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INTERNAL NOTE

IU/S-IVB FORWARD SKIRT ORBITAL AND TRANSLUNAR THERMAL ANALYSES

By

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ABSTRACT

This report determines the maximum and minimum solar and terrestrial thermal energy incident and absorbed by Saturn IB/V vehicles in earth orbit and translunar travel. The influence of this external energy on the Instrument Unit Thermal Conditioning System performance, and consequently its adequacy to maintain the electronic packages at acceptable temperature limits is ascertained. Conclusions are:

a. Methanol/water coolant temperature will deviate from specifications only during translunar cold flights. However, adequate thermal conditioning of the electronic equipment would still be maintained.

b. Instrument Unit missions exceeding 6 1/2 hours, or electronic packages heat dissipation magnitudes lower than 3 kw or higher than 8.5 kw, should be reviewed to ascertain thermal compatibility.

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IU/S-IVB FORWARD SKIRT ORBITAL AND TRANSLUNAR THERMAL ANALYSES

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INTRODUCTION

The Instrument Unit (IU) of Saturn IB and V Vehicles contains most of the instruments and systems for navigation, guidance, control, range safety, telemetry, and tracking of the vehicle. The IU, although developed primarily for the Apollo program in manned lunar exploration, can satisfy other space missions with only minor changes in the electronic and astrionic components; therefore, the IU of both Saturn IB and V is of the same configuration with nearly identical components. These components have an active cooling system to maintain their temperatures within allowable limits. Methanol/water coolant is pumped through the cold plates upon which the electronic equipment is mounted, and the heat dissipated by the electronic equipment is transferred to the conditioned cold plate surface by conduction.

A few of the electronic packages in the IU are not installed on cold plates but, for thermal conditioning, depend on internal passages or enclosing shrouds through which M/W flows. In the S-IVB forward skirt area, all of the electronic packages to be thermally conditioned are mounted on cold plates supplied by the same system of M/W. Resistance to heat flow between the vehicle skin and the IU cold plates, the S-IVB cold plates, and the individually conditioned components varies due to diversity in mounting configurations.

After the M/W has cooled the electronic equipment, it is circulated through the IU sublimator which functions similarly to a water boiler heat exchanger. The ice (or water) in the sublimator is subjected to space vacuum and is sublimed (or evaporated) resulting in cooling the M/W. To maintain the electronic components at specified temperatures, the sublimator should have not only the capacity to remove the heat dissipated by these components, but also it should be capable of removal of any extra heat gained from space environment. There is also the possibility at a particular location on the vehicle of reception or loss of excessive heat in flight which may affect adversely the temperature of the electronic components at that location. Therefore, it is necessary to conduct thermal analyses for the various vehicle locations to determine the effect of external thermal environment on each IU/S-IVB cold plate.

The magnitude of thermal radiation incident on Saturn IB/V IU in earth orbit is a strong function of the date and time of launch. Since dates and times of launch of Saturn vehicles are not fixed, the heat received, and consequently all other thermal data presented in this document are maximum and minimum as based on calculated launch dates and times to produce extreme heating cases. In translunar flight, assumptions are also made to optimize extreme heating conditions since the exact vehicle orientation with respect to the earth and the sun is not fixed for the translunar flight duration. The data presented herein are for orbital and translunar flight.

EXTERNAL THERMAL ENERGY INCIDENT ON THE VEHICLE

A vehicle in space gains or loses heat by radiation. For a vehicle orbiting the earth at an altitude of 100 nautical miles, the more significant external sources of heat (FIG 1) are:

a. Solar radiation: The magnitude of this radiation impinging on a flat plate is approximately 1400 watts/meter^2 (442.4 Btu/hr-ft^2). The spectral distribution of the solar energy is similar to that of a black body at 5800°K.

b. Albedo radiation (reflected solar radiation from the earth and its atmosphere): The magnitude of this radiation is approximately 40% of the solar radiation, and its spectral distribution is the same as solar radiation.

c. Planetary (or earth) radiation: The magnitude of this radiation impinging on a flat plate is approximately 125 watts/meter^2 (66.36 Btu/hr-ft^2). The spectral distribution of the earth radiation is similar to that of a black body at 228°K.

Therefore, the magnitude of thermal energy incident to any circumferential location on the vehicle is the summation of the following products:

a. Product of the solar radiation intensity and the geometric factor between the sun and that particular location on the vehicle.

b. Product of the albedo radiation intensity and the geometric factor between sun - earth and that particular location on the vehicle.

c. Product of the earth radiation intensity and the geometric factor between the earth and that particular location on the vehicle.

A digital computer program is used to determine geometric factors and incident radiation intensities for any vehicle position at a certain orbit location; however, to determine extreme thermal energy incident on the vehicle for the total orbit, the date and time of launch, which determines the length of time a vehicle travels in the earth shadow must be known. It is mainly this magnitude of time tnat distinguishes between maximum and minimum shadow orbit, and consequently minimum and maximum vehicle heating cases.

Maximum and Minimum Heating Orbits

The length of time a vehicle is in the earth shadow is a function of the launch angle of inclination, launch latitude, launch longitude, date and time of launch, and the orbit altitude. With the exception of launch date and time, the orbit parameters for Saturn IB/V are either physically fixed or defined. So, the length of time the vehicle spends in the earth's shadow is a direct function of the undetermined date and time of launch. Analysis conducted on a digital computer program, indicates the launch date and time for extreme shadow orbits are:

a. Minimum Shadow Orbit (i. e., Maximum Heating Orbit)
Time in Shadow: 1877.7 seconds
Date of Launch: 273 days after Vernal Equinox
(approximately Dec. 21)
Time of Orbital Injection: 15:00 hours Universal Time
(10:00 A. M. EST)

b. Maximum Shadow Orbit (i. e., Minimum Heating Orbit)
Time in Shadow: 2241.7 seconds
Date of Launch: 90 days after Vernal Equinox
(approximately Jun 21)
Time of Orbital Injection: 18.324 hours Universal Time
(1:19:26 P. M. EST)

Consequently, launch parameters for maximum and minimum heating orbits are given in Tables I and II respectively, and the symbols used in these tables are illustrated in FIG 2. The inclination of the earth's axis with respect to the sun during the different seasons, which in conjunction with other launch parameters causes extreme shadow orbits, is illustrated in FIG 3.

Maximum and Minimum Heating Incident on The Vehicle in Orbit

With the launch parameters specified, and the launch date and time to yield extreme heating orbits calculated, the heat incident on 24 equally spaced peripheral segments on the vehicle is computed for each 10 degrees in orbit. This, as previously stated, required computation of the geometric factor between the sun, and the earth, and each vehicle segment for each 10 degrees increment in orbit. The results of maximum and minimum heat incident are plotted for 12 equally spaced vehicle segments (FIG 4 and 5). These figures show the incident heat on each of the specified vehicle segments as a function of the vehicle position in orbit. The vehicle circumferential segments (nodes) location relative to vehicle positions is defined in FIG 6 for the IU, and in FIG 7 for the S-IVB. Energy received by each segment varies from a maximum when the segment is directly facing the sun, to a minimum when the segment is in the earth's shadow. Initial time indicated on the abscissa is from downrange cut-off--ascent heating is not considered. It is also assumed for these calculations that the vehicle orbits the earth with Position I towards the center of the earth, and that the vehicle does not roll. The incident heat on the entire vehicle is independent of vehicle roll, but for any circumferential location on the vehicle, the incident heat depends on orientation of that particular location with respect to the sun and the earth.

Maximum and Minimum Heating Incident on the Vehicle During Translunar Travel of IU/S-IVB

During the first two hours of translunar travel of Saturn V Apollo mission, the following flight parameters were assumed to yield maximum and minimum heating conditions:

a. For maximum heating conditions, the vehicle longitudinal axis is perpendicular to the sun-earth center lines (FIG 8).

b. For minimum heating conditions, the vehicle longitudinal axis is parallel to the sun-earth center lines (FIG 8).

From the geometry of the vehicle (with respect to the sun and earth) and the rate of its travel, total incident heat is calculated for maximum and minimum heating conditions as a function of altitude and time in translunar travel and tabulated in Table III. This incident heat is also shown in FIG 9, averaged per vehicle unit area, as a function of time in translunar travel. It appears that shortly after S-IVB second burn, albedo and planetary radiation become negligible and the heat received by the vehicle--regardless of its orientation with respect to the sun and the earth--falls within the indicated band of FIG 9. For subsystem testing purposes, the maximum and minimum incident heat on a cold plate or on individual thermally conditioned component, is 442 and zero Btu/hr-ft^2 respectively. These values assume that any vehicle position is at right angles or parallel to the earth-sun center lines for the duration of the translunar flight.

EXTERNAL THERMAL ENERGY ABSORBED

Optical Characteristics of IU/S-IVB External Skin

The incident heat on the vehicle, as calculated previously, is partially reflected while the remainder is absorbed by the skin. The percentage of the incident heat that will be absorbed by the vehicle is a function of the optical characteristics of the skin, the surface finish, and the temperature of the source. The skin absorptance for solar radiation is equal to its absorptance for albedo radiation and depends on the color of the paint on the skin of the vehicle, while the absorptance for earth radiation is independent of the paint color. The reason for this is that radiation from the sun contains all energy levels due to its spectral distribution being similar to that of a black body at high temperature (FIG 10 shows distribution of solar energy) and, therefore, is selective to colors, but the energy emitted by the earth is in the infrared region of the solar spectrum and is non-selective to colors. Based on the current IU/S-IVB optical coating (black paint), the absorptance for solar and albedo radiation (α_S) is 0.9. The absorptance for the earth infrared radiation (α) is also 0.9. At the expected temperature levels of the vehicle-skin, the energy emitted by the skin will be in the infrared region also and emittance will be the same as the absorptance for earth infrared radiation; i.e., $\alpha = \epsilon = 0.9$.

It should be noted that while emissivity is independent of the paint color, it is dependent on the type of paint. For instance, a surface painted with silicone aluminum will have an emissivity of approximately 0.3. If the same surface were painted with oil paint, it will have an emissivity of approximately 0.9 regardless of the paint color.

Maximum and Minimum Heat Absorbed in Orbit and in Translunar Flight

The product of external incident energy, and the respective skin absorptance of that energy, determines the magnitude of the heat absorbed by the vehicle. FIGS 11 and 12 present maximum and minimum heat absorbed by each of the 12 peripheral segments of the vehicle at any point in orbit. FIGS 13 and 14 show maximum and minimum heating absorbed by any vehicle peripheral segment averaged over one complete orbit. These values are obtained by integration of the area under the curve for each of the vehicle segments presented in FIGS 11 and 12.

The maximum heat absorbed averaged over one orbit (FIG 13) resembles a sine wave with a weighted average value of 106 Btu/hr-ft^2; the energy peaks are at a high value of 246 Btu/hr-ft^2 and at a low value of 4 Btu/hr-ft^2. The minimum heat absorbed (FIG 14) has a lower weighted average (83.6 Btu/hr-ft^2) and less deviation (124 Btu/hr-ft^2 maximum and 40 Btu-hr-ft^2 minimum). During translunar travel, the maximum and minimum heat absorbed are represented in FIG 15 and show that the maximum heat absorbed in translunar flight is higher than in orbital flight and the minimum heat absorbed in translunar flight is also lower than in orbital flight. This indicates that worse heating conditions occur during translunar flight. Table IV is a summary of extreme heat absorbed values. The heat-absorbed data presented in (FIG 11 - FIG 15) is used to:

a. determine vehicle skin temperature.

b. determine the heat gain/loss to the thermal conditioning system.

c. duplicate heat absorbed in thermal testing of IU/S-IVB--such as in Flight System Test (S-IU-500FS).

d. duplicate heat absorbed in thermal testing of subsystem of IU/S-IVB forward skirt electronics--such as testing of electronics on individual cold plates.

IU/S-IVB EXTERNAL SKIN TEMPERATURE

Basic Heat Balance Equation

To determine the external transient temperature of the vehicle skin in orbit and in translunar flight, a heat balance equation must be solved for each vehicle peripheral zone. The general form of the equation can be written:

$$\frac{dT}{d\theta} = \frac{Qs \pm Q_{cp} - Q\ \text{emitted}}{\text{Mass of node X Specific heat of node}}$$

Where Qs is the solar, albedo, and earth radiation absorbed, Q_{cp} is the heat gain/loss by radiation and conduction from the cold plate adiabatic surface, and Q emitted is the heat radiated to space. Qs was determined in the previous chapter, and Q emitted can be determined from the Stefan - Boltzman Law of radiation if the skin temperature is known. Q_{cp} is a function of conduction and radiation resistance to flow of thermal energy between the vehicle skin and the cold plate. Q_{cp} is also dependent on the vehicle skin temperature and will be discussed in the following chapters.

Thermal Resistance Between Vehicle Skin and IU Cold Plates

The difference in temperature between the vehicle skin and the adiabatic cold plate back-surface is the driving potential for the flow of heat. In orbit, and during translunar travel, the flow of heat to or from the skin is by conduction and radiation. The conduction heat path is through mounting brackets and bolts which fasten the cold plates to the skin. Four identical corner brackets (FIG 16) and one center bracket of different configuration (FIG 17) are used per each IU cold plate. These brackets and the attaching bolts constitute the major means of heat transmission between the vehicle skin and the cold plates. The other mode of heat flow between the inner vehicle skin and the back of the cold plates is by radiation , which has been reduced in the IU to a practical minimum by applying a low-emissivity coating to these surfaces.

The specified minimum emissivity (ϵ) for the back of the IU cold plates, and for the inner IU skin is 0. 3; however, if either surface emissivity is lower than 0. 3, the other surface emissivity can be high enough so that the product of both emissivities is a maximum allowable of 0.1. Total resistance for heat flow by conduction and radiation is illustrated in the thermal resistance diagram of FIG 18. Net conduction resistance between IU skin and the cold plate, assuming perfect contact between surfaces, is calculated at 0.07 hr-°F/Btu. (Experimental work will be performed to verify this value). Similar analyses were conducted for internally cooled components. Details of construction and resistance diagrams for these components are not included in this report but are available upon request.

Thermal Resistance Between Vehicle Skin and S-IVB Cold Plates

As in the case of the IU, the heat flow between the S-IVB cold plates and the vehicle skin is by conduction and radiation. However, the majority of heat flow to or from the S-IVB cold plates is by radiation rather than by conduction because:

a. the neoprene rubber in the cold plate mounting brackets acts as an insulator

b. the surface emissivity of vehicle inner skin and cold plate back surface is relatively high (Emissivity of S-IVB cold plate back surface = emissivity of S-IVB inner skin = 0.8)

Structural details of S-IVB forward skirt and cold plate mounting configuration are shown in FIG 19. Total resistance for heat flow is illustrated in the thermal resistance diagram of FIG 20. Net conduction resistance between the S-IVB skin and the cold plate is approximately 1.3 hr - °F/Btu.

IU/S-IVB Forward Skirt External Skin Temperature

For Solution of the IU/S-IVB forward skirt skin temperatures, these items must be considered:

a. conduction from surrounding nodes

b. radiation and conduction interchange between the back surface of the cold plate and the vehicle skin inner surface

c. external radiation absorbed

d. emitted radiation to space.

Initial extreme skin temperatures at point of orbital injection were calculated to be 200°F and 100°F for a hot and a cold ascent respectively. Extreme transient skin temperatures were then calculated in orbit and in translunar travel. The results are presented for the following parameters:

a. Maximum and minimum IU external and internal skin temperature history, in orbit and translunar, for 12 equally spaced nodes on the vehicle perimeter (FIGS 21-44).

b. Maximum and minimum S-IVB forward skirt temperature history, in orbit and translunar, for 18 equally spaced nodes on the vehicle perimeter (FIGS 45-62).

c. Maximum and minimum IU external and internal skin temperature for each vehicle node averaged over a complete orbit (FIGS 63 - 64).

d. Maximum and minimum S-IVB forward skirt temperature for each vehicle node averaged over a complete orbit (FIGS 65-66).

From the figures, it is seen that orbital temperature of some nodes is higher during maximum shadow orbit than they are during minimum shadow orbit; however the average temperature for the entire IU/S-IVB forward skirt is higher during minimum shadow orbit. Highest orbital average skin temperatures for any cold plate location is 54°C (130°F) and the lowest is -37°C (-34°F); however skin temperatures at vehicle locations with no cold plates, or with individually conditioned components, could be much more severe due to the absence of internal adiabatic surface. During translunar travel, the maximum IU/S-IVB skin temperature is 88°C (190°F), and the minimum IU/S-IVB skin temperature is -39°C (-38°F), and can occur for any vehicle cold plate position since the vehicle orientation with respect to the earth and the sun is assumed random. For maximum temperature conditions, it is assumed that translunar injection occurred at the orbit location in which the vehicle receives maximum heating. These extreme temperature values are summarized in Table V along with extreme instantaneous temperatures, and can be used for qualification testing of cold-plate mounted electronic equipment.

EFFECT OF EXTERNAL ENVIRONMENT ON THERMAL CONDITIONING SYSTEM OPERATION

Skin temperatures of the vehicle and thermal resistance values calculated previously are used to determine the heat gain/loss from the IU/S-IVB to the environment of space. This heat gain/loss when added to the heat dissipation of the electronic equipment and to any internal losses to the LH_2 bulkhead, Lunar Excursion Module (LEM), and the Spacecraft LEM Adapter determines such things as adequacy of the sublimator, and whether heating is required for cold missions. These values can also dictate the exact amount of water required for inflight cooling and can be used in subsystem testing. The data are presented in this manner:

a. Maximum and minimum heat gain/loss versus time in flight for each IU cold plate location (FIGS 67-85).

b. Maximum and minimum heat gain/loss versus time in flight for each S-IVB cold plate location (FIGS 86-101).

c. Maximum and minimum heat gain/loss for each IU cold plate location averaged over one complete orbit (FIGS 102-103).

d. Maximum and minimum heat gain/loss for each S-IVB cold plate location averaged over one complete orbit (FIGS 104-105).

A summary of the extreme heat gain/loss values as obtained from the above figures for orbital flight and as calculated for translunar flight is given in Table VI. It is indicated from this table that the maximum heat gain/loss per individual cold plate is 1470 Btu/hr (.4 kw gain) and -720 Btu/hr (0.2 kw loss). The maximum external heat gain/loss for the total IU/S-IVB cold plates and internally conditioned components is 1,479 Btu/hr (0.4 kw gain), and 19,246 Btu/hr Btu/hr (5.6 kw loss).

RESULTS

Maximum External Heat Gain and Loss Per Cold Plate

The maximum external heat loss to space from any cold plate is .2 kw, and the maximum external heat gain is .4 kw per cold plate. Based on these data and the present temperature limits of the electronic equipment, the only critical component is the stabilized platform. Consequently, this component has been partially isolated from the exterior skin on SA-204 and subsequent vehicles.

Maximum Total Heat Loss

The maximum external heat loss to space from the entire IU/S-IVB cold plates and electronic packages system is 5.6 kw, and occurs in translunar flight. Other heat gain/loss sources from the IU/S-IVB total system are:

a. Internal heat loss to the S-IVB LH_2 bulkhead due to radiation interchange. This is a maximum of 1 kw (Ref. 1).

b. Heat loss to the sublimator due to excess cooling at low or zero heat loads. This results in an extra cooling (heat loss) of 1.2 kw.

c. Heat gain to the system due to electronic equipment heat dissipation. The minimum Saturn V IU electronic equipment heat dissipation is 3.4 kw (Ref. 2). Assuming that the S-IVB forward skirt electronic equipment minimum heat dissipation in orbit and translunar flight is negligible, the maximum total heat loss from the IU/S-IVB cold plates and electronic components system is 4.4 kw (3.4 kw - 5.6 kw - 1 kw - 1.2 kw). Based on this heat loss, the M/W temperature inlet to the cold plates, at the end of two hours of translunar flight, could drop as much as 4.7°F (2.6°C) below the specified temperature of 59 ±1°F. The resulting M/W minimum temperature is still above the minimum allowable temperature of the electronic packages, and therefore, no heating is required for the total system for a maximum of 3 orbits and 2 hours of translunar flight.

Maximum Total Heat Gain

The maximum external heat gain from space to the entire IU/S-IVB cold plates and electronic packages is 0.4 kw and occurs in translunar flight. The IU electronic equipment maximum heat dissipation is 4.4 kw (Ref. 2), and the S-IVB forward skirt electronic equipment maximum heat dissipation in orbital and translunar flight based on SA-203 heat dissipation is 1.1 kw. Internal heat gain is assumed negligible. Thus, the maximum total heat gain is approximately 6 kw. This is less than the present sublimator maximum heat rejection capacity of 9 kw, and consequently the M/W temperature inlet to the cold plates should not exceed the specified temperature of 59 ± 1°F (15 ± .5°C). This also indicates that Saturn IB/V sublimator minimum heat rejection capacity should be at least equal to 6 kw to satisfy current orbital and translunar heat loads. An oversized sublimator, however, will help cool the M/W at a faster rate immediately after vehicle ascent phase and upon initial sublimator start up. Maximum water weight for IU/S-IVB cooling could also be based upon a maximum of 6 kw for Saturn IB/V.

CONCLUSIONS

1. If the vehicle were to encounter hottest orbit or translunar orientation, the M/W temperature inlet to the cold plates should not exceed the specified temperature of 59 ± 1°F. However, external heat gain to the stabilized platform could be excessive. Isolation of this component from the vehicle skin has been included on SA-204 and subsequent vehicles.

2. If the vehicle were to encounter coldest orbit or translunar orientation, the M/W temperature to the cold plates could drop as much as 4.7°F (2.6°C) at the end of 2 hours translunar travel. The extent of this over-cooling should not cause any electronic packages to reach its minimum specified temperature limit.

3. IU missions exceeding 6 1/2 hours, or electronic packages heat dissipation magnitudes lower than 3 kw or higher than 8.5 kw, should be reviewed to ascertain thermal compatibility.