOLED RTG WITH ISOTHERMAL HOUSING

(Fin thicknesses quadrupled for visibility)



All fins have trapezoidal cross-section, with 0.38mm fin tip thickness

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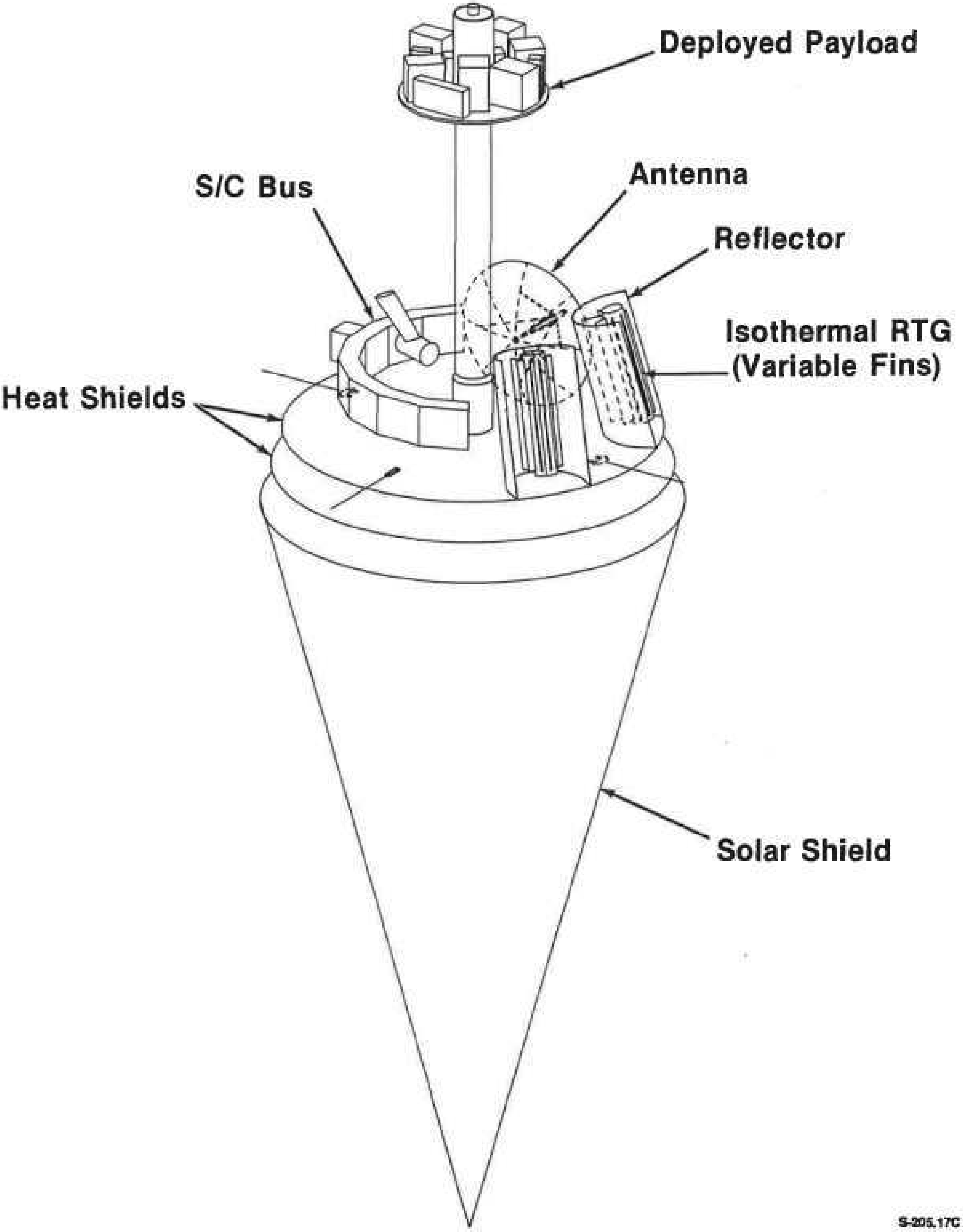
OBLIQUE RTG ALTERNATIVE, TO REDUCE DOSE RATE AT DEPLOYED PAYLOAD



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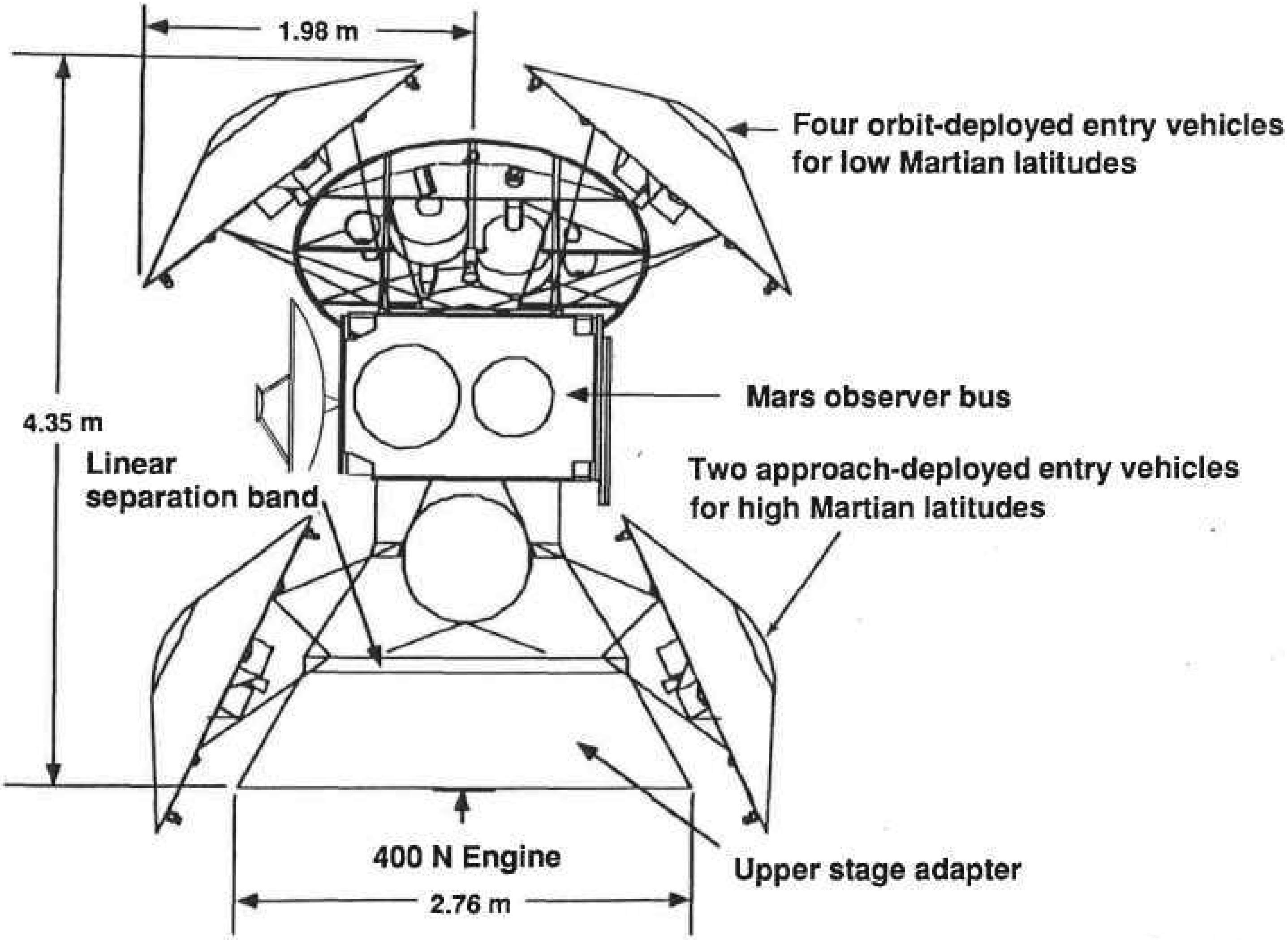
Mission No. 3:

MARS GLOBAL NETWORK MISSION

- Principal Mission Goals:
  - Cover Mars with network of ~24 small landers and/or penetrators
  - Record images during and after descent
  - Determine the structure, mineralogy, and chemistry of Martian soil
  - Search for possible subsurface ice and evidence of life
  - Collect long-term seismological and meteorological data

MARS GLOBAL NETWORK MISSION:

In one of the concepts studied at JPL, each of two Orbiter spacecraft dispenses six Mars entry vehicles



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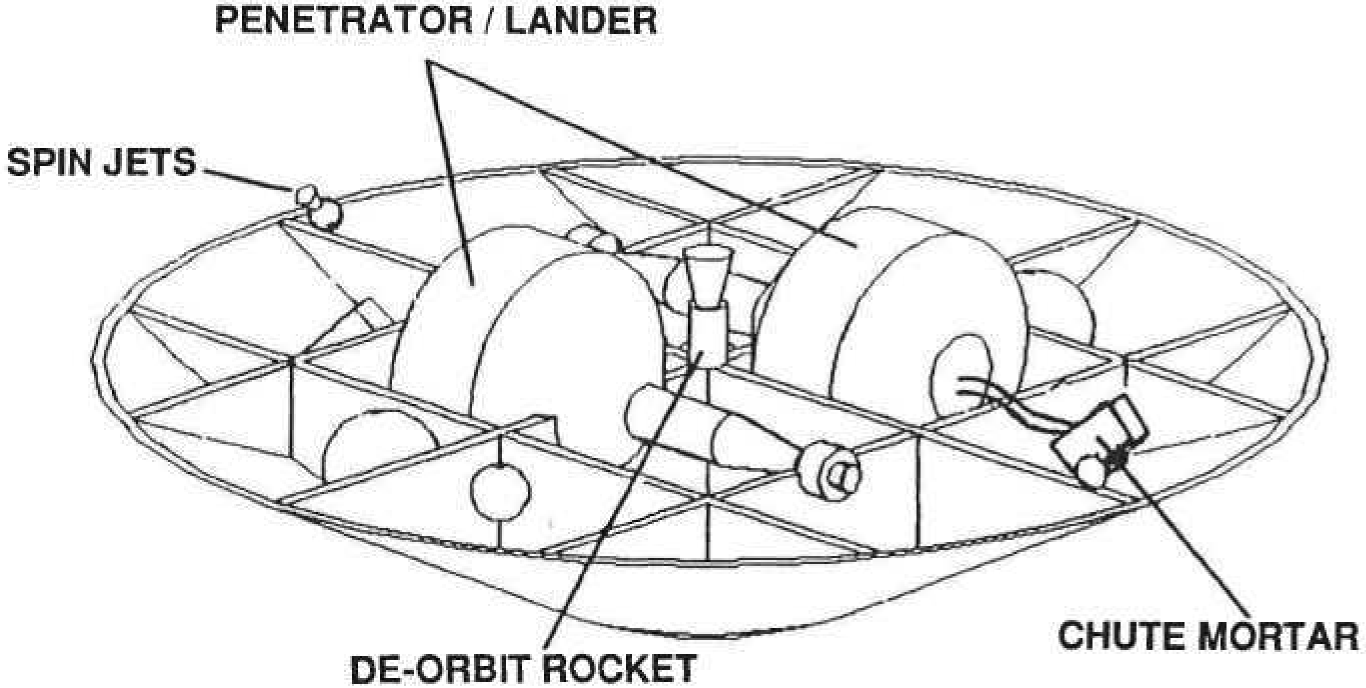
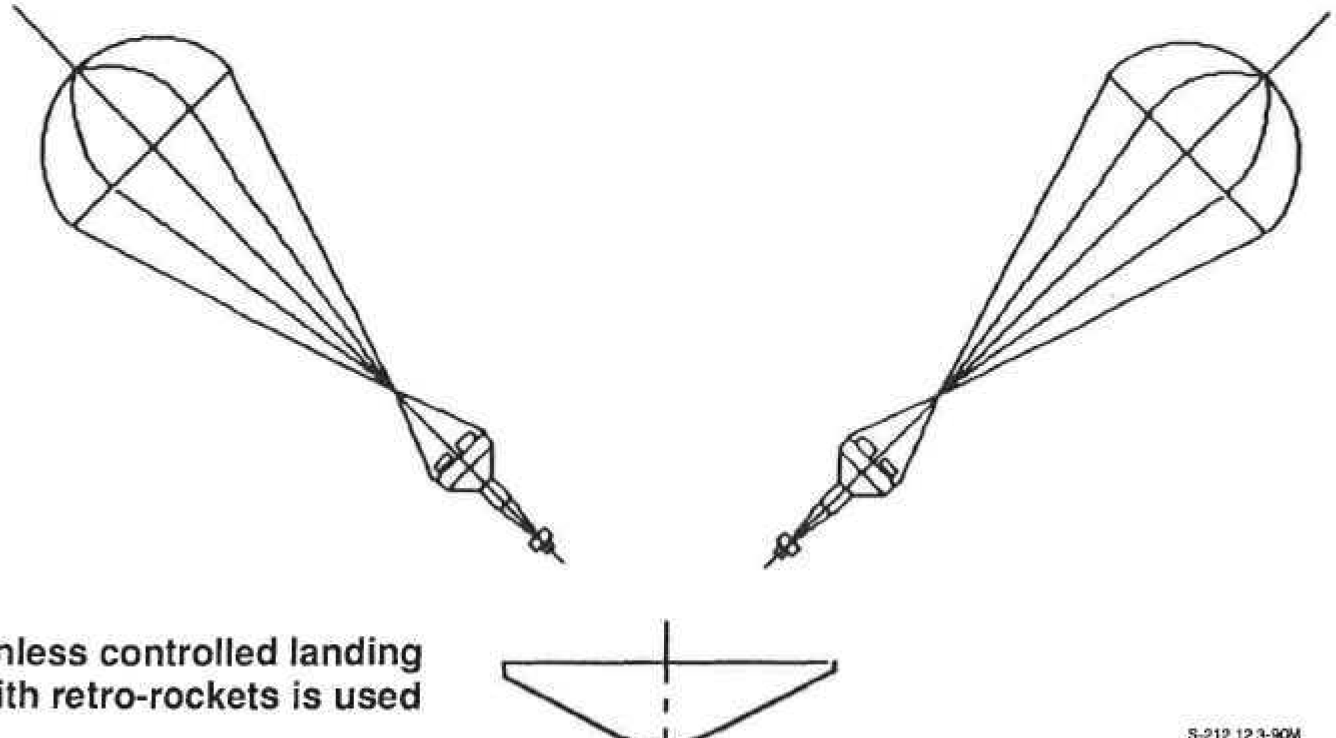
EACH ENTRY VEHICLE CONTAINS TWO PENETRATOR / LANDERS



AFTER EXTRACTION FROM AEROSHELL AND PARACHUTE DESCENT, PENETRATOR/LANDERS IMPACT MARS AT 60-100 m/sec*



*Unless controlled landing with retro-rockets is used

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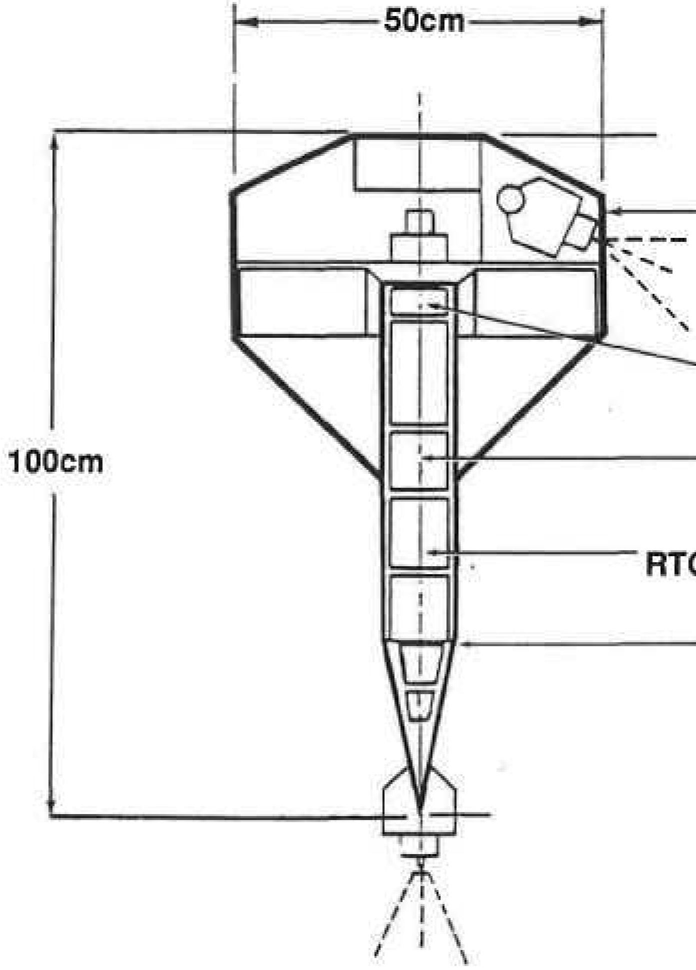
S-212.08 3-90M

ORIGINAL JPL CONCEPT CALLED FOR COMBINED PENETRATOR AND LANDER

Free to separate during Mars impact, but connected by umbilical wire



LANDER (AFTBODY)
To study surface chemistry, seismology meteorology, and visual imagery, and to communicate with orbiter

Umbilical

Batteries for periodic high-density communications bursts to orbiting spacecraft

RTG (~3 watt) for continuously recharging batteries

PENETRATOR (FOREBODY)
To study subsurface chemistry and seismology, soil structure, search for subsurface water and signs of life, generate power

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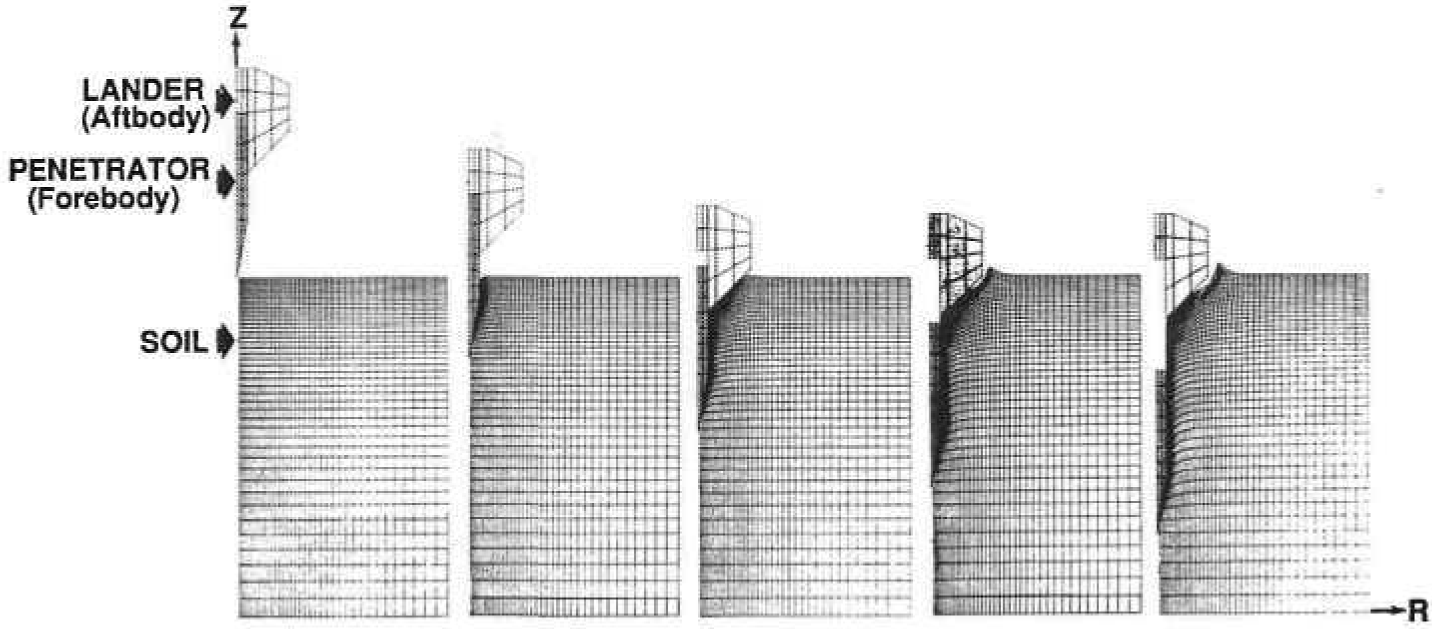
DECELERATION OF PENETRATOR/LANDER AFTER 100 m/sec IMPACT ON TYPICAL SOIL

(Results of Hydrocode Analysis)



TIME, msec	0	4	8	12	16
PENETRATION, m	0/0	0.39/0	0.73/0.15	1.01/0.20	1.23/0.20
VELOCITY, m/sec	100/100	92/92	76/24	62/2	52/1
G-LOAD	0/0	432/432	540/1340	310/400	270/0

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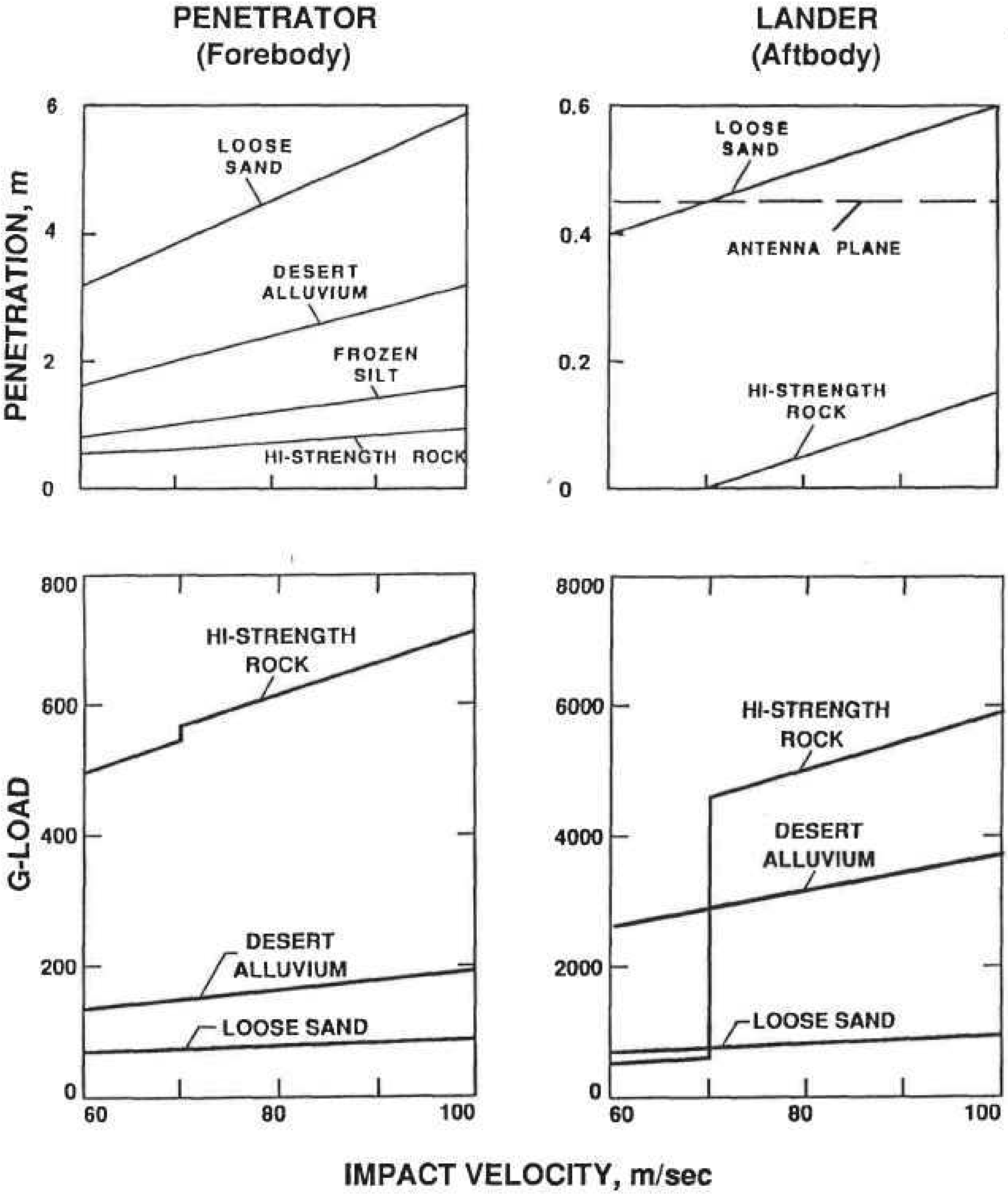
EFFECT OF IMPACT VELOCITY AND SOIL TYPE ON PENETRATION DEPTH AND G-LOAD



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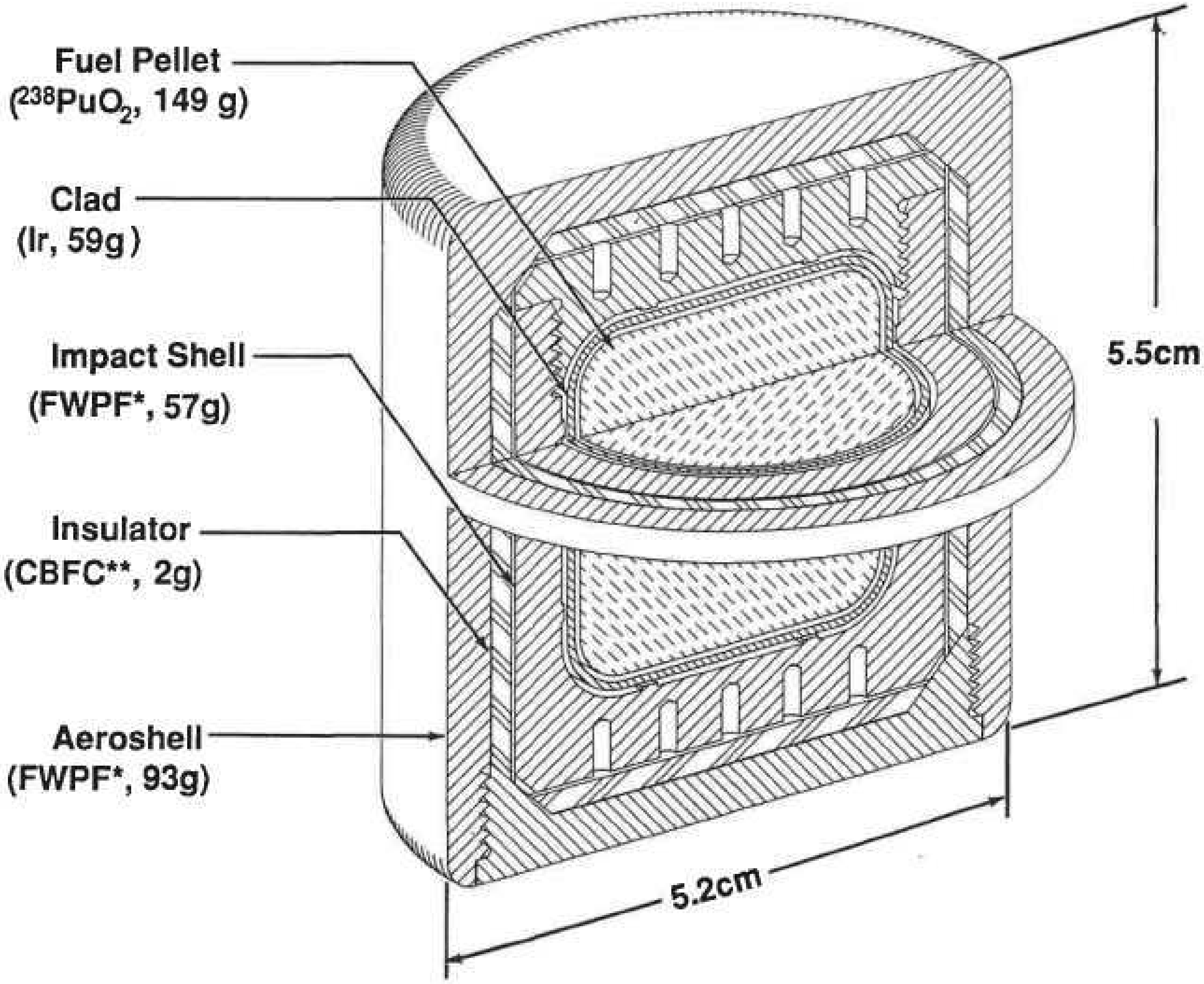
RECENT CHANGES IN JPL MISSION PLAN

- Separate penetrators (~8) for short-time functions (chemistry, mineralogy, soil structure, search for ice and evidence of life)
- Separate surface landers (~20) for long-time functions (seismology, meteorology)
- Short-life penetrators powered by batteries
- Only the long-life landers have RTGs
- Impact survival of RTGs is enabled by equipping landers with small retrorockets, to reduce their impact velocity
- To reduce mass of required retrorockets, rugged (impact-resistant) RTGs are desired

S-219.07B 5-90M

RTG HEAT SOURCE
WITH SELF-CONTAINED SAFETY PROVISIONS
(62.5 thermal watts, 360g)

- **Fuel Pellet and Clad Identical to Flight-Proven Galileo RTG**
- **Impact Shell, Insulator, and Aeroshell use Identical Materials and Thicknesses as Flight-Proven Galileo RTGs**



*Fine Weave Pierced Fabric, a 90% dense carbon-carbon composite
**Carbon-Bonded Carbon Fiber, a 10% dense carbon-carbon composite

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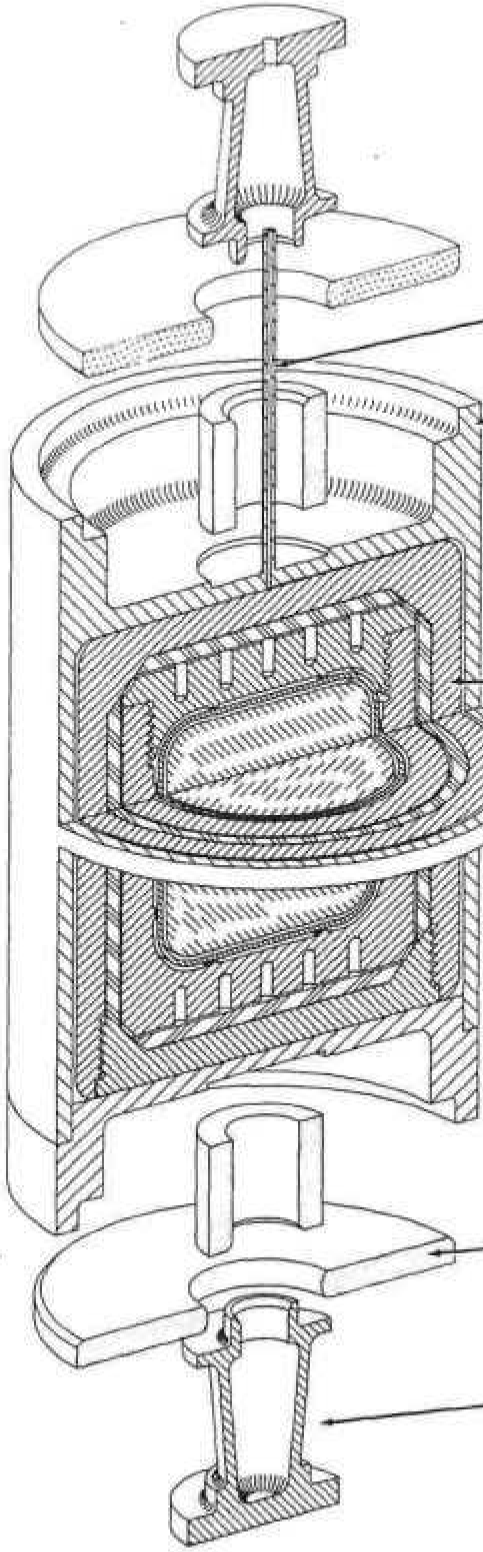
HEAT SOURCE, CANISTER, AND STRUCTURAL SUPPORTS



Helium Vent Tube (Mo)

Canister (Mo), 561g
Prevents release of alpha-generated helium into evacuated converter

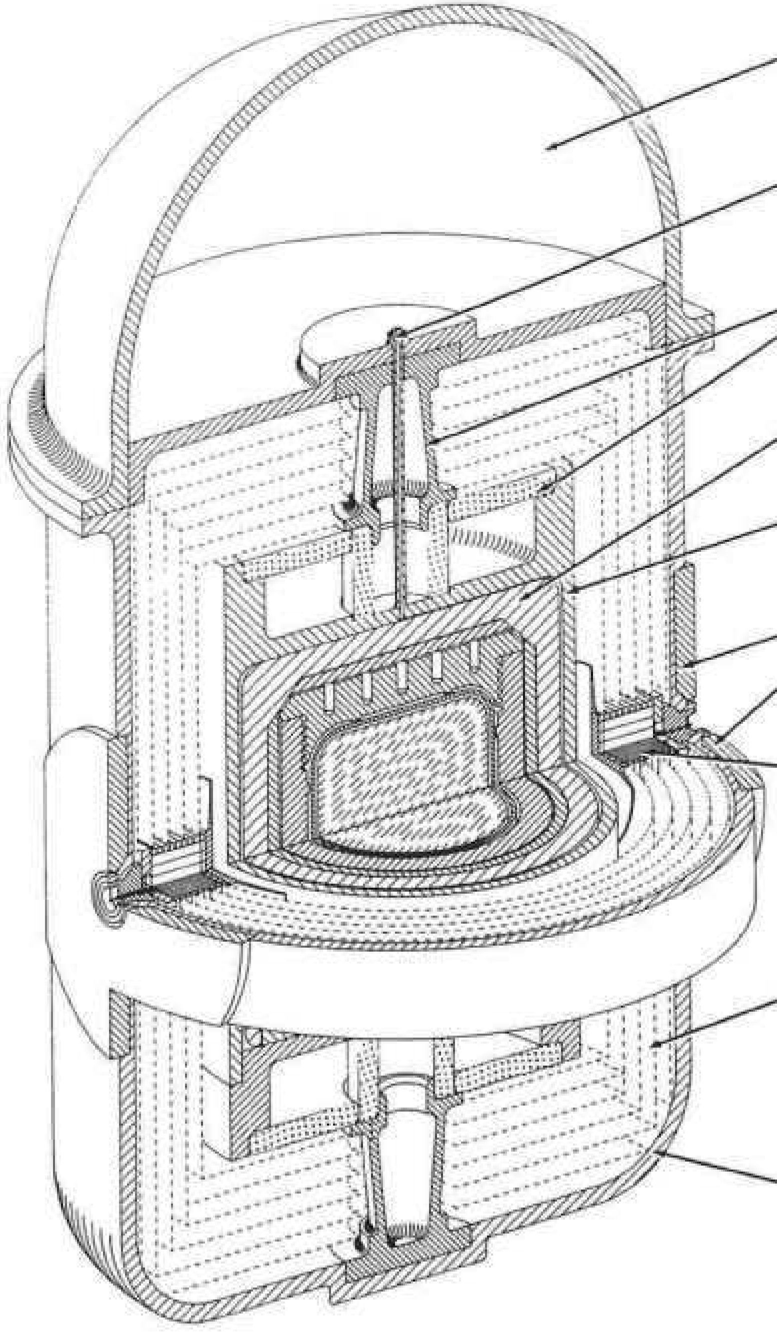
Heat Source, 360g

Thermal Insulator (ZrO_2), 52g

Support Stud (Ti), 36g

S-212.18

RTG FOR MARS GLOBAL NETWORK MISSION



Helium Accumulator
(10 atm after 10 years)

Helium Vent

Structural Supports

Heat Source

Canister

Heat Spreader
(Cu, 2, 28g)

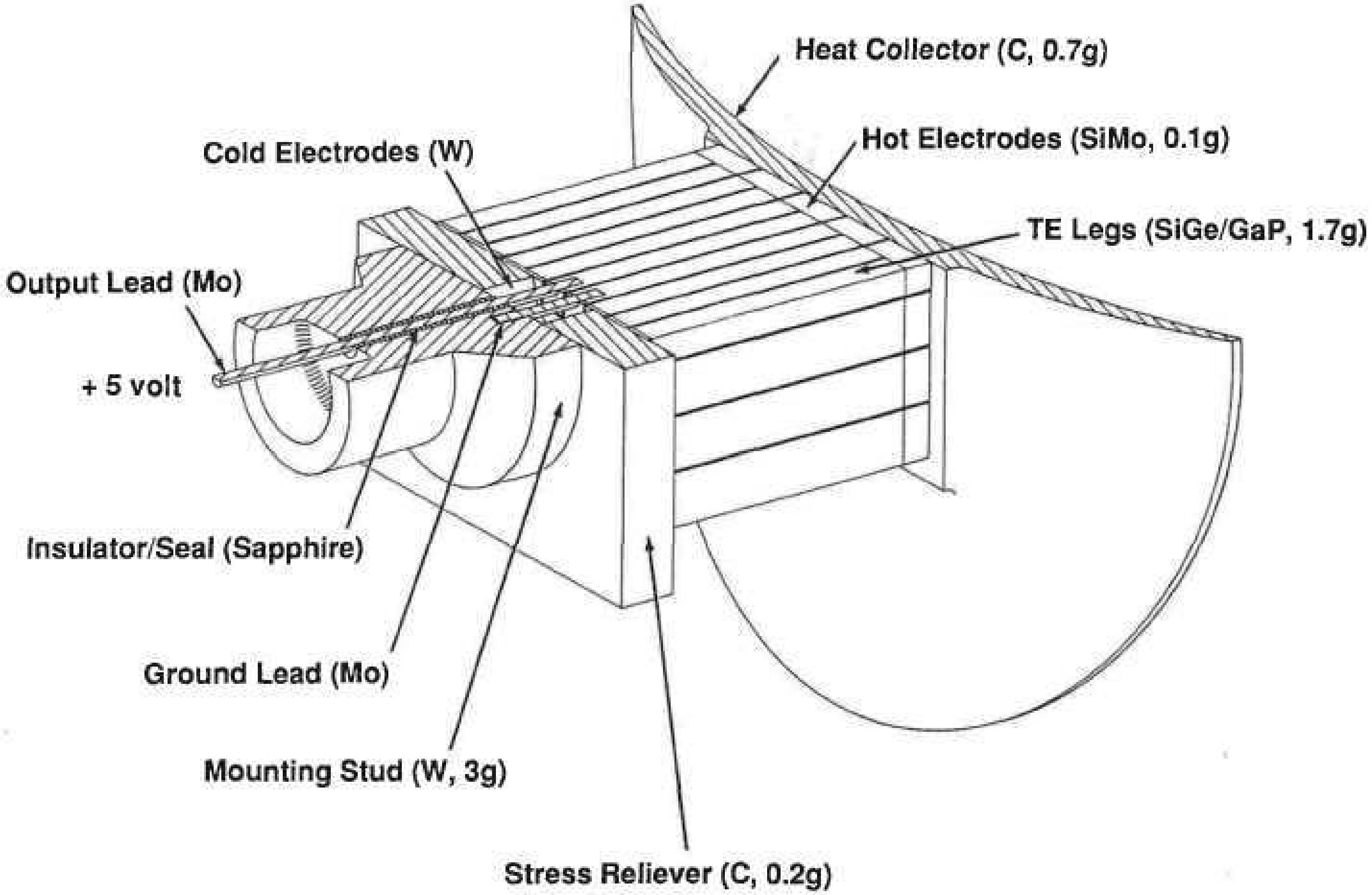
Thermoelectric
Multicouple
(2, 12g)

Multifoil
Thermal Insulation
(Mo, 60, 218g)

RTG Housing
(Ti, 698g)

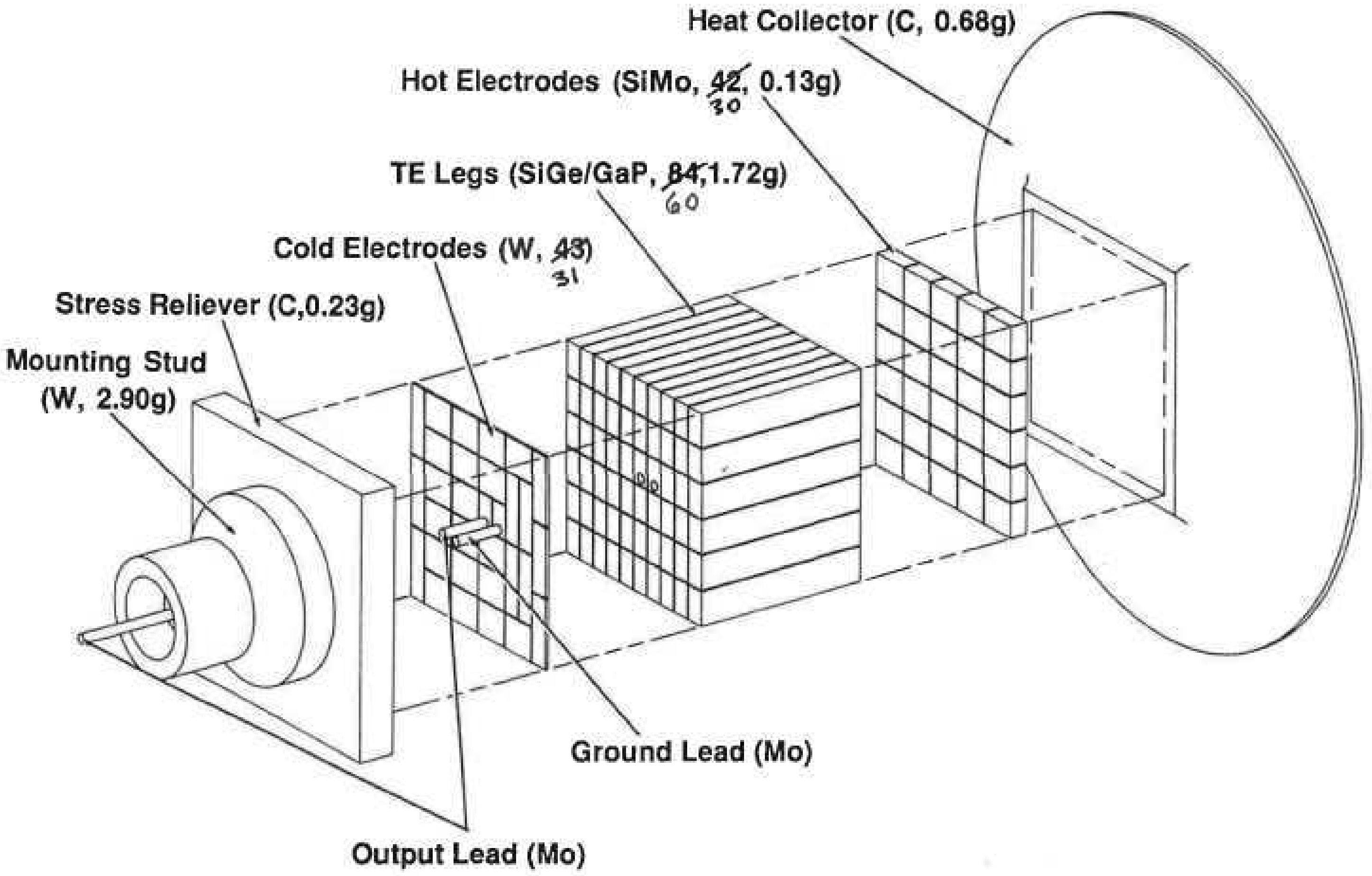
THERMOELECTRIC MULTICOUPLE

Sectioned at Midplane to show Built-in Ground Lead and Sealed Output Lead



THERMOELECTRIC MULTICOUPLE

Exploded View



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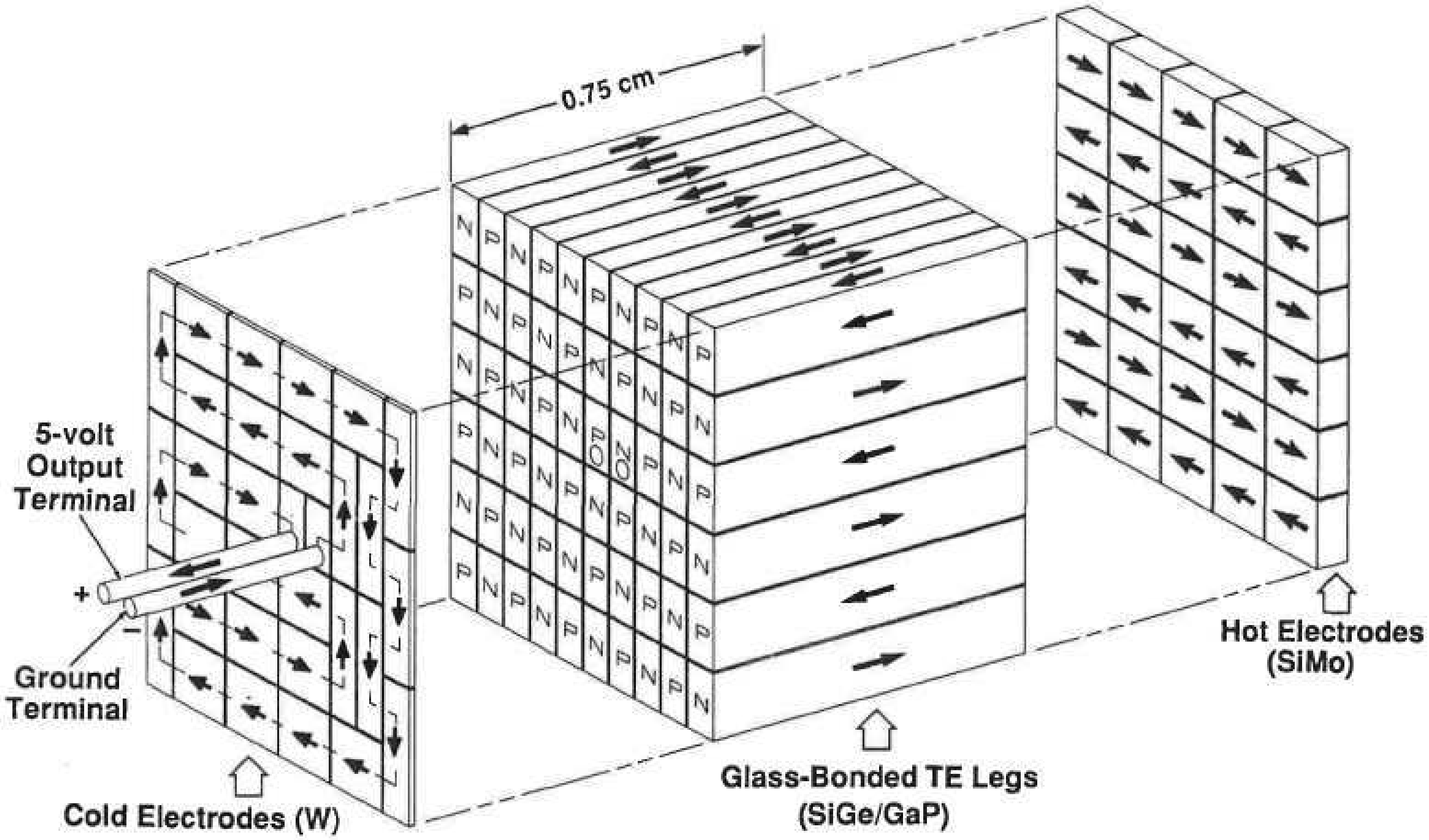
MULTICOUPLE THERMOPILE

Exploded View Showing Current Path Through 60 Alternating N- and P- Legs



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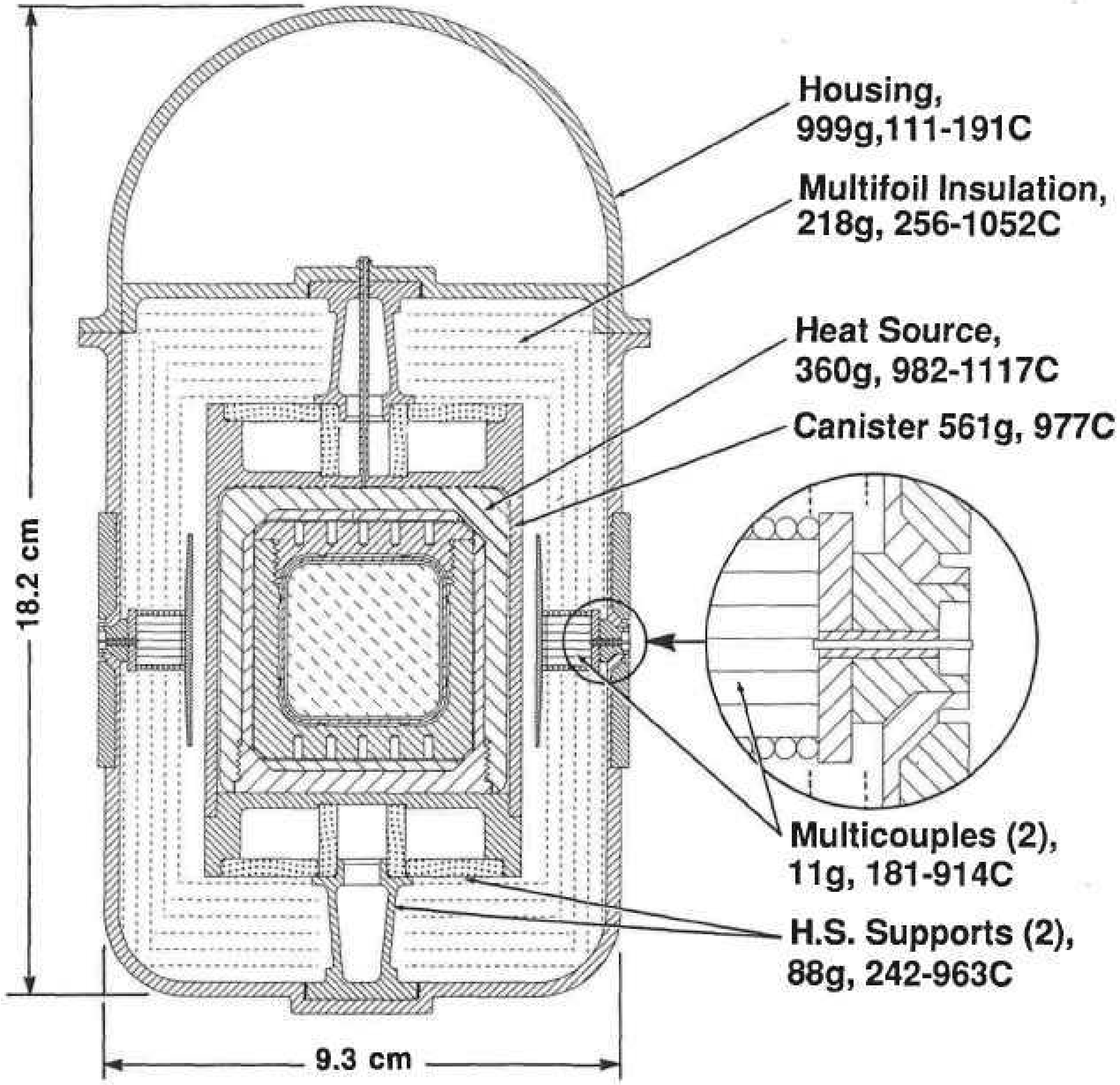
PERFORMANCE OF ILLUSTRATIVE 3.0-WATT RTG

Size, Masses, Temperatures, Heat Flows, Efficiencies, and Output



Heat Flow (w) :	
Fuel	62.5
H.S. Supports	19.1
Insulation	10.9
TE Legs	32.5

Efficiency (%) :	
Thermal	57.0
Material	9.0
Multicouple	8.6
System	4.9

Output :	
Current	0.546 Amp
Voltage	5.60 Volt
Power	3.06 Watt
Mass	2.05 kg

RTG RUGGEDNESS ENHANCED BY:

- Basing heat source on impact-tested and flight-proven GPHS design
- Enclosing heat source in strong refractory-metal canister
- Structurally supporting the canned heat source without contacting the more fragile TE elements
- Using multicouple instead of unicouples, and eliminating need for voltage step-up
- Providing each multicouple with internal ground lead and single sapphire-sealed RTG terminal, to eliminate need for fragile feedthroughs
- Using titanium or stainless for RTG housing, to permit all-welded enclosure, and to eliminate compression seals
- Providing integral helium accumulator, to eliminate need for vents to outside and for semi-permeable seals

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