TRANSIT THERMAL CONTROL DESIGN FOR GALILEO ENTRY PROBE FOR PLANET JUPITER

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ABSTRACT

A totally passive design has been completed for the thermal control of the Galileo entry probe during its transit to the planet Jupiter. The design utilizes radio-isotope heater units, multilayer insulation blankets and a thermal radiator, in conjunction with a design conductance support structure to achieve both the required storage and critical initial planet atmosphere entry temperatures. The probe transit thermal design has been completed and verified based on thermal vacuum testing of a prototype probe thermal test model.

INTRODUCTION

The Galileo Probe is being prepared for exploration of the atmosphere of the planet Jupiter in an extension of the earlier Pioneer Probes which successfully sampled the atmosphere of the planet Venus. The environments for the Galileo Probe present unusual and challenging thermal design requirements. The planet Jupiter's size, distance from both the sun and earth, and potential range in atmosphere composition and density profiles are primary contributors to the uniqueness of these thermal requirements.

This paper summarizes the design, development, and test verification for the probe design for thermal control of the probe during its transit from earth and up to its initial entry into the Jupiter atmosphere.

The probe is designed for attachment to the Galileo Orbiter. The Orbiter/Probe Assembly is to be carried by the Shuttle in a launch from Cape Kennedy to a parking orbit about the earth. The combined Orbiter/Probe Assembly is to then be put into a transfer orbit for the planet Jupiter. The nominal time for this joined assembly transit phase is approximately 730 days from its separation from the Shuttle until it is at a proper location and trajectory relative to Jupiter.

The normal attitude and orientation of the Galileo Orbiter and Probe, during its transit from earth to Jovian capture, is such that the Orbiter completely shades the Probe from solar insolation. There are intermittent periods, during this transit phase, when the Orbiter/Probe attitude is changed to permit interrogation by earth control stations. Direct solar heating of the Probe forebody section may occur during these brief periods, dependent upon the transit trajectory and earth/sun relative positions. The maximum time during which direct solar heating of the probe can occur during these periods has been limited by system considerations to four (4) hours.

The Probe will then be separated from the Orbiter for its continued approach to the planet. This separation will occur 75 ± 25 days before the Probe will begin its entry into the planet's atmosphere. The primary (and coldest) thermal design transit environment for the Probe is this nominal 75 day period. The solar insolation, at this location in our solar system, of approximately 5 watts/ft^2, is insufficient and too trajectory-constraining to effect solar heating for Probe thermal control.

PROBE TRANSIT THERMAL DESIGN REQUIREMENTS

Pre-Separation Phase

A design probe interior average temperature range was selected for the nominal 720 days of transit (i.e. while joined to the Orbiter) based on the storage/life characteristics of the lithium oxygen entry battery cells and the experiment, telemetry and control components storage temperature requirements. The design range considers the above maximum of four (4) hours duration, during which the Orbiter attitude can be such that the sun may illuminate portions of the Probe or adjacent Orbiter surfaces. The Probe design temperature range and Orbiter: Probe thermal interface conditions are summarized in Table 1.

Up to five (5) watts of electrical power can be provided to the Probe from the Orbiter during this first transit phase. However, the Orbiter power requirements are such that a goal for the Probe design was to accomplish its thermal control without use of this power.

Post-Separation Phase

The primary Probe design environment is that encountered during the 50 to 100 days following the Probe's separation from the Orbiter, as the Probe approaches the Jupiter planet. The design objective is for the Probe's interior average temperature to equilibrate to 0°C ± $^{10^\circ\mathrm{C}}_{-5^\circ\mathrm{C}}$ following its separation from the Orbiter. This minimum temperature is that which the lithium oxygen battery cells are sufficiently warm to provide the electrical energy as required for experiment, telemetry and control upon planet atmosphere entry. The maximum temperature was selected so that maximum experiment operation time will be realized during the Probe's descent into the planet's atmosphere. This operational time period will be limited to that time at which the equipment ceases operation due to the excessive descent environment-induced temperatures.

PROBE THERMAL DESIGN PHILOSOPHY

Preliminary studies indicated that post-separation transit thermal control of the Probe by either controlled electrical heating or utilization of an enhanced thermal capacitance was spacecraft weight prohibitive.

The basic one-watt, U238, Radio-isotope Heating Units (RHUs) used so successfully for local appendage heating for the JPL Voyager Spacecraft and earlier military applications offered a promising low-weight thermal energy source. The design problem in the utilization of the RHUs for Probe transit thermal control is the accommodation of the RHU's continuous thermal dissipations during all phases of pre-launch, launch, and transit, and the resulting Probe temperatures.

A Probe thermal design evolved from considerations of the various Probe thermal environments which incorporates the direct exposure of a specific area of the Probe heat shield nose as a space thermal radiator. This direct exposure of the Probe nose increases the required number of RHU watts at significant associative costs. However, the objective of this direct exposure is to provide a design bias on the heat loss "paths" and the resulting Probe thermal equilibration temperatures for each launch and transit phase.

The other basic elements of the Probe transit thermal design are a multiple layer insulation (MLI) blanket set, a three-element Probe: Orbiter support adapter set having a design thermal radiative/conductive characteristic and three Probe: support adapter thermal insulators. The basic Probe transit thermal control configuration is shown in Figure 1.

The Probe design thus contains no active elements to trim or modulate either the effects of the RHU thermal output or the heat loss from the Probe exterior during this design post-separation planet approach period. The Probe interior temperature distribution realized during this period will be primarily determined by the insulation blanket's performance (e.g., effective emissivity) and the thermal energy radiated directly from Probe exposed surfaces (including the separation support interface surfaces). As indicated previously, the equilibrated temperatures of the individual Probe components attained during this phase will be their "start-up" temperatures at the beginning of entry into the Jovian atmosphere, and will constrain the experiment's operational period

Similarly, the Probe's pre-separation transit interior temperature is dependent upon achieving a sensitive design balance between the continuous thermal dissipation of the radio-isotope heater units (RHUs), the heat loss thru the Probe support structure, the insulation blankets, from the exposed heatshield nose area, and thru radiation to the adjacent Orbiter surfaces.

PROBE TRANSIT THERMAL CONTROL ELEMENTS

Radio-Isotope Heating Units (RHUs)

The RHUs are the only source of thermal energy for the Probe during its post-separation transit phase. The RHU design is a weight-reduced version of the earlier Pioneer RHU. Each RHU contains the precise quantity of U238 isotope to release 1.0 watts of energy at three (3) year's following fabrication. The design half-life for this isotope is 86 years. Each RHU consists of multiple metal cylindrical enclosures of the U238, which contain, absorb, and limit the isotope gamma and neutron radiation. The outermost metal cylinder is, in turn, enclosed in a machined graphite cylinder with the resulting outside nominal dimensions of 2.5 cm. O.D. x 3.1 cm. in length. The nominal weight for each RHU is 38 gm.

The RHUs are attached to the interior surface of the Probe forebody and aft cover heat shield aluminum liners as shown in Figure 1. The number used and location of the RHUs were analytically determined based on MLI blanket, nose radiator and temperature gradient considerations.

MLI Blanket Set

The primary component in the Probe assembly which will determine the RHU thermal dissipation requirement is the multiple layer insulation (MLI) blanket set. This blanket set will restrict the heat loss from the relatively large Probe forward and aft exterior surfaces (approximately 3.5 m^2). There is an extensive history in the design and utilization of MLI insulation for nearly every satellite and space vehicle system. The Galileo MLI blanket's application requirement is unique, with regards to this experience, in that it is essential that their thermal insulation performance be precisely known and maintained. If the blanket's heat loss is greater than the design range during the Probe's planet approach, then the equilibrated Probe's interior temperature will be colder than the design limit for activation of the Probe payload and power assemblies. Conversely, if the blankets provide greater insulation than their design range, then the temperatures of the Probe's payload and power assemblies will be higher than the design limit. Both science payload and power system mission performance will be significantly affected by storage and activation temperatures in excess of +20°C.

The MLI blankets have been configured such that joints, penetrations, fasteners, electrostatic (ESD) grounding and installation effects will be minimum in their effect on Probe heat loss while in transit environments. Thermal vacuum testing and blanket manufacturing control are essential to the Probe thermal design. The Probe is expected to encounter charged particle fields, as it approaches Jupiter, of approximately 40 times greater than those encountered by geosynchronous satellites orbiting the earth. Particular care has been given to providing electrical grounding of all of the Probe exterior elements. A black, electrically-conductive coated, vacuum deposited aluminum, Kapton outer layer was used as the outer layer for all of the MLI blanket areas which could experience solar heating. All surfaces of the blankets and tapes were provided a ground path to the electrically-conductive, phenolic carbon, forward heat shield.

Probe Space Thermal Radiator

The design objective of the direct exposed Probe thermal radiator is to bias the heat leak from the Probe such that it is predominantly via the Probe forebody surface. This bias thus minimizes the thermal differences between the post-separation environment effects and pre-separation thermal effects of the Orbiter upon the Probe aft surfaces and support interface. The second design objective of the nose radiator is to desensitize the Probe's thermal balance equilibration temperature to the MLI blanket set's thermal performance. The accompanying Figure 2 summarizes, schematically, the design Probe thermal balance distribution goals for both the Probe's pre-separation and post-separation thermal environments.

It was recognized early in the Probe transit thermal design concept effort that there should be some means of realistically accomplishing a trim on the thermal balance of the final Probe flight assembly in view of:

1. MLI blanket set installation effects on realized blanket performance.
2. Differences in thermal performance between development and flight MLI blanket set thermal performances.
3. Substantial efforts involved in the Probe heat shield disassembly required to add or remove internally-mounted RHUs to achieve design equilibration temperatures.

A "trimable" thermal radiator design evolved which employed use of a stable, low emissivity tape, in conjunction with the inherent high emissivity of the Probe forebody phenolic graphite forebody heat shield. The design involved space exposure of a specific area of the forebody nose phenolic carbon surface and a proportioned area of exposed adjacent low emissivity (ϵ_H) tape-covered forebody. All other significant surface areas of the post-separation Probe are enclosed by the MLI blanket set.

A vacuum-deposited gold coated Kapton tape, with a silicone adhesive was selected for the low ϵ_H radiator tape. Thermal balance adjustment of the Probe flight set can then be effected by removal (or addition) of the taped areas of the exposed forebody to compensate for the realized final assembly MLI blanket set performance.

Probe Support Attachments

The Probe nominal design temperature during its early transit phase (i.e. while joined with the Orbiter) is -10°C, which is 10°C less than its nominal design temperature following separation from the Orbiter. The thermally conductive coupling of the Probe thru its supports with the Orbiter offered a means of compensation for the effects of the thermal radiative presence of the orbiter relative to the Probe aft surfaces. This compensation is possible since the Probe support, Orbiter mounting interface temperature is lower than the Probe design internal temperature.

A Probe support thermal design was accomplished that provides a net conductive heat transfer thru the three support assemblies to the Orbiter to compensate for the radiative presence of the Orbiter. The design includes a carbon phenolic conical insulator between the local Probe mating surfaces and the three support assemblies. This design also depends upon a low thermal conductance and a low emissivity of the three support assemblies. The low thermal conductance is achieved by the use of titanium alloy 6AL-4V and minimum strut cross-sections. Low emissivity of the surfaces of the three support assemblies is obtained by covering them with the same gold-coated Kapton tape used for achieving low ϵ_H on the selected areas of the Probe forebody space thermal radiator.

Electrical Heaters

The Probe transit thermal control design was accomplished in time-parallel, both with the JPL Orbiter design effort and several planet-entry Probe trade considerations which presented potential design/support interface uncertainties. Three 1.66W thermostatically-controlled electrical heaters were incorporated into the Probe design to prevent excessively low interior temperatures during the pre-separation transit phase in the event that the Orbiter: support adapter's interface temperature evolved to < -150°C, or increased Probe weight necessitated larger support assembly cross-sections and/or materials with increased Probe support net conductive heat loss.

The design objective has continued to be for a totally passive pre-separation transit Probe thermal control (i.e. no electrical heating).

DESIGN TRADES

An analytical model was constructed of the Probe to simulate, thermally, its response and equilibration to the various mission thermal environments. The basic model was configured to represent the Probe in its primary design post-separation mission phase. The model, as constructed, consisted of 104-nodes and simulated a 1/6 section of the Probe, reflecting its symmetry and the need for prediction accuracy of local temperatures with consideration of computer trade costs. This model was used to assess the sensitivity of the post-separation Probe configuration to the number of RHUs, MLI blanket set thermal performance, space radiator area exposure and radiator tape effective emissivity.

A second analytical model was constructed by the addition of nodes to thermally simulate the Probe and support adaptor's effects on the Probe responses and equilibration to the pre-separation transit environment, in combination with the Orbiter thermal interfaces.

This pre-separation Probe model continued the symmetrical representation of 1/6 of the Probe and included conductance to the adjacent support adapter and simulation of the adjacent Orbiter thermal radiative presence. The resulting model consisted of 136-nodes and also included simulation of the three previously identified thermostatically-controlled electrical heaters.

The post-separation and pre-separation Probe thermal models were exercised to predict equilibrated temperatures for various combinations of MLI effective thermal performance, number of RHUs, total radiator exposed area, radiator tape effective emissivity, and tape coverage. Figures 3 and 4 show the results from several of these trades. A specific Probe design was selected, based on these trades, as the design having the minimum sensitivity to the probable range in design parameters.

The final selected Probe design thermal parameters are summarized in Table 2. These Probe thermal models were also modified to permit evaluation of both thermal response and equilibrated Probe temperatures to specific storage and Shuttle Bay thermal environments.

PROBE THERMAL BALANCE TESTS

The passive thermal design of the Probe and its critical post-separation equilibration temperature made thermal vacuum testing an essential part of the thermal design development. Such testing in the post-separation configuration was necessary to provide an assessment of:

1. The MLI blanket set thermal performance.
2. The nose radiator thermal performance.
3. The equilibration temperature and Probe interior temperature gradients with the selected 31 RHU complement.
4. A calibration of the effect of RHU dissipation on Probe equilibration temperature.
5. A calibration of the effect of radiator gold tape coverage on Probe equilibration temperature.

Similarly, thermal balance test in the pre-separation Probe configuration was necessary to provide an assessment of:

1. The adequacy of the thermal conductance designed support adaptors to compensate for the effect of the Orbiter's thermal presence upon the Probe's equilibration temperature.
2. The effects of Orbiter: adaptor interface and Orbiter thermal sink temperatures upon the Probe equilibration temperature.

3. An assessment of the electrical heater power requirements.

4. The equilibration temperature and Probe interior temperature gradients with the selected 31 RHU complement.

The Probe structural test model, with an experiment package in place, was fitted with 44 simulated (electrically-heated) 1-watt RHUs. The design gold tape radiator pattern was applied to its forward heat shield nose, leaving the selected surface exposure of 660 cm^2 of phenolic graphite. A design 3-element, MLI blanket set was installed and the Probe assembly was properly completed for thermal vacuum testing in its post-separation configuration. The assembly was then installed in a liquid nitrogen-cooled vacuum test chamber. The Probe assembly was brought to temperature equilibration at two RHU complement dissipation levels (33 and 39W). The corresponding Probe internal average equilibration temperatures were -21.5 and -12.3°C. The Probe was then modified by adding an additional 465 cm^2 of gold tape to the nose radiator and again exposed, with 39 watts of dissipation, to the liquid nitrogen vacuum simulated post-separation environment. The resulting equilibration Probe average internal temperature was +.8°C. The accompanying Figures 5 and 6 summarize these test results.

The Probe and test facility were then modified to provide simulation of the effects of a range of Orbiter: support adapter and Orbiter radiative thermal sink temperatures upon the Probe. This pre-separation Probe configuration (with the "added taped" radiator) was brought to temperature equilibration with 39 RHU watts, for the design Orbiter adaptor interface and sink temperatures of -150°C, 0°, and +31°C. Figure 7 summarizes the resulting equilibration Probe average internal temperatures.

The electrical heaters were energized during the final stages of the pre-separation Probe's equilibration to the design -150°C Orbiter interface conditions. All three of the independently-controlling thermostats turned "off" their corresponding heaters at this condition.

CONCLUSIONS

The passive transit thermal design for the Probe is validated for both the post-separation and pre-separation design conditions.

Both the MLI blanket and the thermal radiator's performance were somewhat less than initially expected but are within the design adjustment capability. This reduced performance results primarily from two design development decisions:

1. The initial MLI blanket design involved enclosure of all of the Probe aft surfaces, as well as a part of the forward heat shield surface, with a single MLI element. This design was changed to two individual MLI elements covering these Probe surfaces to simplify the blanket configuration and

Probe: blanket assembly procedures. This design change resulted in approximately a 300% increase in the blanket set joint length and a reduced set thermal performance.

2. A somewhat similar design change involved the installation of the radiator gold tape as butting strip segments rather than overlapping segments. This decision resulted in an approximate 20 mil. average gap exposure of the carbon phenolic heat shield between each segment. This exposure resulted in an approximate 30% increase in the effective emissivity of the taped radiator area.

Evaluation of the test results indicates that the realized thermal performance parameters for the individual MLI blanket elements and the radiator were as follows:

- Aft MLI element effective emissivity (ϵ_{eff}) $\sim$ .021.
- Transition MLI element ϵ_{eff} $\sim$ .04.
- Forward MLI element ϵ_{eff} $\sim$ .024.

  Overall (area average) MLI set ϵ_{eff} $\sim$ .026.
- Area Average gold taped radiator section ϵ_H $\sim$ .075.
- Bare phenolic carbon ϵ_H $\sim$ .89.

The Probe pre-separation electrical heaters and thermostats are not needed and may be removed from the flight Probe hardware.

TABLE 1

PROBE TRANSIT THERMAL DESIGN REQUIREMENTS AND INTERFACE CONDITIONS

DESIGN PROBE INTERNAL TEMPERATURES	DESIGN TEMP.	RANGE TOLERANCE
EARLY TRANSIT PHASE (W/SUN)	-10°C	+30°C -10°
TRANSIT (W/O SUN)	-10°C	+20° -10°
POST SEPARATION (JOVIAN ATMOSPHERE ENTRY)	0°C	+10°C - 5°C
ORBITER/ADAPTOR THERMAL INTERFACE	W/SUN	W/O SUN
MOUNTING TEMPERATURE	-50°C	-150°C
EFFECTIVE RADIATION SINK (FOR ADAPTOR AND AFT COVER)	-50°C	-150°C

ELECTRICAL

HEATING (≤5 WATTS) AVAILABLE FROM ORBITER DURING EARLY TRANSIT PHASE.

TABLE 2

SELECTED PROBE TRANSIT THERMAL CONTROL DESIGN CHARACTERISTICS

- 3 Element MLI Blanket
  - 2-Mil. VDA Kapton inner and outer layers.
  - 11 layers Dacron Mesh, alternated with 10 layers .25 Mil. VDA Mylar
  - Pre-Separation, space-exposed blanket areas had Sheldahl conductive (Carbon Polyester) covering.
  - All Kapton and Mylar layers were electrostatically grounded to local conductive heat shield.
- Design Exposure of 5444 cm^2 of Forebody Nose as Thermal Radiator
  - Coverage of 4784 cm^2 of this exposed Forebody with gold-coated 2-Mil. Kapton tape.
- Nominal Complement of 31 1-watt RHUs, with Mounting Brackets for additional 13 RHUs
  - Nominal RHU distribution consisting of:

    6, located on Aft Heat Shield Liner

    7, located on Forward Heat Shield Frustrum Liner

    18, located on Forward Payload Support Ring
- Conical Carbon Phenolic Insulator (.2" thick) between Probe and 3 Support Adaptor Mounting Surfaces
- Thermal Conductance Designated Titanium (6 AL-4V) Support Adaptors (3), with Low ϵ_H Gold Taped Surfaces
- Thermostatically-controlled 1.66W Electrical Heaters (3) Bonded to Probe Internal Longerons

FIGURE 1

GALILEO PROBE TRANSIT THERMAL CONTROL DESIGN

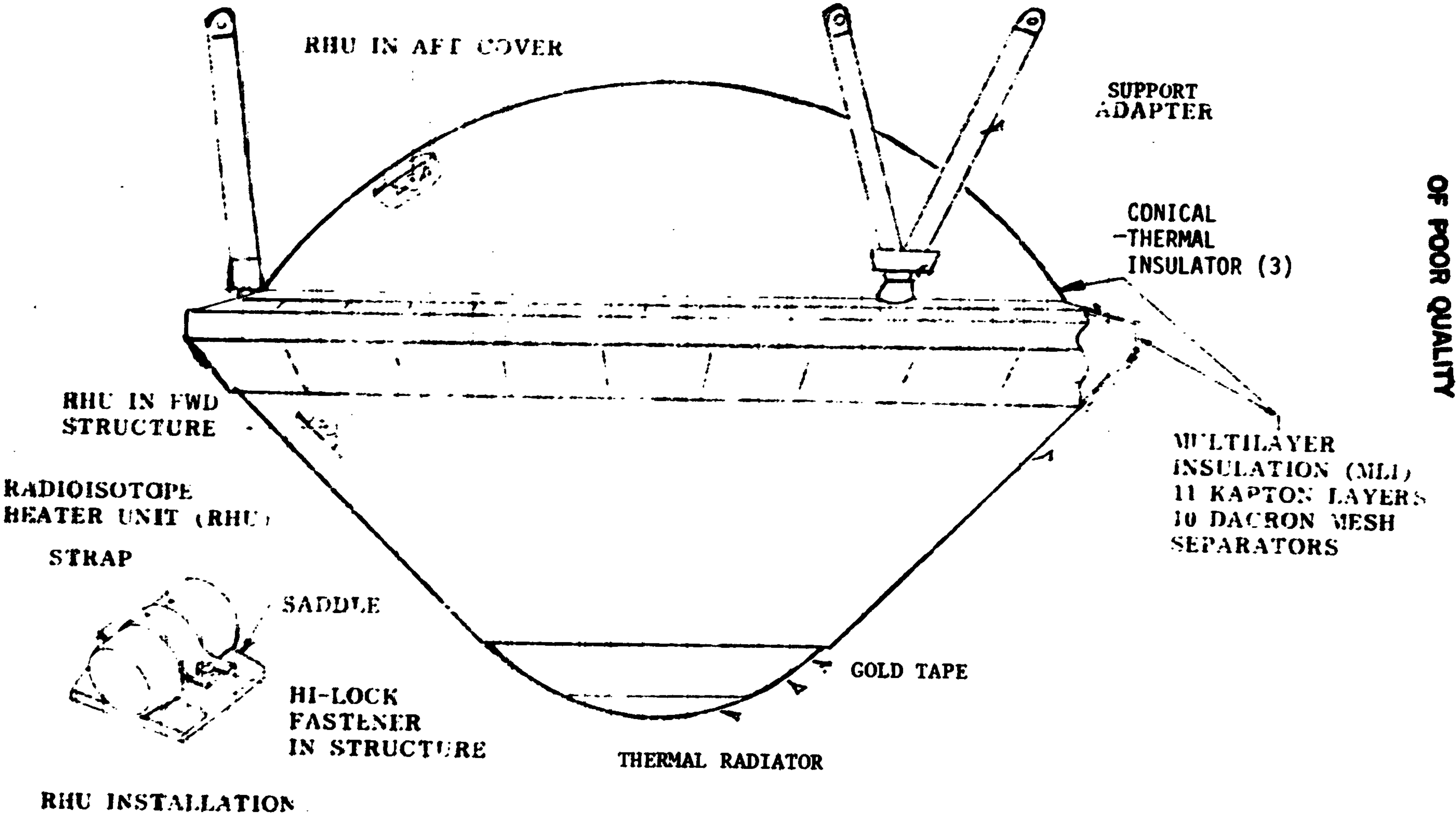
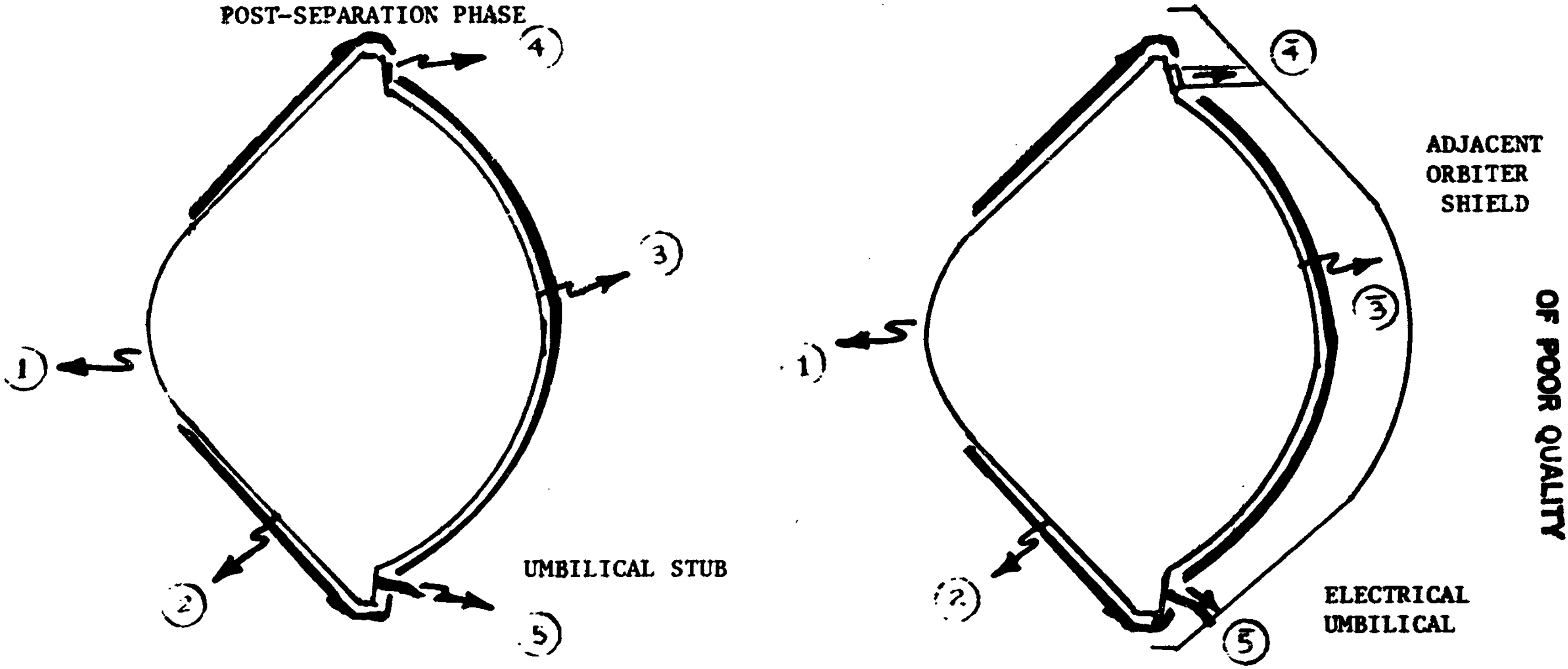


FIGURE 2

PROBE TRANSIT THERMAL BALANCE



THERMAL LOSS		PREDICTED	TEST
Nose Radiator	1	56%	37%
Forward MLI	2		17%
Transition MLI AFT MLI	3	43%	19%
Support Surface	4	< 1%	< 8%
Umbilical Stub	5	< 1%	-

THERMAL LOSS		PREDICTED	TEST
Nose Radiator	1	44%	39%
Forward MLI	2		18%
Transition MLI	3	30.5%	19%
AFT MLI			20%
Support Adaptor	4	25.5%	< 7%
Electrical Umbilical	5	< 1%	

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FIGURE 3

RADIATOR AND MLI BLANKET PERFORMANCE
EFFECTS ON PROBE POST-SEPARATION TEMPERATURE

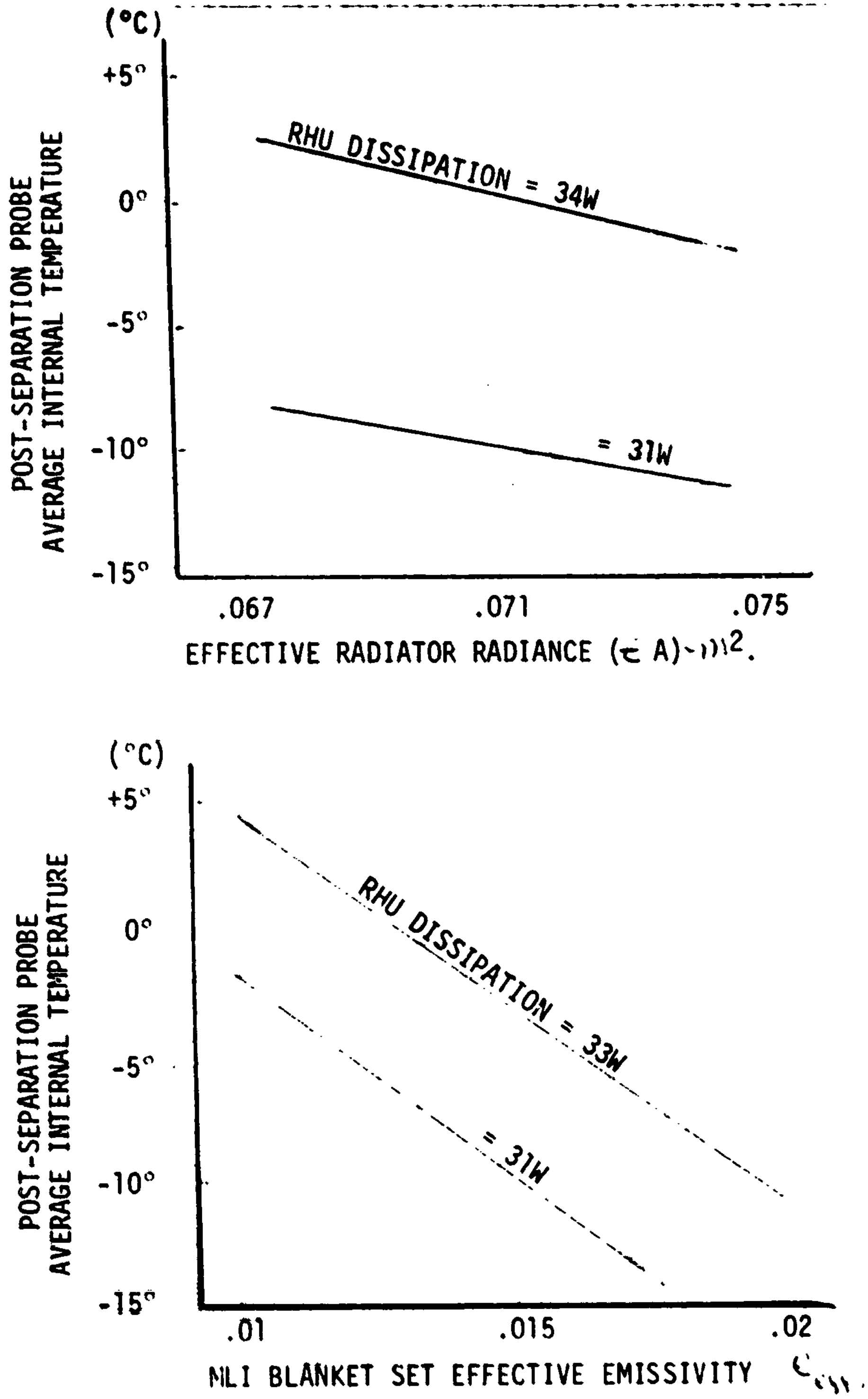

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FIGURE 4
SUPPORT INTERFACE AND MLI BLANKET
EFFECTS ON PROBE PRE-SEPARATION TEMPERATURE

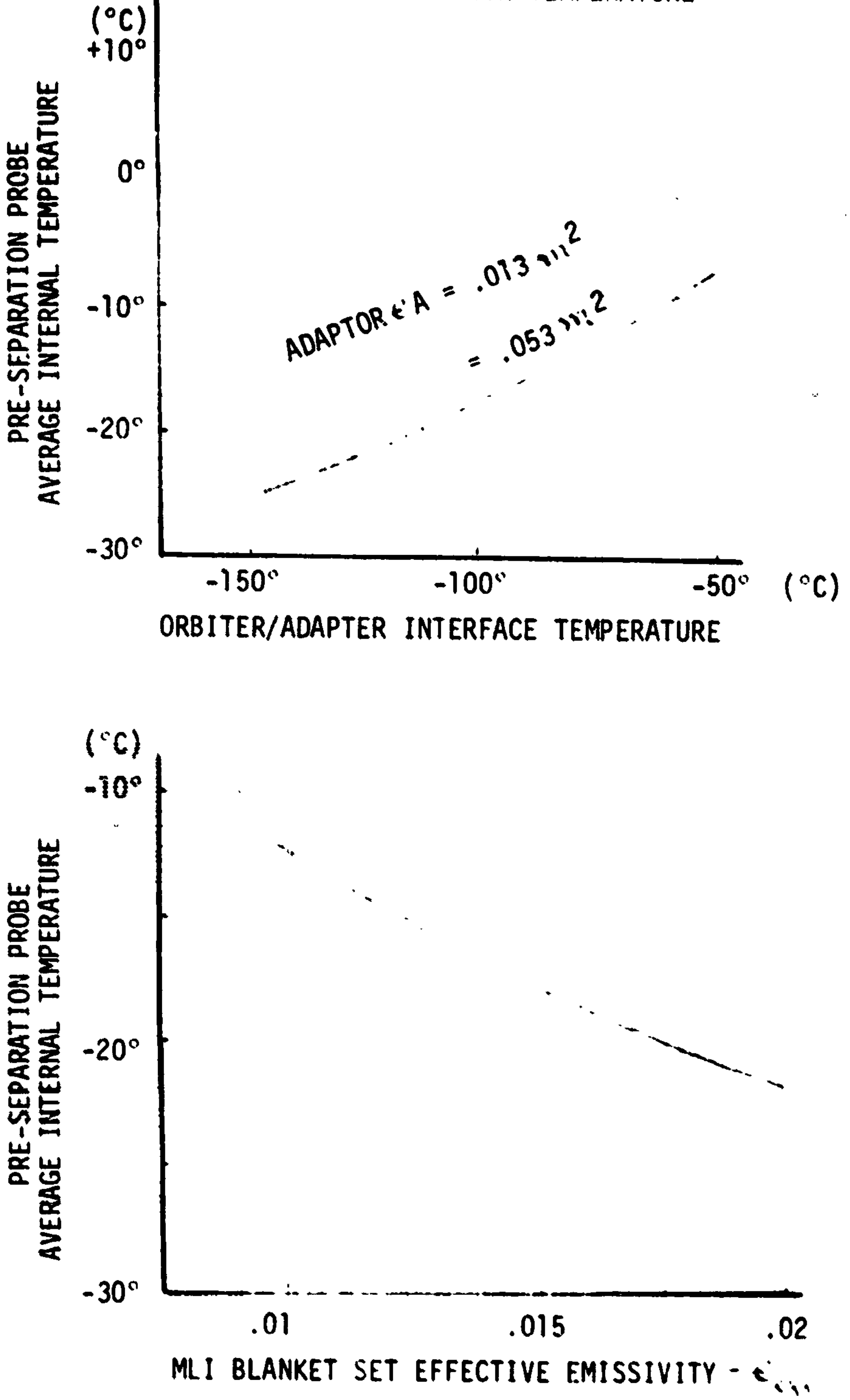

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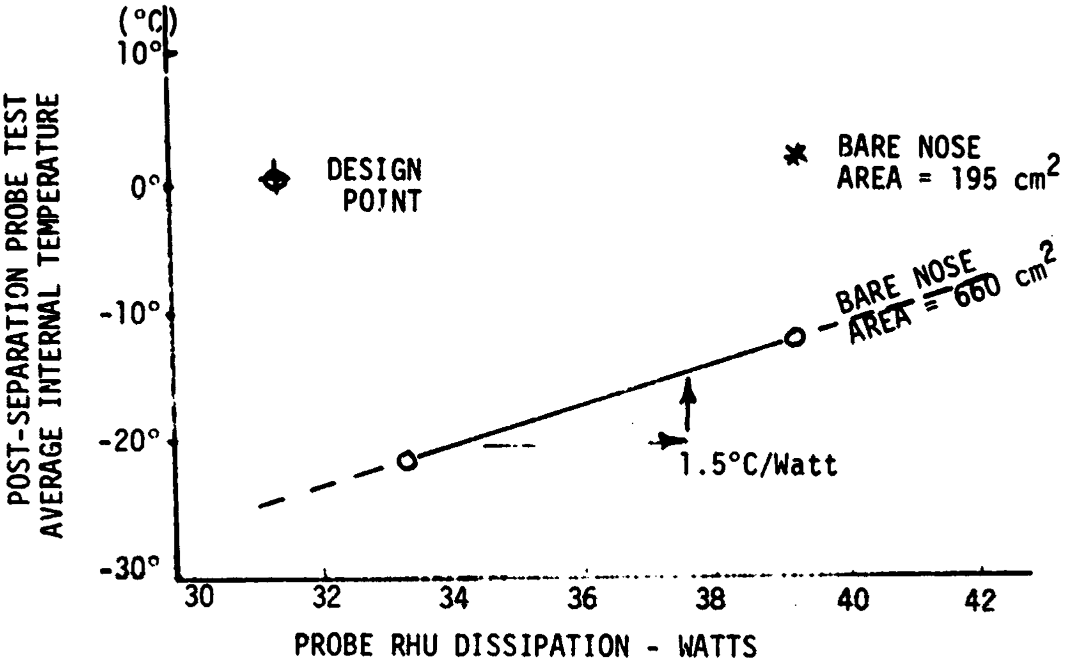
FIGURE 5
POST-SEPARATION TEST EFFECTS OF RHU DISSIPATION
AND RADIATOR TAPE COVERAGE ON AVERAGE PROBE TEMPERATURE



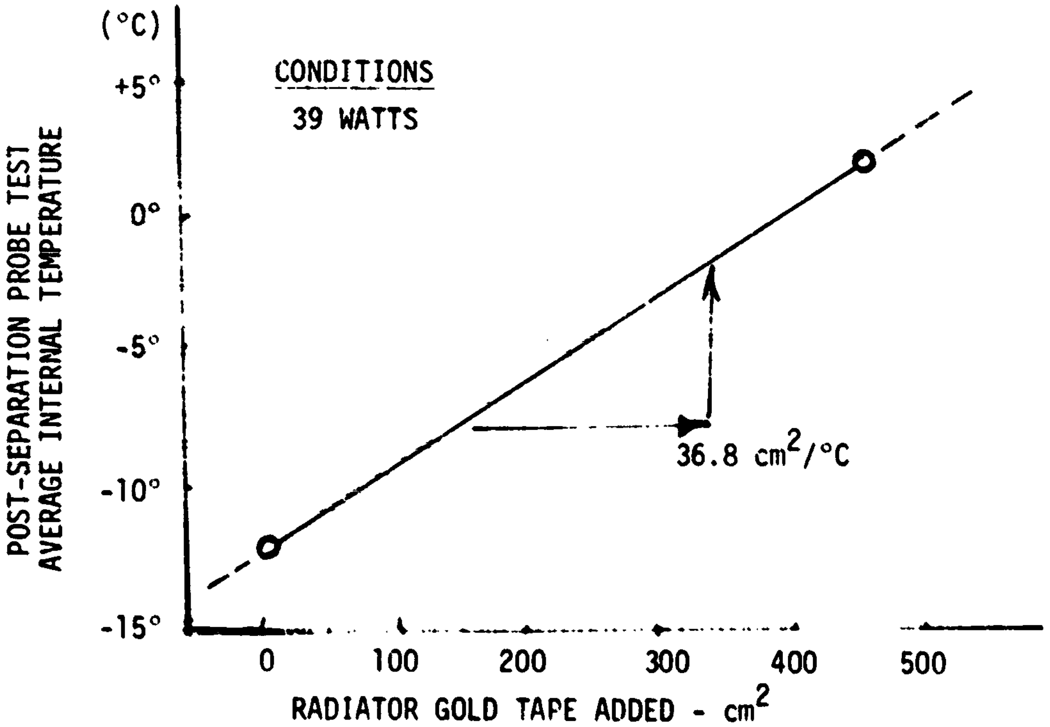


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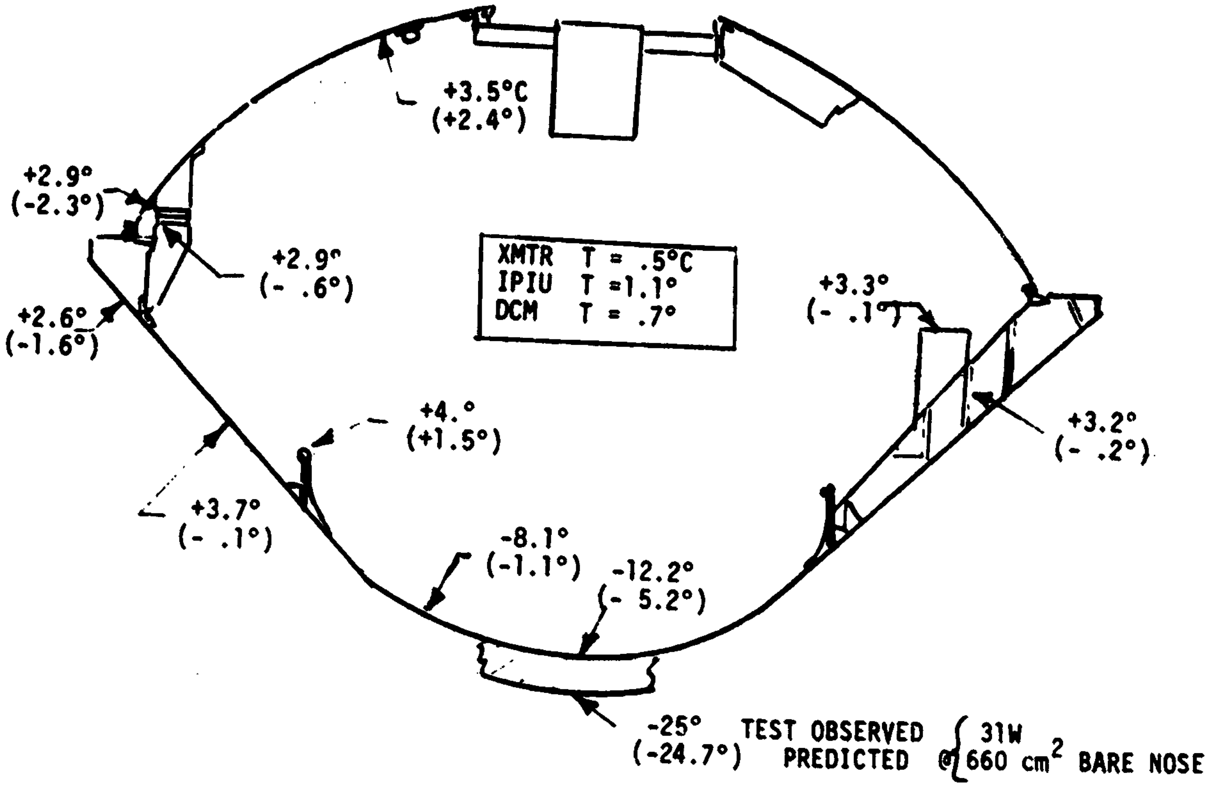
FIGURE 6
POST-SEPARATION PROBE EQUILIBRATION TEMPERATURES
(39 WATTS & 195 cm² BARE NOSE)



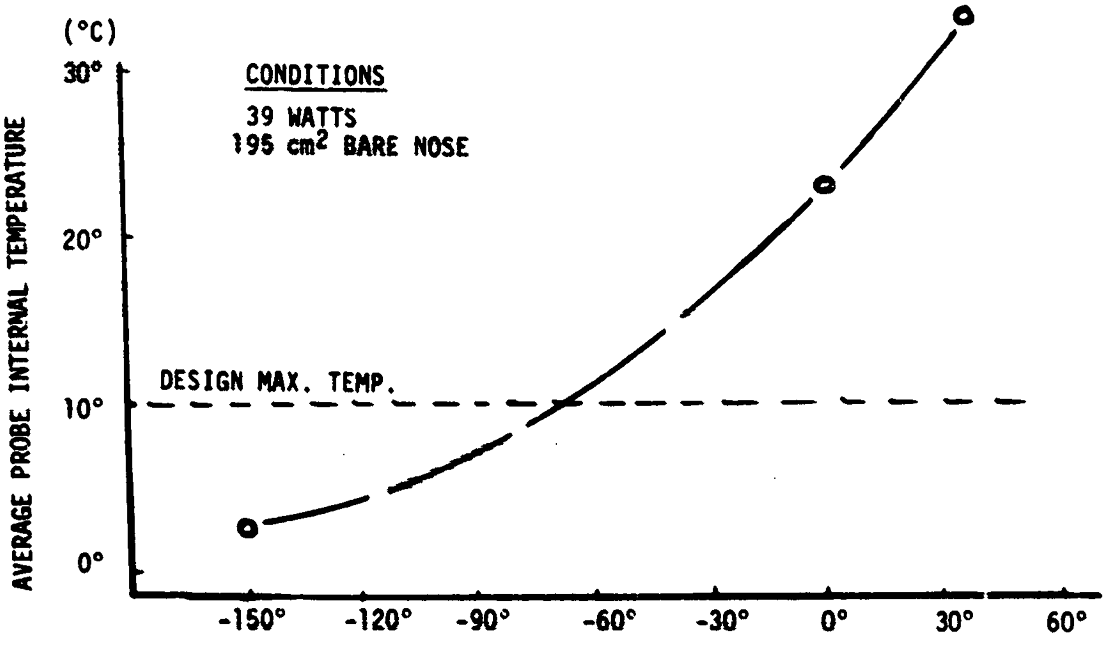


FIGURE 7
PRE-SEPARATION PROBE AFT SINK AND ADAPTOR
MOUNTING INTERFACE TEMPERATURE - °C