138

20029-H017-R0-00 cy 1

NASA CR-
144386

# THERMO-STRUCTURAL DESIGN ANALYSIS FOR ADVANCED MANNED SPACECRAFT SYSTEMS

TASK 701C

PROJECT TECHNICAL REPORT

## THE RELATIVE EFFECTS OF ENTRY PARAMETERS ON THERMAL PROTECTION SYSTEM WEIGHT

Contract No. NAS 9-12330

20 December 1971



Prepared for
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas





Prepared by
Applied Technology Laboratory
TRW Systems Group

TRW
SYSTEMS GROUP

V38
39

20029-H017-R0-00 cy 1

NASA CR-
144386

# THERMO-STRUCTURAL DESIGN ANALYSIS FOR ADVANCED MANNED SPACECRAFT SYSTEMS

TASK 701C

PROJECT TECHNICAL REPORT

# THE RELATIVE EFFECTS OF ENTRY PARAMETERS ON THERMAL PROTECTION SYSTEM WEIGHT

Contract No. NAS 9-12330 20 December 1971



Prepared for
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas



Prepared by
Applied Technology Laboratory
TRW Systems Group



TRW
SYSTEMS GROUP

ABSTRACT

Shielding a spacecraft from the severe thermal environment of an atmospheric entry requires a sophisticated thermal protection system (TPS). Thermal computer program models have been developed for two such TPS designs proposed for the space shuttle orbiter. The multilayer systems, a reusable surface insulation TPS and a re-radiative metallic skin TPS, have been sized for a cross-section of trajectories in the entry corridor. This analysis indicates the relative influence of the entry parameters on the weight of each TPS concept. The results are summarized graphically in Figures 8 and 9. The trajectory variables considered were down-range, cross-range, orbit inclination, entry interface velocity and flight path angle, maximum heating rate level, angle of attack and ballistic coefficient. Variations in cross-range and flight path angle over the ranges considered had virtually no effect on the required entry TPS weight. The TPS weight was significantly more sensitive to variations in angle of attack than to dispersions in the other trajectory parameters considered in the study.

## ABSTRACT

Shielding a spacecraft from the severe thermal environment of an atmospheric entry requires a sophisticated thermal protection system (TPS). Thermal computer program models have been developed for two such TPS designs proposed for the space shuttle orbiter. The multilayer systems, a reusable surface insulation TPS and a re-radiative metallic skin TPS, have been sized for a cross-section of trajectories in the entry corridor. This analysis indicates the relative influence of the entry parameters on the weight of each TPS concept. The results are summarized graphically in Figures 8 and 9. The trajectory variables considered were down-range, cross-range, orbit inclination, entry interface velocity and flight path angle, maximum heating rate level, angle of attack and ballistic coefficient. Variations in cross-range and flight path angle over the ranges considered had virtually no effect on the required entry TPS weight. The TPS weight was significantly more sensitive to variations in angle of attack than to dispersions in the other trajectory parameters considered in the study.

TABLE OF CONTENTS

## LIST OF FIGURES

LIST OF TABLES

## LIST OF SYMBOLS

| Symbol | Description | Units |
|---|---|---|
| $A$ | Area | $ft^2$ |
| $C_D$ | Coefficient of drag | - |
| CR | Cross-range | n.m. |
| $F$ | Local heating factor | - |
| $h$ | Enthalpy | Btu/lb |
| $i$ | Inclination angle | ° |
| Le | Lewis number | - |
| Pr | Prandtl number | - |
| $Q$ | Total heat load | $Btu/ft^2$ |
| $q$ | Heating rate | $Btu/ft^2$-sec |
| $r$ | Radius | ft |
| $R$ | Range | n.m. |
| Re | Reynolds number | - |
| $t$ | Time of heating | sec |
| $u$ | Velocity | ft/sec |
| $v$ | Relative velocity | ft/sec |
| $W$ | Weight or unit weight | lb, $lb/ft^2$ |
| $\Delta W$ | Change in unit weight | $lb/ft^2$ |
| $W/C_DA$ | Ballistic coefficient | - |
| $x$ | Surface distance from nose | ft |

| Greek | | Units |
|---|---|---|
| $\alpha$ | Angle of attack | $^\circ$ |
| $\varepsilon$ | Emissivity | - |
| $\gamma$ | Flight path angle | $^\circ$ |
| $\rho$ | Density | $lb/ft^3$ |
| $\sigma$ | Stephan-Boltzmann constant | $.476 \times 10^{-12} \dfrac{Btu}{ft^2 \sec R^4}$ |
| $\mu$ | Viscosity | lb/ft--sec |

| Subscripts | |
|---|---|
| D | Dissociation |
| e | Earth orbital |
| m | Maintained |
| o | Sea level |
| r | Recovery |
| s | Surface |
| t | Total |
| 2 | Properties behind the shock |
| w | Wall |

## INTRODUCTION

The space shuttle orbiter will be designed for multiple reuse with a minimum of refurbishment. This reuse requirement necessitates the design of a thermal protection system (TPS) that can withstand the atmospheric entry heating environment without degrading. Two multilayer TPS concepts which meet this requirement are the reusable surface insulative (RSI) system proposed by North American Rockwell (NR) and the metallic skin reradiative system developed by the McDonnell Douglas Astronautics Company (MDAC). Because the weight of the TPS impacts the vehicle structural payload capability, it is an important consideration in selecting the TPS design and in choosing the entry corridor.

The purpose of this study is to size the two TPS concepts described above for a cross-section of trajectories in the entry corridor and to establish the sensitivity of the TPS weights to changes in the entry trajectory parameters.

Several steps are necessary to determine the total weight of a TPS. From simulated entry trajectories spacecraft reference heating rates can be calculated. Coupled with surface heating rate distributions, these reference rates can be converted to local heating rates. Minimum TPS insulation thicknesses required to maintain prescribed temperature limits are then determined using a standard thermal analysis program. Local and total TPS weights can be calculated directly from these data. Figure 1 illustrates the steps taken in the analysis. The presentation of total required TPS weights for a selection of entry trajectories will show the relative effects of each entry parameter on the weight of the TPS.

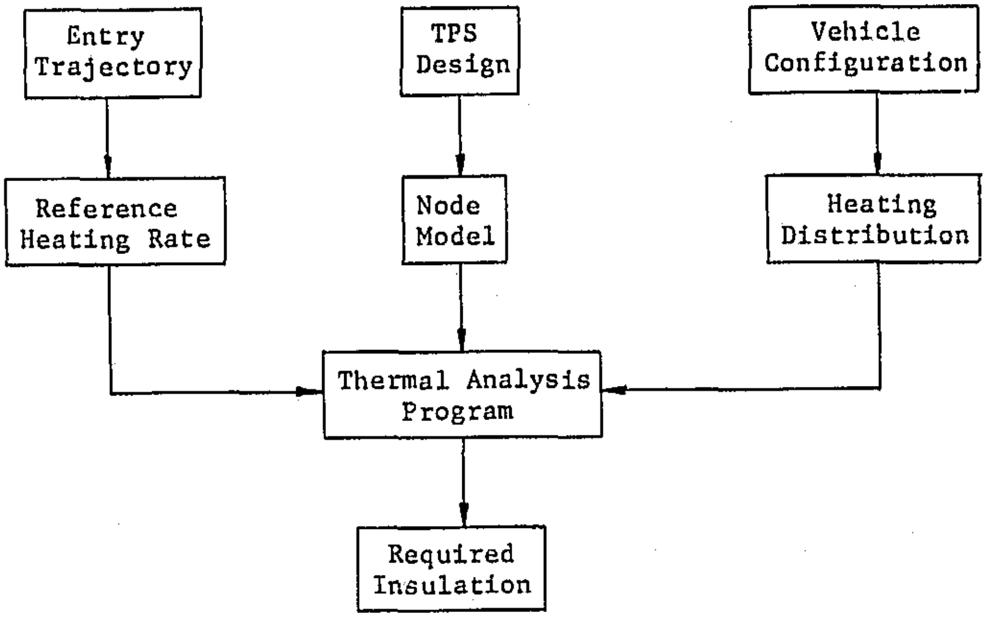


Figure 1. Basic Analysis Steps

## HEATING RATES

The heating distribution along the spacecraft surface is a function of the angle of attack (the angle between the path of flight and the horizontal axis of the vehicle). For nominal orbiter entries the guidance maintains a constant angle of attack during the period of significant heating. For this reason the heating factors used to convert the reference heating rate to local rates are constant. To simplify the analysis, the wetted surface of the orbiter fuselage has been divided into 12 panel areas as illustrated in Figure 2. These panels which represent both sides of the symmetrical vehicle, or twice the area shown, have been numbered and are referred to as panels 1, 2, 3, etc. Average heating factors determined for each panel for the range of angles of attack were presented in Reference 1 and are given as Figures A-1 through A-3 in the Appendix. Wing and stabilizer panel data are not given because only fuselage TPS's were considered in the present analyses.

Velocity, altitude and angle of attack histories for 24 trajectories within the entry corridor were supplied by NASA/MSC. A reference heating rate, the stagnation heating on a one-foot radius sphere, has been calculated using the MSC F144 computer program (Reference 2). This program employs Equation 1, the Detra, Kemp and Riddell stagnation heating expression from Reference 3.

$$q = \frac{17600}{r^{.5}} \left(\frac{\rho}{\rho_o}\right)^{.5} \left(\frac{U}{U_e}\right)^{3.15} \left(\frac{h_r - h_w}{h_r - h_{w_{300K}}}\right) \qquad (1)$$

During the subsonic portion of the flight, the vehicle is oriented such that the flow over the fuselage is similar to flow over a flat plate. In order to simulate the convection cooling during the subsonic flight, Equation (2) which calculates cold wall flat plate turbulent heating

$$q = 0.0296 \; Re^{0.8} \; Pr^{-2/3} \; \frac{u}{x} \; (h_r - h_w) \qquad (2)$$

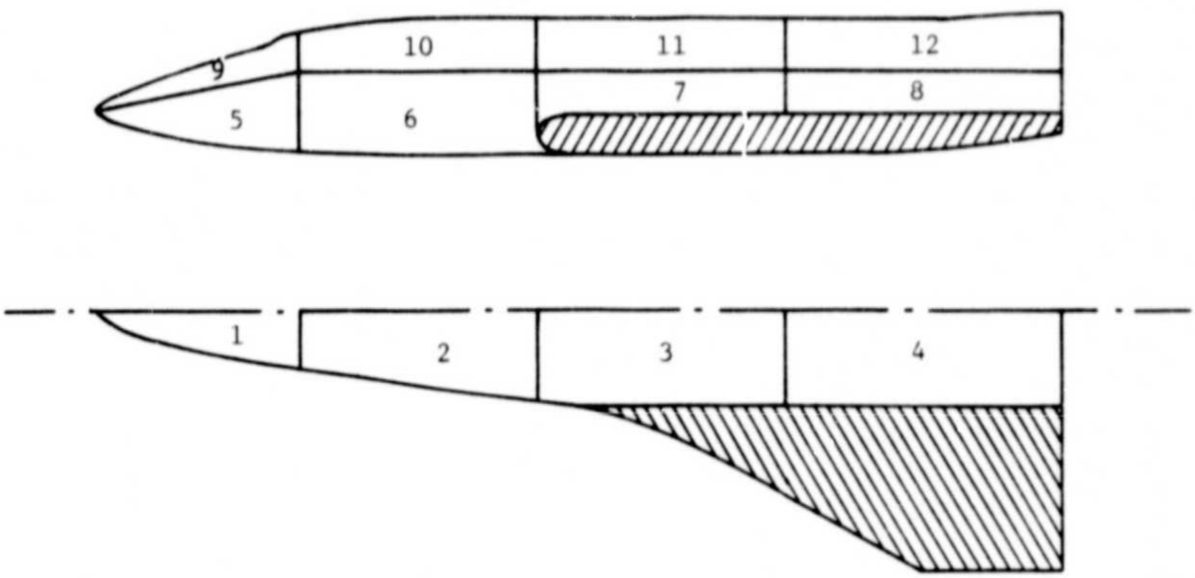


Figure 2. Fuselage Panels of Orbiter Vehicle (NR Drawing No. 999-61)

was added to the F144 program. The wall enthalpy used in Equation (2) was selected for a temperature of 0°F and then corrected for the actual wall temperature during the TPS response calculations. Figure 3 is a typical plot of flat plate cooling versus the distance x from the leading edge. In order to reduce the number of separate heating rate histories to be computed, a constant value for x of 50 feet was used for all locations. As seen in Figure 3, the flat plate cooling rate is relatively constant for greater distances, and the 50-foot value is thermally conservative for shorter distances. In retrospect the subsonic cooling proves to have little effect on the peak temperatures experienced within the TPS.

A local pressure history was also calculated for each trajectory using the F144 program. The pressures, estimated using the Newtonian pressure coefficient, were used in determining pressure dependent material properties.

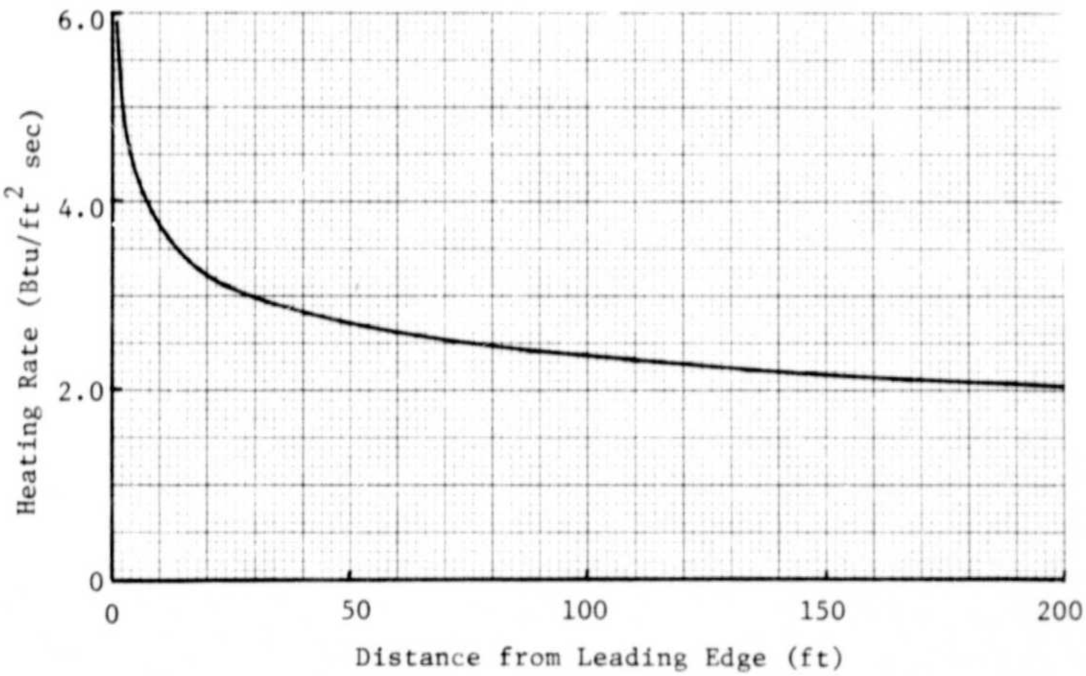


Figure 3. Flat Plate Heating Distribution, Typical Case

## TPS DESIGNS

The NR reusable surface insulative system (see Figure 4) is a multi-layer system. The outer insulation layer, LI-1500, is a silica material with a maximum reuse temperature of 2500°F. It is bonded to a titanium subpanel, which has a temperature limit of 600°F. Structural support members extend from the titanium subpanel inward to the aluminum tank wall. A soft insulator, TG-15000, is attached to the backface of the subpanel and extends around the structural supports. These supports provide a standoff region of several inches between the TG-15000 and the aluminum tank wall. The structural integrity of the aluminum requires that the temperature of the tank wall not exceed 300°F. A foam insulation lines the interior surface of the cryogenic tank. Since the fuel tanks are essentially empty during entry, the foam backface is treated as an adiabatic surface in the analysis.

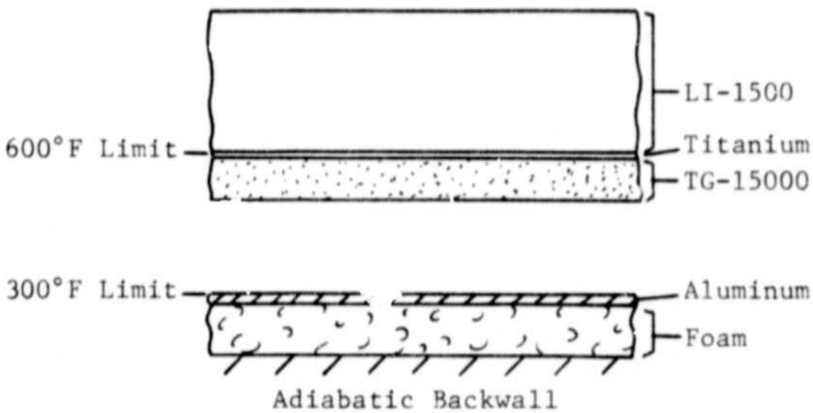


Figure 4. Insulative TPS Cross Section

Figure 5 is a cross-section of the MDAC proposed metallic re-radiative TPS. The metallic shingle and the shingle substructure are offset from the tank walls by structural support members. In order to provide a thermally efficient design, the shingle and substructure are constructed of the metal which is most effective for the entry environment experienced by a particular panel (Reference 4). The materials and the respective weights required

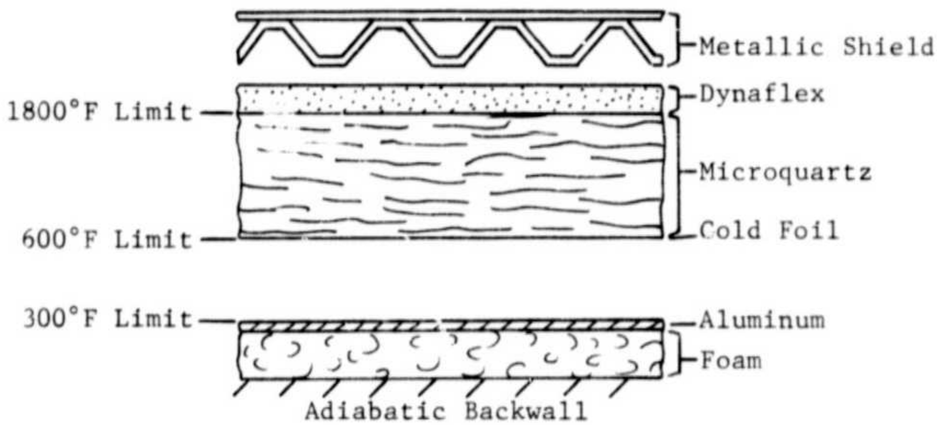


Figure 5. Metallic TPS Cross-Section

for a given peak surface temperature are presented in Figure A-4. The insulation is attached to the support members such that radiation gaps are left between it and both the shingle structure and the aluminum tank wall. The insulation consists of two layers, the exterior dynaflex and the interior microquartz. Dynaflex is a soft insulation similar to TG-15000 with a maximum reuse temperature of 2800°F. Microquartz, however, has a maximum reuse temperature of 1800°F and in this structure must be protected by the dynaflex in high heating regions. In order to reduce the radiation heat transfer to the aluminum tank wall, the backface of the microquartz is covered with a gold foil. The adhesive used to attach the foil has a degradation temperature of 600°F. Again the aluminum tank wall backed with foam insulation must be maintained below 300°F.

Because of manufacturing limitations minimum insulation thicknesses of 0.25 inch will be used for cases requiring less material based on predicted thermal conditions.

## THERMAL MODELS

The Systems Improved Numerical Differencing Analyzer (SINDA) program (Reference 5) was used to calculate temperatures within the TPS's. This program requires an input of the node model, material properties and trajectory data. The ØPTIMZ subroutine (Reference 6) of SINDA, which was developed specifically for sizing multilayer TPS's for prescribed indepth temperature limits, was utilized to determine the required insulation thicknesses. Since an averaged heating rate factor was assigned to each fuselage panel, a one-dimensional thermal model was used. Because the high conductivity (metal) components in the TPS are relatively thin and because the actual aero heating variation across a given panel is small in general, the use of an average heating factor and a one-dimensional analysis was considered acceptable.

The node model used for the surface insulative system is illustrated in Figure 6. Because of the high conductance of the titanium facesheet and of the aluminum tank wall, temperature gradients through both are neglected. The thermal capacitances, however, are considered. The LI-1500 is sized to maintain the titanium facesheet below 600°F, and the thickness of the TG-15000 must be sufficient to limit the tank wall to 300°F. The interdependence of these insulation layers requires the iterative analysis performed by the ØPTIMZ subroutine. When low heating rates produce surface temperatures less than 600°F, the LI-1500 layer is omitted.

Figure 7 is a schematic of the metallic TPS node model. As in the surface insulative model the thermal capacitances but not the conductances of the two metallic layers are used. As stated in the TPS description, the dynaflex insulation is only needed to maintain the microquartz below 1800°F. The microquartz is sized to maintain its backface temperature below 600°F, the limit for the adhesive which supports the gold foil. In all but the highest heat load cases if the foil does not reach 600°F, its low emissivity, 0.08, keeps the tank wall from exceeding 300°F. Depending on the heat load, the microquartz must be sized to meet either the 600°F backface temperature limit or the 300°F tank wall limit. For the lower heating rate cases for which the dynaflex is omitted, ØPTIMZ can size the microquartz for one limit with no iteration.

## MATERIAL PROPERTIES

The thermal properties, conductivity and specific heat of the TPS materials are functions of temperature, and due to porosity, the insulator properties are also pressure dependent. Table A-1 lists all material properties used in this study.

## ENTRY TRAJECTORIES

The orbiter guidance flies a two phase entry. A constant flight level, or reference heating rate, and angle of attack are maintained for the first phase and a constant g-load is held in the second phase. A reference heating rate of 80 Btu/ft$^2$-sec and a g-load of 1.5 are the two modes for the nominal trajectory. The 24 trajectories listed in Table 1 were provided by NASA (Reference 7) for the corridor analysis. Trajectory 1 is the nominal entry and represents the nominal value of each parameter. The

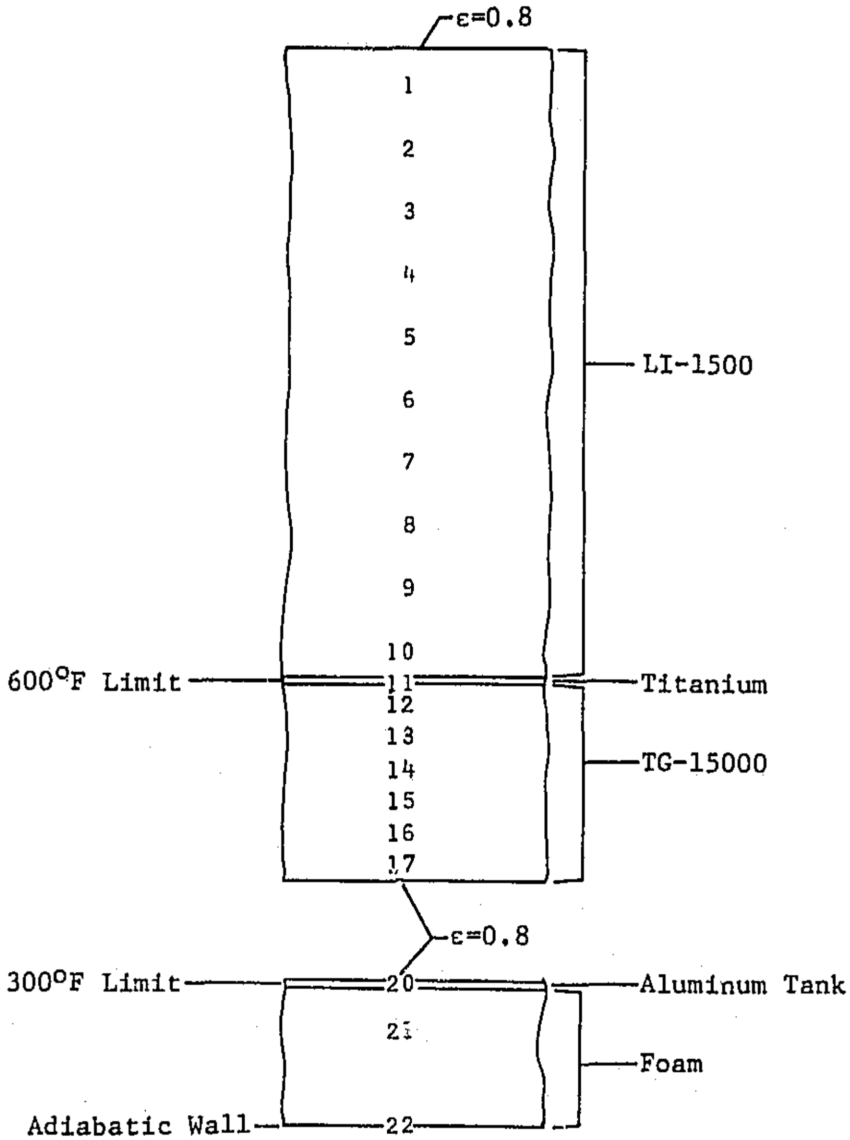


Figure 6. Surface Insulative TPS Node Model

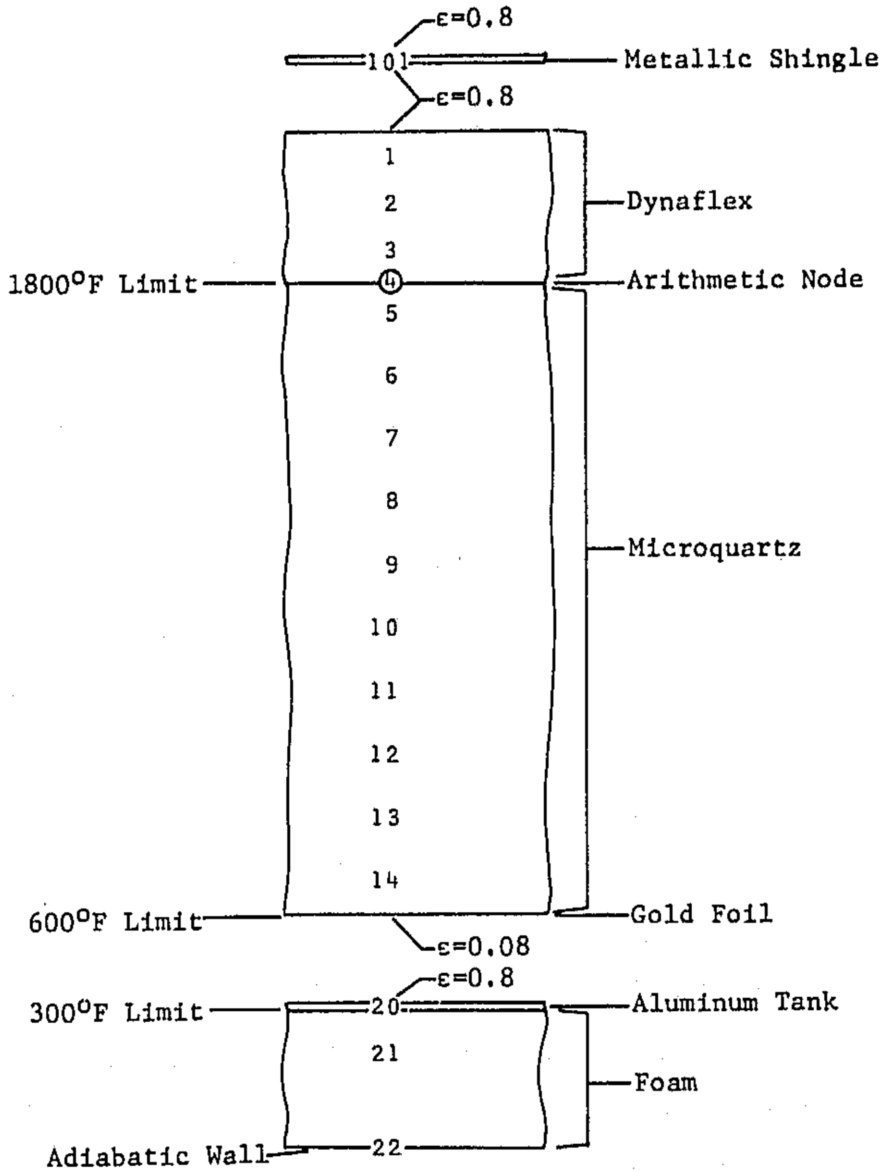


Figure 7. Metallic TPS Node Model

variation of eight entry parameters (range, cross-range, inclination, entry interface velocity and flight path angle, ballistic coefficient, angle of attack and flight level) has been included in this study. In order to ascertain the influence of each parameter, each trajectory has nominal values for all but one parameter. Variation of only one parameter at a time was obtained by bank angle modulation; however, in some cases it was necessary to adjust an additional parameter to obtain the desired off-nominal value. Variation in $q_m$ was required to achieve the changes in range and angle of attack, and flight path angle was varied in the velocity distribution and in one flight level dispersion. Trajectory 24 was the only off-nominal g-load, 2.5 g.

The reference heating rate histories of the trajectories are plotted in Figures A-5 through A-12. For comparison the histories are grouped by parameter variation and the nominal heating rate, trajectory 1, is presented on each figure.

## TPS SIZING

To develop curves of insulation unit weight versus heating factor, sizing runs were made for each trajectory for three to six heating factors depending on the deviation of the trajectory from the nominal trajectory. At this stage two parameters, cross-range and flight path angle, will be eliminated because the effects of these parameters on the TPS weights are negligible. The results of the sizing runs for trajectories 4, 5, 6, 14, 15, 16 and 17 are tabulated in Table 2 along with selected cases of the nominal trajectory. The data indicates effects on insulation weight of less than one percent even at the maximum deviation of each parameter from the nominal; therefore, these seven trajectories will no longer be considered in this study.

Table 1. Trajectory Parameters

| Trajectory Number | Down Range R (n.m.) | Cross Range CR (n.m.) | Inclination Angle i (°) | Velocity v (ft/sec) | Flight Path Angle (°) | Ballistic Coefficient $W/C_DA$ (Variation) | Angle of Attack (°) | Heat Rate Maintained $q_m$ ($Btu/ft^2 \cdot sec$) |
|---|---|---|---|---|---|---|---|---|
| 1 | 5375 | 0 | 55 | 26000 | -1.45 | 0 | 30 | 80 |
| 2 | 6062 | 0 | 55 | 26000 | -1.45 | 0 | 30 | 70 |
| 3 | 4838 | 0 | 55 | 26000 | -1.45 | 0 | 30 | 90 |
| 4 | 5375 | 1412 | 55 | 26000 | -1.45 | 0 | 30 | 80 |
| 5 | 5375 | 933 | 55 | 26000 | -1.45 | 0 | 30 | 80 |
| 6 | 5375 | 533 | 55 | 26000 | -1.45 | 0 | 30 | 80 |
| 7 | 5375 | 0 | 28.5 | 26000 | -1.45 | 0 | 30 | 80 |
| 8 | 5375 | 0 | 90 | 26000 | -1.45 | 0 | 30 | 80 |
| 9 | 5375 | 0 | 55 | 25000 | -0.24 | 0 | 30 | 80 |
| 10 | 5375 | 0 | 55 | 25500 | -0.98 | 0 | 30 | 80 |
| 11 | 5375 | 0 | 55 | 26500 | -1.82 | 0 | 30 | 80 |
| 12 | 5375 | 0 | 55 | 27000 | -2.15 | 0 | 30 | 80 |
| 13 | 5375 | 0 | 55 | 26000 | -1.30 | 0 | 30 | 80 |
| 14 | 5375 | 0 | 55 | 26000 | -1.35 | 0 | 30 | 80 |
| 15 | 5375 | 0 | 55 | 26000 | -1.65 | 0 | 30 | 80 |
| 16 | 5375 | 0 | 55 | 26000 | -1.75 | 0 | 30 | 80 |
| 17 | 5375 | 0 | 55 | 26000 | -1.45 | -25% | 30 | 80 |
| 18 | 5375 | 0 | 55 | 26000 | -1.45 | +25% | 30 | 80 |
| 19 | 5375 | 0 | 55 | 26000 | -1.45 | 0 | 20 | 100 |
| 20 | 5375 | 0 | 55 | 26000 | -1.45 | 0 | 40 | 80 |
| 21 | 5375 | 0 | 55 | 26000 | -1.45 | 0 | 50 | 65 |
| 22 | 5375 | 0 | 55 | 26000 | -1.35 | 0 | 30 | 70 |
| 23 | 5375 | 0 | 55 | 26000 | -1.45 | 0 | 30 | 100 |
| 24* | 5375 | 0 | 55 | 26000 | -1.45 | 0 | 30 | 150 |

*2.5 g entry

Table 2. Required Insulation Weights, CR and $\gamma$ Dispersions

| Trajectory Number | Variable Parameter | Required Insulation Weights ($lb/ft^2$) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Insulative TPS Heating Factors | | | Metallic TPS Heating Factors | | | |
| | | .17 | .08 | .02 | .17 | .10 | .06 | .02 |
| 1 | Nominal | 3.14 | 2.50 | 1.38 | 1.492 | 1.012 | .808 | .383 |
| 4 | CR=1412 nm | 3.16 | 2.52 | 1.43 | 1.492 | 1.013 | .809 | .383 |
| 5 | CR= 933 nm | 3.14 | 2.51 | 1.41 | 1.492 | 1.010 | .808 | .384 |
| 6 | CR= 533 nm | 3.14 | 2.50 | 1.39 | 1.492 | 1.012 | .808 | .384 |
| 14 | $\gamma$=-1.30° | 3.18 | 2.52 | 1.43 | 1.488 | 1.005 | .806 | .388 |
| 15 | $\gamma$=-1.35° | 3.16 | 2.53 | 1.43 | 1.480 | 1.010 | .806 | .395 |
| 16 | $\gamma$=-1.65° | 3.19 | 2.52 | 1.41 | 1.500 | 1.015 | .815 | .395 |
| 17 | $\gamma$=-1.75° | 3.14 | 2.51 | 1.40 | 1.481 | 1.011 | .800 | .385 |

Notes: 1. Insulation weight of the Insulative TPS include both the LI-1500 external and the TG-15000 internal insulation materials.
2. Insulation weights of the metallic TPS are for the internal microquartz insulation (plus dynaflex for Panel 1).

Figures A-13 and A-14 present the unit weight versus heating factor curves developed for each of the 17 remaining trajectories for both heat shields. An examination of the panel heating factors reveals that panel 1 is the only location where the surface temperature exceeds 1800°F; therefore, the dynaflex layer of the metallic TPS can be omitted for the other panels. For this reason Figure A-14, the unit weight curves for the metallic TPS, is not extended to include the panel 1 heating factor, and the insulation unit weights are the microquartz unit weights. The panel 1 required insulation weights calculated by SINDA for the metallic TPS are presented only in the tables.

From the curves of Figures A-1, A-2 and A-3 the panel heating factors were obtained for each of the four angles of attack. For the $\alpha = 30°$ trajectories, the local factors and the corresponding insulation unit weights obtained from Figure A-3 are tabulated in Table A-2 for the insulative TPS. Multiplying these unit weights by the respective panel areas, produces the total insulation weights presented in Table A-3 for the individual panels and for the entire fuselage TPS. These same steps are used in Table A-4 to yield the total required weights for trajectories 19, 20 and 21, the angle of attack variation.

Employing the same method to calculate the metallic TPS insulation weights, Tables A-5 and A-6 list the unit and total weights for the trajectories with $\alpha = 30°$, and Table A-7 contains the data for trajectories 19, 20 and 21. The metallic TPS, however, requires additional steps to determine the total TPS weight. The metal shingles which form the outer skin must be designed for the maximum surface temperature of each panel. The maximum panel surface temperatures were estimated as the re-radiation equilibrium temperature based on the $q_m$ of each trajectory. Using Equation 4, the estimated maximum surface temperatures in Table A-8

$$T_s = \left(\frac{F\ \dot{q}_m}{\varepsilon\ \sigma}\right)^{1/4} - 460 \qquad (4)$$

have been calculated. The respective unit weights are obtained from Figure A-4 and multiplied by the panel area to produce the total weights of Table A-9.

## TOTAL TPS WEIGHTS

Certain fixed weights including coatings, metallic structure and insulation packaging must be included in the TPS weight totals. These weights are 1.95 $lb/ft^2$ for the insulative system and 0.84 $lb/ft^2$ for the metallic system, or 23556 lb and 10147 lb respectively for a TPS surface area of 12080 $ft^2$. These fixed weights include the following components:

**Insulative System**

| | |
|---|---|
| Titanium subpanel and supports | 1.10 $lb/ft^2$ |
| Surface coating | .35 |
| Adhesive bond | .30 |
| Insulation packaging | .20 |
| | 1.95 $lb/ft^2$ |

**Metallic System**

| | |
|---|---|
| Support struts | .26 $lb/ft^2$ |
| Drag links and fillings | .18 |
| Insulation retention | .10 |
| Insulation packaging | .30 |
| | .84 $lb/ft^2$ |

The tabulations of the TPS total weights for each trajectory are given in Table 3. These final totals show the surface insulative system to be 40 to 80% heavier than the metallic system, a condition which should prove a major factor in the TPS design decision. By plotting the total weight versus the individual parameter dispersions (see Figures 8 and 9), the sensitivity of the TPS weight to each parameter variation is shown. (The reader should be cautioned that these curves do not necessarily provide correct total weights for intermediate parameter values as the TPS panels do not react uniformly to trajectory changes.) These curves are presented on identical total weight scales so that the relative importance of each may be judged.

The variations in angle of attack cause the most significant weight changes for both TPS concepts. The effect of heating rate on the metallic TPS is easily seen by comparing the $q_m$ curves of Figures 7 and 8. The surface temperature criteria in the selection of the metallic shingle outweighs the effect of total heat load on the insulation since the metallic weight increases significantly with increasing $q_m$. All the other parameters show only moderate influences on the weights.

Table 3. Total TPS Weights

| | Insulative TPS | | Metallic TPS | | |
|---|---|---|---|---|---|
| Trajectory Number | Insulation Weight (lb) | Total* Weight (lb) | Insulation Weight (lb) | Shingle Weight (lb) | Total** Weight (lb) |
| 1 | 14866 | 38422 | 4901 | 10161 | 25209 |
| 2 | 15738 | 39294 | 4709 | 9600 | 24456 |
| 3 | 14535 | 38091 | 4808 | 10275 | 25230 |
| 7 | 14464 | 38020 | 4775 | 10161 | 25083 |
| 8 | 16120 | 39676 | 5145 | 10161 | 25453 |
| 9 | 13736 | 37292 | 4544 | 10161 | 24852 |
| 10 | 14451 | 38007 | 4742 | 10161 | 25050 |
| 11 | 15667 | 39223 | 5061 | 10161 | 25369 |
| 12 | 16379 | 39935 | 5220 | 10161 | 25528 |
| 17 | 13161 | 36717 | 4354 | 10161 | 24662 |
| 18 | 16797 | 40353 | 5424 | 10161 | 25732 |
| 19 | 26165 | 49721 | 6877 | 10156 | 27180 |
| 20 | 10615 | 34171 | 3876 | 10043 | 24066 |
| 21 | 8288 | 31844 | 2994 | 9172 | 22313 |
| 22 | 15969 | 39525 | 4864 | 9600 | 24611 |
| 23 | 14313 | 37869 | 4746 | 10344 | 25237 |
| 24 | 11960 | 35516 | 4902 | 11248 | 26297 |

* Includes fixed weight of 1.95 $lb/ft^2$ or 23556 lb
**Includes fixed weight of 0.84 $lb/ft^2$ or 10147 lb

Notes: 1. Insulation weight of the Insulative TPS include both the LI-1500 external and the TG-15000 internal insulation materials.
2. Insulation weights of the metallic TPS are for the internal microquartz insulation (plus dynaflex for Panel 1).

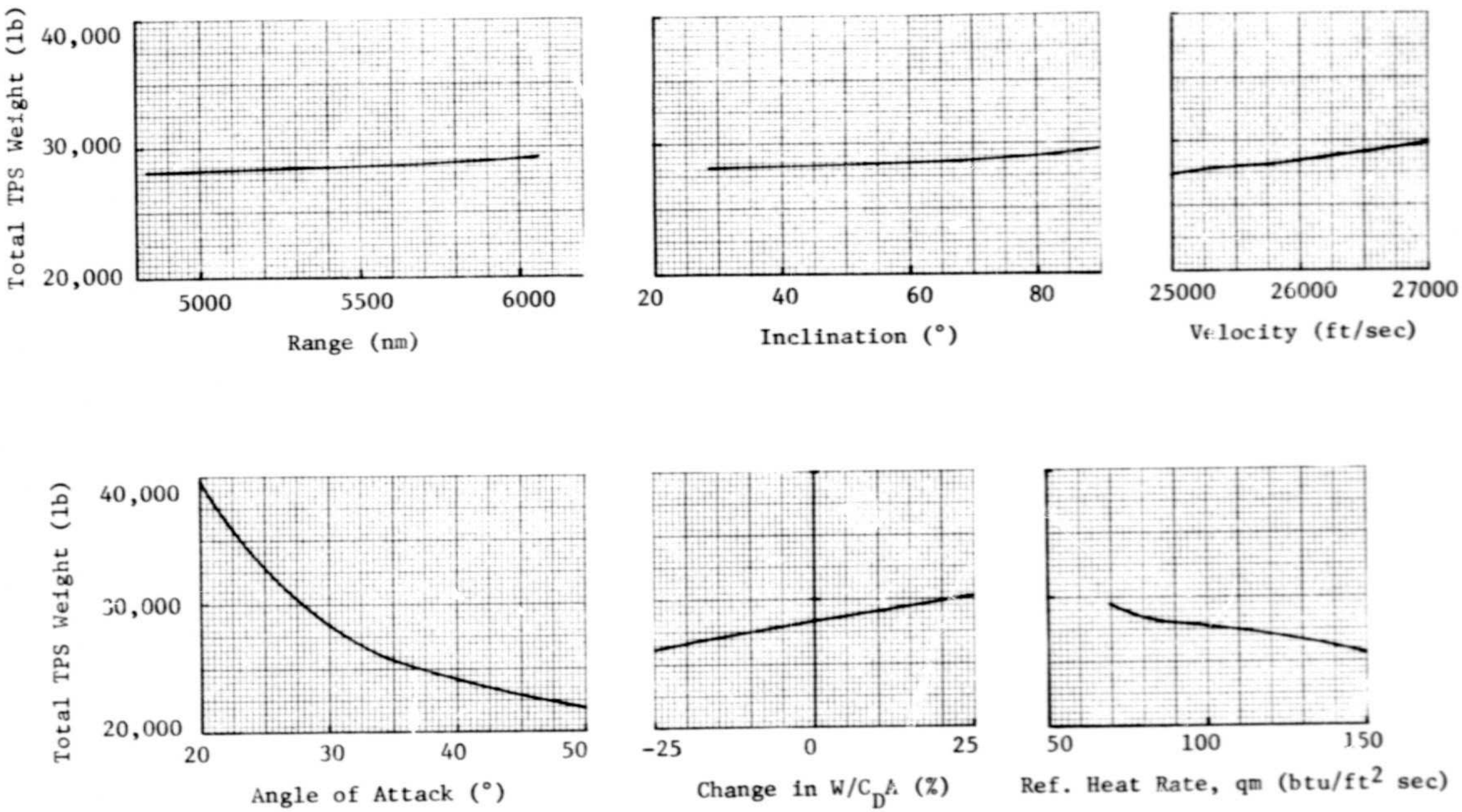


Figure 8. Effects of Entry Parameters on Insulative TPS Weight.

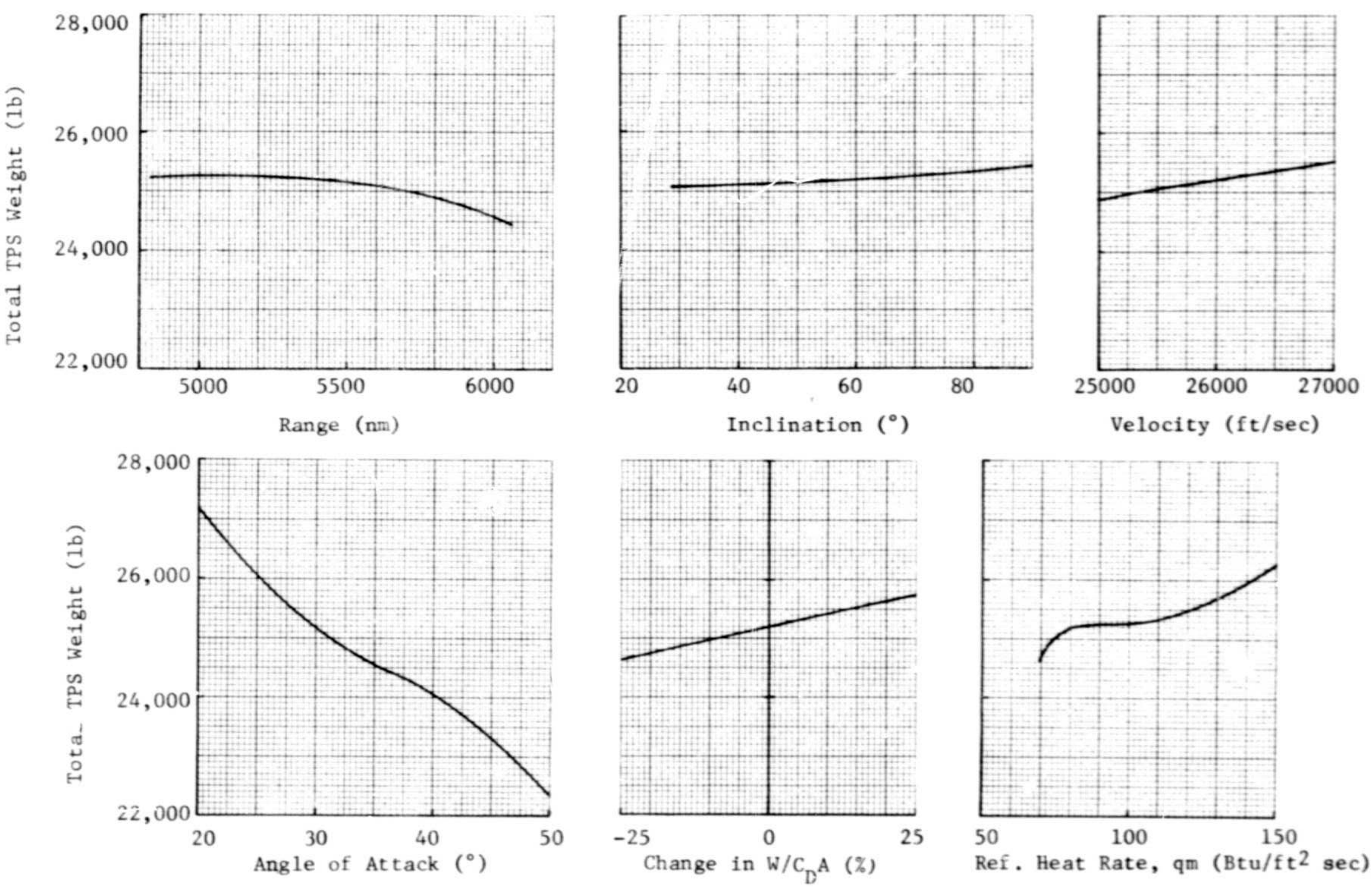


Figure 9. Effects of Entry Parameters on Metallic TPS Weight.

APPENDIX

## Table A-1

### Material Thermophysical Properties

1. LI-1500
   Density: 15 lb/ft$^3$
   Specific Heat: c (Btu/lb-°F)

| T(°F) | 0 | 80 | 260 | 440 | 620 | 800 | 980 | 1340 | 1700 | 2060 | 2430 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| c | 0.072 | 0.151 | 0.198 | 0.234 | 0.263 | 0.280 | 0.[illegible]87 | 0.294 | 0.306 | 0.316 | 0.320 |

Conductivity: k (Btu/ft-sec°F)

| | k x 10$^4$ | | | | |
|---|---|---|---|---|---|
| T(°F) \ P(atm) | .000132 | 0.00132 | 0.0132 | 0.132 | 1.0 |
| 0 | 0.0393 | 0.0440 | 0.0648 | 0.0741 | 0.0810 |
| 300 | 0.0486 | 0.0532 | 0.0717 | 0.0787 | 0.085[illegible] |
| 700 | 0.0625 | 0.0671 | 0.0810 | 0.1088 | 0.1203 |
| 1400 | 0.1041 | 0.1088 | 0.1388 | 0.2083 | 0.2314 |
| 2000 | 0.1550 | 0.1597 | 0.2360 | 0.3239 | 0.3610 |
| 2500 | 0.2129 | 0.2175 | 0.3124 | 0.4350 | 0.4836 |

2. TITANIUM ALLOY (TI-CAL-4V)
   Density: 276.45 lb/ft$^3$
   Specific Heat: c (Btu/lb-°F)

| T(°F) | 0 | 400 | 600 | 800 | 1200 |
|---|---|---|---|---|---|
| c | 0.13 | 0.14 | 0.15 | 0.16 | 0.18 |

Conductivity: k (Btu/ft-sec°F)

| T(°F) | 0 | 100 | 1200 |
|---|---|---|---|
| k | 0.0011 | 0.0012 | 0.0031 |

3. TG-15000
   Density: 3 lb/ft$^3$
   Specific Heat: c (Btu/lb-°F)

| T(°F) | 100 | 300 | 2000 |
|---|---|---|---|
| c | 0.220 | 0.235 | 0.235 |

Conductivity: k(Btu/ft-sec-°F)

| | k x 10$^4$ | | | | |
|---|---|---|---|---|---|
| T(°F) \ P(atm) | 1x10$^7$ | 2x10$^5$ | 9x10$^4$ | 0.011 | 1.0 |
| 0 | 0.00083 | 0.00111 | 0.0111 | 0.0344 | 0.0389 |
| 80 | 0.00694 | 0.00806 | 0.0178 | 0.0402 | 0.0508 |
| 300 | 0.0117 | 0.0142 | 0.0347 | 0.0667 | 0.0778 |
| 500 | 0.0278 | 0.0306 | 0.0519 | 0.0986 | 0.110 |
| 700 | 0.0611 | 0.0778 | 0.150 | 0.169 | 0.402 |

Table A-1 (continued)

4. DYNAFLEX
Density: 6.0 lb/ft$^3$
Specific Heat: c (Btu/lb-°F)

| T(°F) | 0 | 400 | 800 | 1200 | 1600 | 2000 | 2400 |
|---|---|---|---|---|---|---|---|
| c | 0.216 | 0.216 | 0.244 | 0.262 | 0.270 | 0.276 | 0.278 |

Conductivity: k (Btu/ft-sec-°F)

| | k x $10^4$ | | | |
|---|---|---|---|---|
| T(°F) \ P(atm) | 0.001 | 0.01 | 0.1 | 1.0 |
| 0 | 0.0083 | 0.0125 | 0.0250 | 0.0250 |
| 600 | 0.0667 | 0.0903 | 0.1167 | 0.1167 |
| 1200 | 0.158 | 0.214 | 0.251 | 0.253 |
| 1800 | 0.328 | 0.392 | 0.438 | 0.450 |
| 2200 | 0.472 | 0.550 | 0.617 | 0.625 |

5. MICROQUARTZ
Density: 3.5 lb/ft$^3$
Specific Heat: c (Btu/lb-°F)

| T(°F) | 0 | 200 | 500 | 1000 | 1500 | 2000 |
|---|---|---|---|---|---|---|
| c | 0.20 | 0.20 | 0.24 | 0.27 | 0.29 | 0.30 |

Conductivity: k (Btu/ft-sec-°F)

| | k x $10^4$ | | | | |
|---|---|---|---|---|---|
| T(°F) \ P (atm) | 0.00013 | 0.001 | 0.01 | 0.1 | 1.0 |
| 0 | 0.0083 | 0.0236 | 0.0486 | 0.0583 | 0.0625 |
| 400 | 0.0278 | 0.0417 | 0.0750 | 0.0972 | 0.1000 |
| 800 | 0.0722 | 0.0819 | 0.117 | 0.156 | 0.160 |
| 1200 | 0.135 | 0.144 | 0.175 | 0.226 | 0.232 |
| 1400 | 0.172 | 0.182 | 0.211 | 0.267 | 0.276 |
| 1600 | 0.211 | 0.219 | 0.250 | 0.313 | 0.333 |
| 1800 | 0.253 | 0.261 | 0.292 | 0.368 | 0.400 |

6. CRYOGENIC FOAM

Density: 6.696 lb/ft$^3$

Specific Heat: .23 Btu/lb-°F

Conductivity: .00019 Btu/ft-sec-°F

Table A-2. Required LI-1500 and TG-15000 Insulation Unit Weights, Insulative TPS

| Panel Number | Heating Factor ($\alpha$=30°) | Insulation Unit Weight from Figure A-12 (lb/ft$^2$) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Trajectory Number | | | | | | | | | | | | | |
| | | 1 | 2 | 3 | 7 | 8 | 9 | 10 | 11 | 12 | 17 | 18 | 22 | 23 | 24 |
| 1 | .17 | 3.14 | 3.26 | 3.05 | 3.09 | 3.36 | 2.97 | 3.06 | 3.26 | 3.40 | 2.86 | 3.46 | 3.26 | 2.98 | 2.59 |
| 2 | .07 | 2.38 | 2.48 | 2.28 | 2.32 | 2.55 | 2.21 | 2.32 | 2.48 | 2.59 | 2.12 | 2.65 | 2.53 | 2.24 | 1.88 |
| 3 | .05 | 2.10 | 2.20 | 2.00 | 2.04 | 2.26 | 1.95 | 2.04 | 2.20 | 2.31 | 1.87 | 2.35 | 2.24 | 1.95 | 1.65 |
| 4 | .05 | 2.10 | 2.20 | 2.00 | 2.04 | 2.26 | 1.95 | 2.04 | 2.20 | 2.31 | 1.87 | 2.35 | 2.24 | 1.95 | 1.65 |
| 5 | .039 | 1.89 | 2.00 | 1.81 | 1.84 | 2.05 | 1.76 | 1.84 | 2.00 | 2.10 | 1.69 | 2.13 | 2.04 | 1.77 | 1.49 |
| 6 | .024 | 1.52 | 1.63 | 1.43 | 1.48 | 1.67 | 1.38 | 1.48 | 1.62 | 1.71 | 1.33 | 1.75 | 1.68 | 1.42 | 1.19 |
| 7 | .015 | 1.19 | 1.28 | 1.11 | 1.15 | 1.32 | 1.07 | 1.15 | 1.28 | 1.36 | 1.00 | 1.38 | 1.30 | 1.10 | 0.88 |
| 8 | .0039 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| 9 | .02 | 1.38 | 1.50 | 1.30 | 1.35 | 1.55 | 1.25 | 1.35 | 1.50 | 1.58 | 1.18 | 1.61 | 1.53 | 1.29 | 1.08 |
| 10 | .006 | 0.10 | 0.10 | 0.50 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.50 | 0.38 |
| 11 | .007 | 0.69 | 0.79 | 0.60 | 0.66 | 0.78 | 0.61 | 0.66 | 0.75 | 0.82 | 0.58 | 0.84 | 0.77 | 0.62 | 0.47 |
| 12 | .003 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |

Table A-3. Total Required LI-1500 and TG-15000 Insulation Weights, Insulative TPS

| Panel Number | Panel Area (ft$^2$) | Total Insulation Weight (lb) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Trajectory Number | | | | | | | | | | | | | |
| | | 1 | 2 | 3 | 7 | 8 | 9 | 10 | 11 | 12 | 17 | 18 | 22 | 23 | 24 |
| 1 | 431 | 1353 | 1405 | 1315 | 1332 | 1448 | 1280 | 1319 | 1405 | 1465 | 1233 | 1491 | 1405 | 1284 | 1116 |
| 2 | 928 | 2209 | 2301 | 2116 | 2153 | 2366 | 2051 | 2153 | 2301 | 2403 | 1967 | 2459 | 2348 | 2079 | 1745 |
| 3 | 1306 | 2743 | 2873 | 2612 | 2664 | 2952 | 2547 | 2664 | 2873 | 3017 | 2442 | 3069 | 2925 | 2547 | 2155 |
| 4 | 1408 | 2957 | 3097 | 2816 | 2872 | 3182 | 2746 | 2872 | 3097 | 3252 | 2633 | 3309 | 3154 | 2746 | 2323 |
| 5 | 697 | 1317 | 1394 | 1262 | 1282 | 1429 | 1227 | 1282 | 1394 | 1464 | 1178 | 1485 | 1422 | 1234 | 1039 |
| 6 | 1000 | 1520 | 1630 | 1430 | 1480 | 1670 | 1380 | 1480 | 1620 | 1710 | 1330 | 1750 | 1680 | 1420 | 1190 |
| 7 | 671 | 798 | 859 | 745 | 772 | 886 | 719 | 772 | 859 | 913 | 671 | 926 | 872 | 738 | 590 |
| 8 | 719 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| 9 | 467 | 644 | 700 | 607 | 630 | 724 | 584 | 630 | 701 | 738 | 551 | 752 | 715 | 602 | 504 |
| 10 | 1116 | 112 | 112 | 558 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 558 | 424 |
| 11 | 1539 | 1062 | 1216 | 923 | 1016 | 1200 | 939 | 1016 | 1154 | 1154 | 893 | 1293 | 1185 | 954 | 723 |
| 12 | 1798 | 108 | 108 | 108 | 108 | 108 | 108 | 108 | 108 | 108 | 108 | 108 | 108 | 108 | 108 |
| Total Weight | | 14866 | 15738 | 14535 | 14464 | 16120 | 13736 | 14451 | 15667 | 16379 | 13161 | 16797 | 15969 | 14313 | 11960 |

Table A-4. Required LI-1500 and TG-15000 Weights, Insulative TPS (Angle of Attack Dispersions)

| Panel Number | Panel Area ($ft^2$) | Trajectory 19 Heating Factor ( =20°) | Trajectory 19 Insulation Weight ($lb/ft^2$) | Trajectory 19 Total Weight (lb) | Trajectory 20 Heating Factor ( = 40°) | Trajectory 20 Insulation Weight ($lb/ft^2$) | Trajectory 20 Total Weight (lb) | Trajectory 21 Heating Factor ( = 50°) | Trajectory 21 Insulation Weight ($lb/ft^2$) | Trajectory 21 Total Weight (lb) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 431 | .156 | 4.60 | 1982 | .184 | 2.54 | 1095 | .198 | 2.20 | 948 |
| 2 | 928 | .042 | 3.22 | 2988 | .098 | 2.01 | 1865 | .126 | 1.88 | 1745 |
| 3 | 1306 | .038 | 3.12 | 4075 | .062 | 1.68 | 2194 | .073 | 1.50 | 1959 |
| 4 | 1408 | .043 | 3.24 | 4562 | .057 | 1.63 | 2295 | .064 | 1.41 | 1985 |
| 5 | 697 | .051 | 3.42 | 2384 | .027 | 1.13 | 788 | .015 | 0.52 | 362 |
| 6 | 1000 | .030 | 2.89 | 2890 | .018 | 0.85 | 850 | .012 | 0.42 | 420 |
| 7 | 671 | .019 | 2.47 | 1657 | .011 | 0.55 | 369 | .006 | 0.10 | 67 |
| 8 | 719 | .0039 | 0.10 | 72 | .0039 | 0.06 | 43 | .0039 | 0.06 | 43 |
| 9 | 467 | .020 | 2.52 | 1177 | .020 | 0.93 | 434 | .020 | 0.67 | 313 |
| 10 | 1116 | .006 | 1.50 | 1674 | .006 | 0.10 | 112 | .006 | 0.10 | 112 |
| 11 | 1539 | .007 | 1.64 | 2524 | .007 | 0.30 | 462 | .007 | 0.10 | 154 |
| 12 | 1798 | .003 | 0.10 | 180 | .003 | 0.06 | 108 | .003 | 0.06 | 180 |
| Total Insulation Weight | | | | 26165 | | | 10615 | | | 8288 |

Table A-5. Required Microquartz Insulation* Unit Weights, Metallic TPS

| Panel Number | Heating Factor ($\alpha$=30°) | Insulation Unit Weight from Figure A-13 (lb/ft$^2$) Trajectory Number | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 7 | 8 | 9 | 10 | 11 | 12 | 17 | 18 | 22 | 23 | 24 |
| 1* | .17 | 1.492 | 1.442 | 1.405 | 1.415 | 1.610 | 1.290 | 1.392 | 1.579 | 1.640 | 1.243 | 1.731 | 1.430 | 1.385 | 1.327 |
| 2 | .07 | 0.863 | 0.879 | 0.836 | 0.844 | 0.908 | 0.801 | 0.834 | 0.892 | 0.920 | 0.769 | 0.950 | 0.909 | 0.815 | 0.758 |
| 3 | .05 | 0.735 | 0.730 | 0.715 | 0.717 | 0.771 | 0.682 | 0.712 | 0.756 | 0.785 | 0.653 | 0.810 | 0.756 | 0.704 | 0.666 |
| 4 | .05 | 0.735 | 0.730 | 0.715 | 0.717 | 0.771 | 0.682 | 0.712 | 0.756 | 0.785 | 0.653 | 0.810 | 0.756 | 0.704 | 0.666 |
| 5 | .039 | 0.636 | 0.624 | 0.628 | 0.623 | 0.662 | 0.594 | 0.623 | 0.654 | 0.670 | 0.568 | 0.697 | 0.648 | 0.622 | 0.600 |
| 6 | .024 | 0.449 | 0.420 | 0.462 | 0.438 | 0.467 | 0.430 | 0.438 | 0.462 | 0.473 | 0.405 | 0.496 | 0.442 | 0.462 | 0.461 |
| 7 | .015 | 0.294 | 0.241 | 0.305 | 0.290 | 0.308 | 0.275 | 0.290 | 0.306 | 0.310 | 0.261 | 0.335 | 0.260 | 0.313 | 0.360 |
| 8 | .0039 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | .02 | 0.385 | 0.344 | 0.400 | 0.376 | 0.400 | 0.368 | 0.376 | 0.396 | 0.402 | 0.350 | 0.425 | 0.370 | 0.406 | 0.429 |
| 10 | .006 | 0.073 | - | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | - | 0.073 | 0.149 |
| 11 | .007 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.073 | 0.181 |
| 12 | .003 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

* Panel 1 unit weights are combined dynaflex and microquartz unit weights

Table A-6. Total Required Microquartz Insulation* Weights, Metallic TPS

| Panel Number | Panel Area (ft$^2$) | Total Insulation Weight (lb) Trajectory Number | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 7 | 8 | 9 | 10 | 11 | 12 | 17 | 18 | 22 | 23 | 24 |
| 1 | 431 | 643 | 622 | 606 | 610 | 694 | 556 | 600 | 681 | 707 | 536 | 746 | 616 | 597 | 573 |
| 2 | 928 | 801 | 816 | 776 | 783 | 843 | 743 | 774 | 828 | 854 | 714 | 882 | 844 | 756 | 703 |
| 3 | 1306 | 960 | 953 | 934 | 936 | 1007 | 891 | 930 | 987 | 1025 | 853 | 1058 | 987 | 919 | 870 |
| 4 | 1408 | 1035 | 1028 | 1007 | 1010 | 1086 | 960 | 1002 | 1064 | 1105 | 919 | 1140 | 1064 | 991 | 938 |
| 5 | 697 | 443 | 435 | 438 | 434 | 461 | 414 | 434 | 456 | 467 | 396 | 486 | 452 | 433 | 418 |
| 6 | 1000 | 449 | 420 | 462 | 438 | 467 | 430 | 438 | 462 | 473 | 405 | 496 | 442 | 462 | 461 |
| 7 | 671 | 197 | 162 | 205 | 195 | 207 | 185 | 195 | 205 | 208 | 175 | 225 | 174 | 205 | 242 |
| 8 | 719 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | 467 | 180 | 161 | 187 | 176 | 187 | 172 | 176 | 185 | 188 | 163 | 198 | 173 | 190 | 200 |
| 10 | 1116 | 81 | - | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | - | 81 | 166 |
| 11 | 1539 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 279 |
| 12 | 1798 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Total Weight | | 4901 | 4709 | 4808 | 4775 | 5145 | 4544 | 4742 | 5061 | 5220 | 4354 | 5424 | 4864 | 4746 | 4902 |

*Panel 1 total weights are combined dynaflex and microquartz weights

Table A-7. Required Microquartz Insulation Weights, Metallic TPS (Angle of Attack Dispersion)

| Panel Number | Panel Area ($ft^2$) | Trajectory 19 Heating Factor ($\alpha$=20°) | Trajectory 19 Insulation Weight ($lb/ft^2$) | Trajectory 19 Total Weight (lb) | Trajectory 20 Heating Factor ($\alpha$=40°) | Trajectory 20 Insulation Weight ($lb/ft^2$) | Trajectory 20 Total Weight (lb) | Trajectory 21 Heating Factor ($\alpha$=50°) | Trajectory 21 Insulation Weight ($lb/ft^2$) | Trajectory 21 Total Weight (lb) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1* | 431 | .156 | 2.275 | 981 | .184 | 1.118 | 482 | .198 | 0.958 | 413 |
| 2 | 928 | .042 | 0.976 | 906 | .098 | 0.774 | 718 | .126 | 0.710 | 659 |
| 3 | 1306 | .038 | 0.920 | 1202 | .062 | 0.630 | 823 | .073 | 0.570 | 744 |
| 4 | 1408 | .043 | 0.990 | 1394 | .057 | 0.604 | 850 | .064 | 0.539 | 759 |
| 5 | 697 | .051 | 1.085 | 756 | .027 | 0.390 | 272 | .015 | 0.204 | 142 |
| 6 | 1000 | .030 | 0.783 | 783 | .018 | 0.283 | 283 | .012 | 0.154 | 154 |
| 7 | 671 | .019 | 0.549 | 368 | .011 | 0.158 | 106 | .006 | - | - |
| 8 | 719 | .0039 | - | - | .0039 | - | - | .0039 | - | - |
| 9 | 467 | .020 | 0.572 | 267 | .020 | 0.312 | 146 | .020 | 0.264 | 123 |
| 10 | 1116 | .006 | 0.073 | 81 | .006 | 0.073 | 81 | .006 | - | - |
| 11 | 1539 | .007 | 0.073 | 139 | .007 | 0.073 | 112 | .007 | - | - |
| 12 | 1798 | .003 | - | - | .003 | - | - | .003 | - | - |
| Total Insulation Weight | | | | 6877 | | | 3873 | | | 2994 |

*Panel 1 unit weights are combined dynaflex and microquartz unit weights

Table A-8. Maximum Sustained Surface Temperatures

| Panel Number | $\alpha=20°$, $q_m=100$ | | $\alpha = 30°$, $q_m$ = 150, 100, 90, 80, 70 | | | | | | $\alpha=40°$, $q_m=80$ | | $\alpha=50°$, $q_m=65$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Heating Factor | Max. Surface Temp. (°F) | Heating Factor | Maximum Surface Temp (°F) | | | | | Heating Factor | Max. Surface Temp. (°F) | Heating Factor | Max. Surface Temp. (°F) |
| | | | | $q_m=150$ | $q_m=100$ | $q_m=90$ | $q_m=80$ | $q_m=70$ | | | | |
| 1 | .156 | 2069 | .17 | 2400 | 2125 | 2058 | 1984 | 1904 | .184 | 2033 | .198 | 1950 |
| 2 | .042 | 1362 | .07 | 1832 | 1611 | 1556 | 1498 | 1434 | .098 | 1670 | .126 | 1693 |
| 3 | .038 | 1317 | .05 | 1647 | 1444 | 1394 | 1340 | 1281 | .062 | 1440 | .073 | 1419 |
| 4 | .043 | 1373 | .05 | 1647 | 1444 | 1394 | 1340 | 1281 | .057 | 1400 | .064 | 1358 |
| 5 | .051 | 1453 | .039 | 1519 | 1329 | 1282 | 1232 | 1176 | .027 | 1083 | .015 | 805 |
| 6 | .030 | 1215 | .024 | 1293 | 1124 | 1083 | 1038 | 989 | .018 | 934 | .012 | 736 |
| 7 | .019 | 1034 | .015 | 1099 | 949 | 912 | 872 | 829 | .011 | 773 | .006 | 546 |
| 8 | .0039 | 546 | .0039 | 653 | 546 | 520 | 491 | 460 | .0039 | 491 | .0039 | 443 |
| 9 | .020 | 1054 | .02 | 1215 | 1054 | 1014 | 971 | 925 | .020 | 971 | .020 | 899 |
| 10 | .006 | 660 | .006 | 780 | 660 | 631 | 600 | 564 | .006 | 600 | .006 | 546 |
| 11 | .007 | 704 | .007 | 829 | 704 | 674 | 641 | 605 | .007 | 641 | .007 | 585 |
| 12 | .003 | 482 | .003 | 583 | 482 | 458 | 431 | 402 | .003 | 431 | .003 | 386 |

Table A-9. Metallic Shingle Weights

| Panel Number | Panel Area ($ft^2$) | $\alpha=20$, $q_m=100$ | | $\alpha = 30°$, $q_m=150$ | | $\alpha=30°$, $q_m = 100$ | | $\alpha=30°$, $q_m=90$ | | $\alpha=30°$, $q_m=80$ | | $\alpha=30°$, $q_m=70$ | | $\alpha=40°$, $q_m=80$ | | $\alpha=50°$, $q_m=65$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Unit Weight ($lb/ft^2$) | Total Weight (lb) | Unit Weight ($lb/ft^2$) | Total Weight (lb) | Unit Weight ($lb/ft^2$) | Total Weight (lb) | Unit Weight ($lb/ft^2$) | Total Weight (lb) | Unit Weight ($lb/ft^2$) | Total Weight (lb) | Unit Weight ($lb/ft^2$) | Total Weight (lb) | Unit Weight ($lb/ft^2$) | Total Weight (lb) | Unit Weight ($lb/ft^2$) | Total Weight (lb) |
| 1 | 431 | 2.15 | 926 | 2.30 | 991 | 2.18 | 940 | 2.15 | 936 | 2.13 | 914 | 1.71 | 737 | 2.14 | 922 | 2.10 | 905 |
| 2 | 928 | 1.03 | 956 | 1.53 | 1420 | 1.19 | 1104 | 1.13 | 1049 | 1.05 | 974 | 1.04 | 965 | 1.26 | 1169 | 1.29 | 1197 |
| 3 | 1306 | 1.02 | 1332 | 1.23 | 1606 | 1.04 | 1358 | 1.04 | 1358 | 1.03 | 1345 | 1.02 | 1332 | 1.04 | 1358 | 1.04 | 1358 |
| 4 | 1408 | 1.03 | 1450 | 1.23 | 1732 | 1.04 | 1464 | 1.04 | 1464 | 1.03 | 1450 | 1.02 | 1436 | 1.04 | 1464 | 1.04 | 1464 |
| 5 | 697 | 1.04 | 725 | 1.05 | 732 | 1.02 | 711 | 1.02 | 711 | 1.02 | 711 | 1.02 | 711 | 1.02 | 711 | 0.50 | 349 |
| 6 | 1000 | 1.02 | 1020 | 1.02 | 1020 | 1.02 | 1020 | 1.02 | 1020 | 1.02 | 1020 | 1.02 | 1020 | 1.02 | 1020 | 0.50 | 500 |
| 7 | 671 | 1.02 | 684 | 1.02 | 684 | 1.02 | 684 | 1.02 | 684 | 0.50 | 336 | 0.50 | 336 | 0.50 | 336 | 0.50 | 336 |
| 8 | 719 | 0.50 | 360 | 0.50 | 360 | 0.50 | 360 | 0.50 | 360 | 0.50 | 360 | 0.50 | 360 | 0.50 | 360 | 0.50 | 360 |
| 9 | 467 | 1.02 | 476 | 1.02 | 476 | 1.02 | 476 | 1.02 | 476 | 1.02 | 476 | 1.02 | 476 | 1.02 | 476 | 1.02 | 476 |
| 10 | 1116 | 0.50 | 558 | 0.50 | 558 | 0.50 | 558 | 0.50 | 558 | 0.50 | 558 | 0.50 | 558 | 0.50 | 558 | 0.50 | 558 |
| 11 | 1539 | 0.50 | 770 | 0.50 | 770 | 0.50 | 770 | 0.50 | 770 | 0.50 | 770 | 0.50 | 770 | 0.50 | 770 | 0.50 | 770 |
| 12 | 1798 | 0.50 | 899 | 0.50 | 899 | 0.50 | 899 | 0.50 | 899 | 0.50 | 899 | 0.50 | 899 | 0.50 | 899 | 0.50 | 899 |
| Total Weight | | | 10156 | | | | | | 10275 | | 10161 | | 9600 | | 10043 | | 9172 |

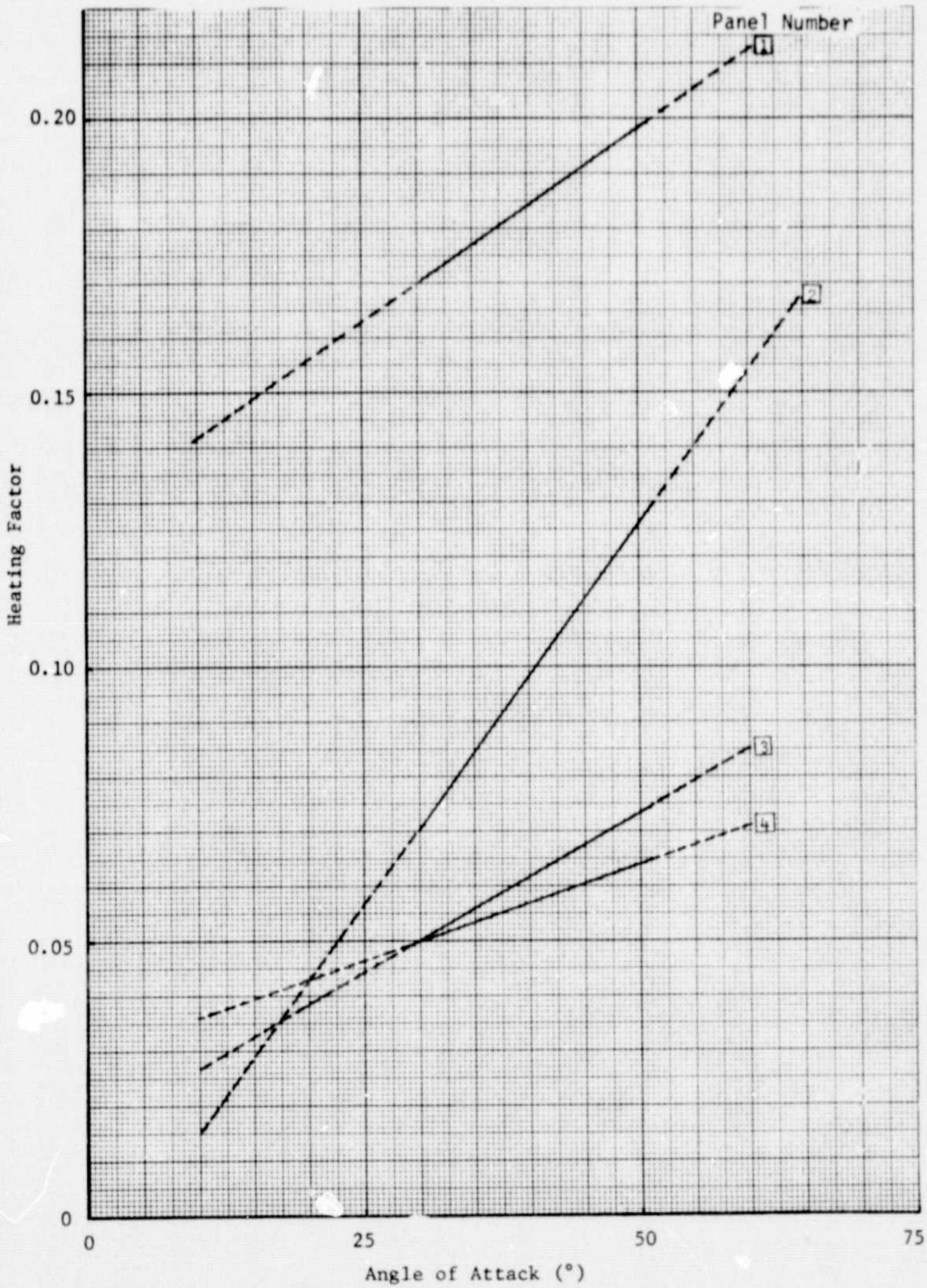


Figure A-1. Local Heating Factors, Panels 1, 2, 3, and 4

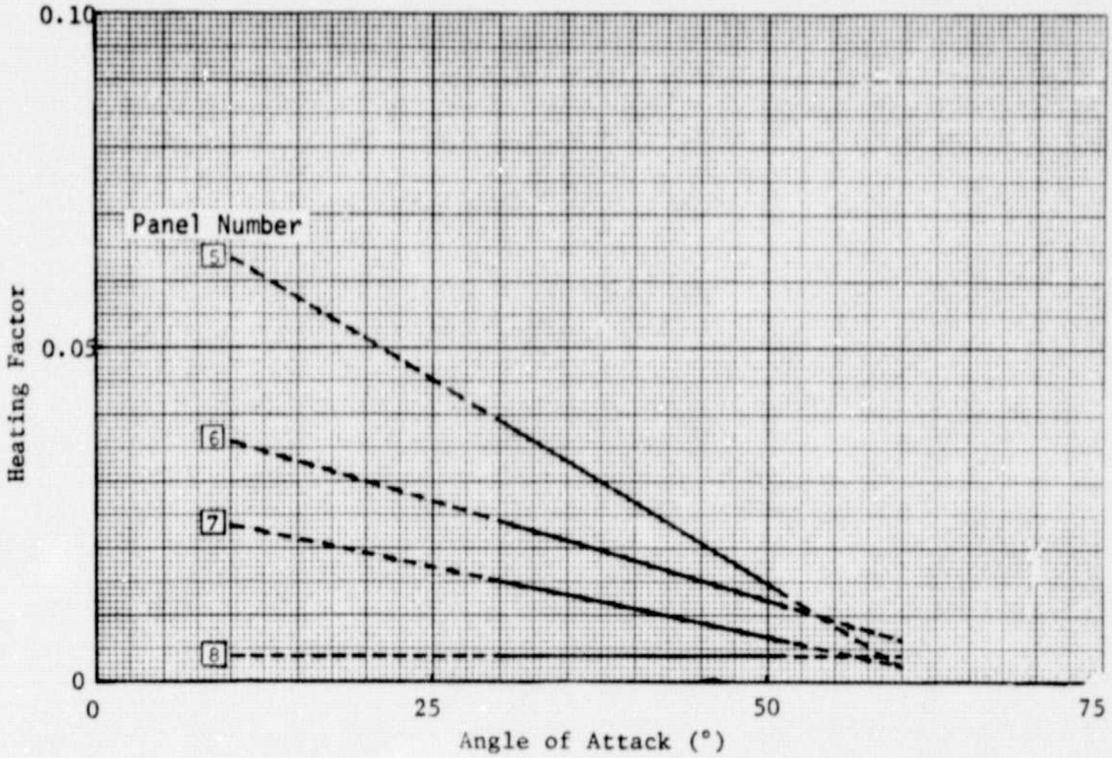


Figure A-2.  Local Heating Factors, Panels 5, 6, 7, and 8

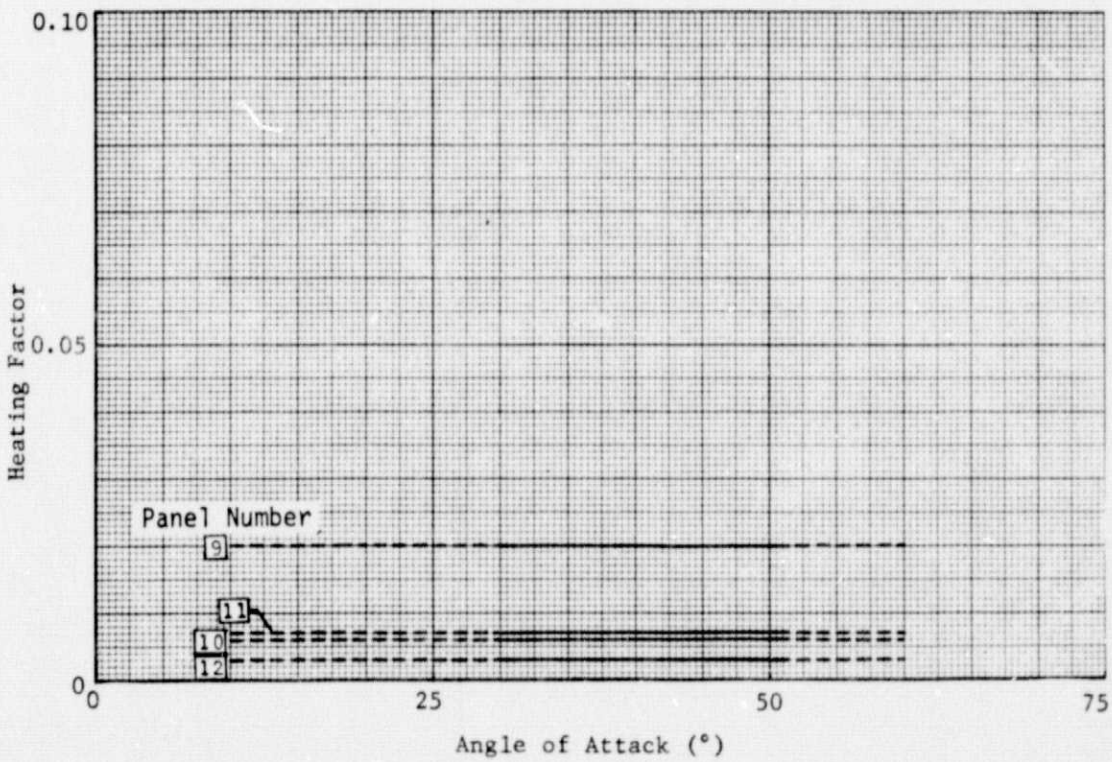


Figure A-3.  Local Heating Factors, Panels 9, 10, 11, and 12

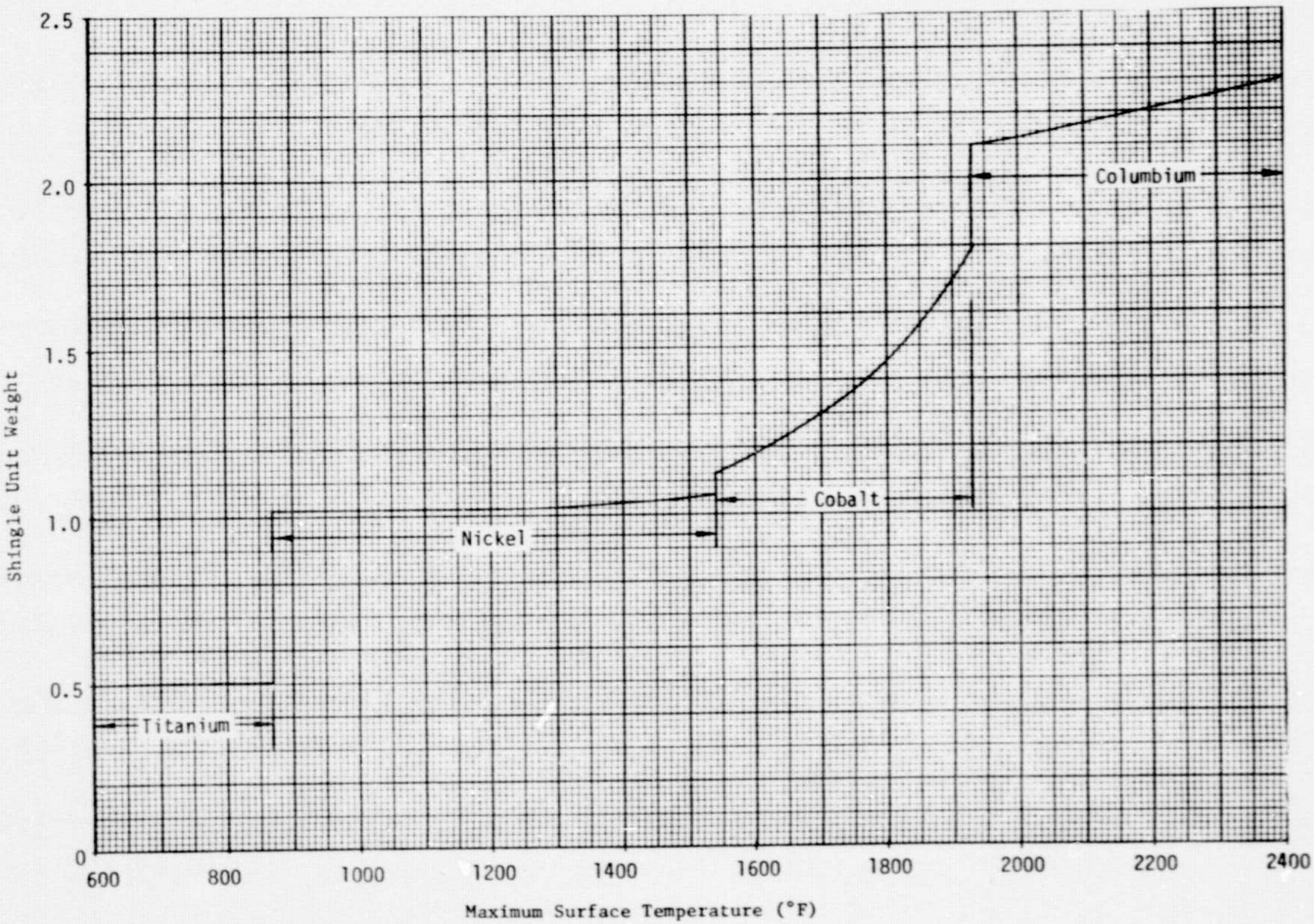


Figure A-4. Required Shingle Weight for Metallic TPS

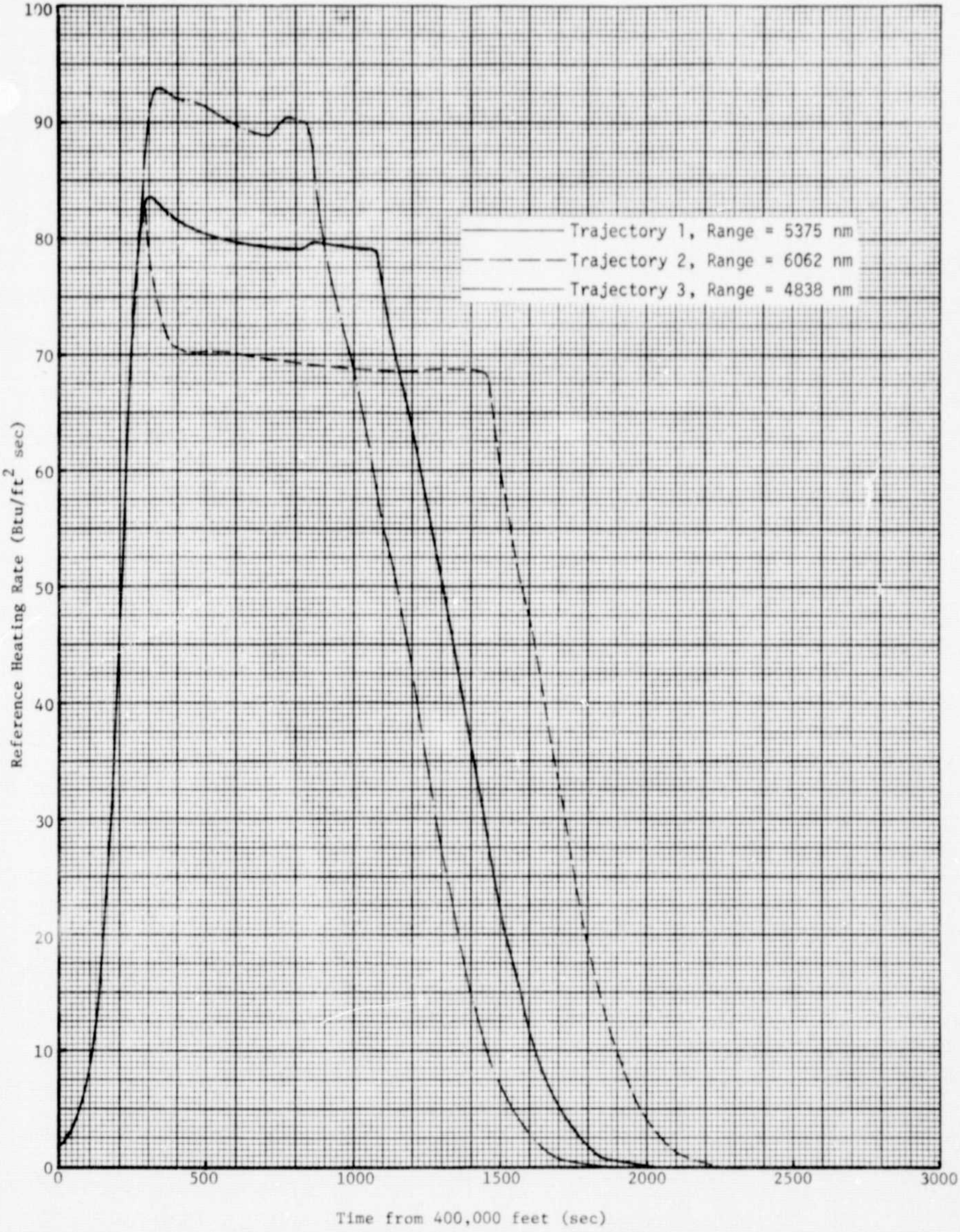


Figure A-5. Reference Heating Rate Histories, Range Dispersion

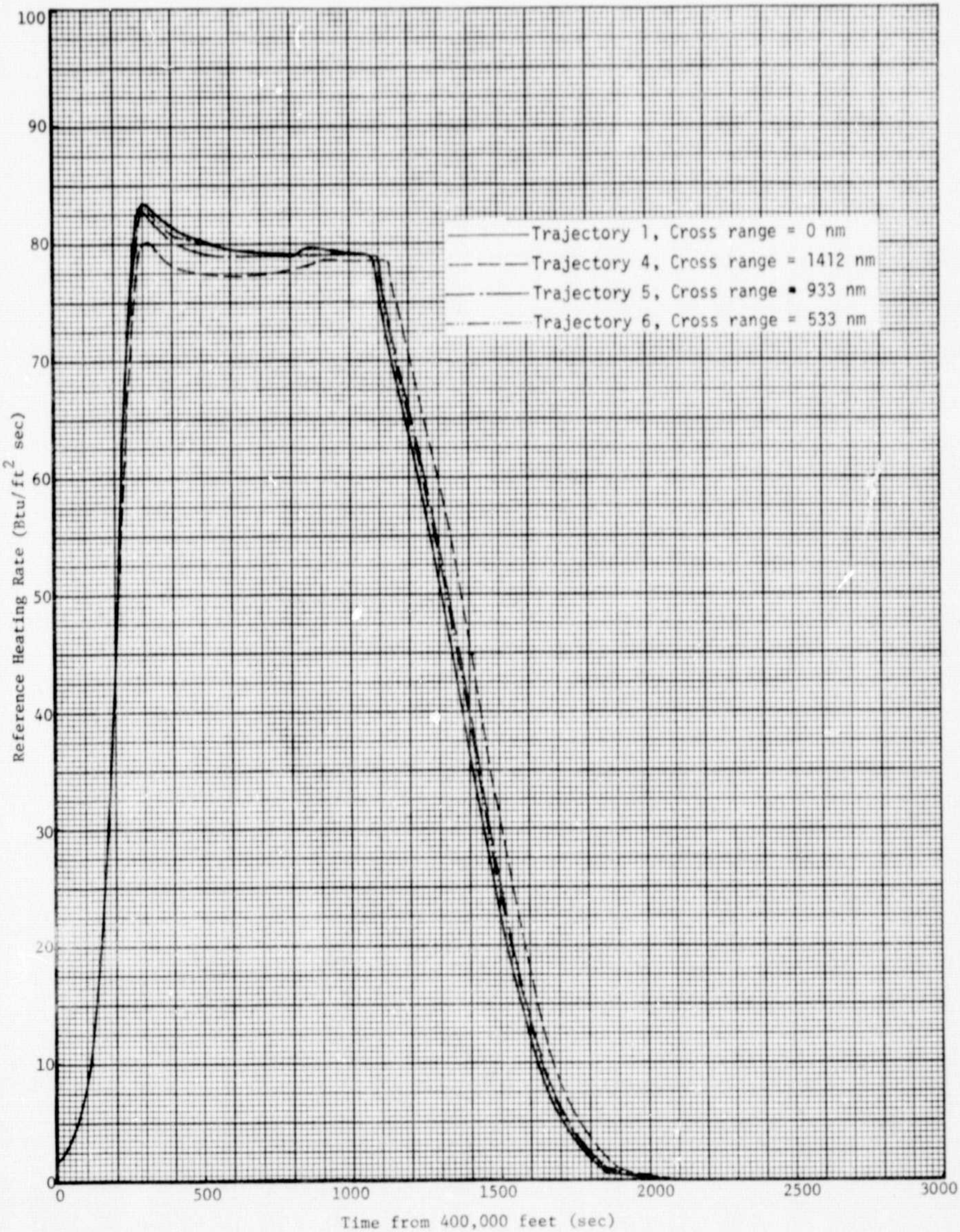


Figure A-6. Reference Heating Rate Histories, Cross Range Dispersion

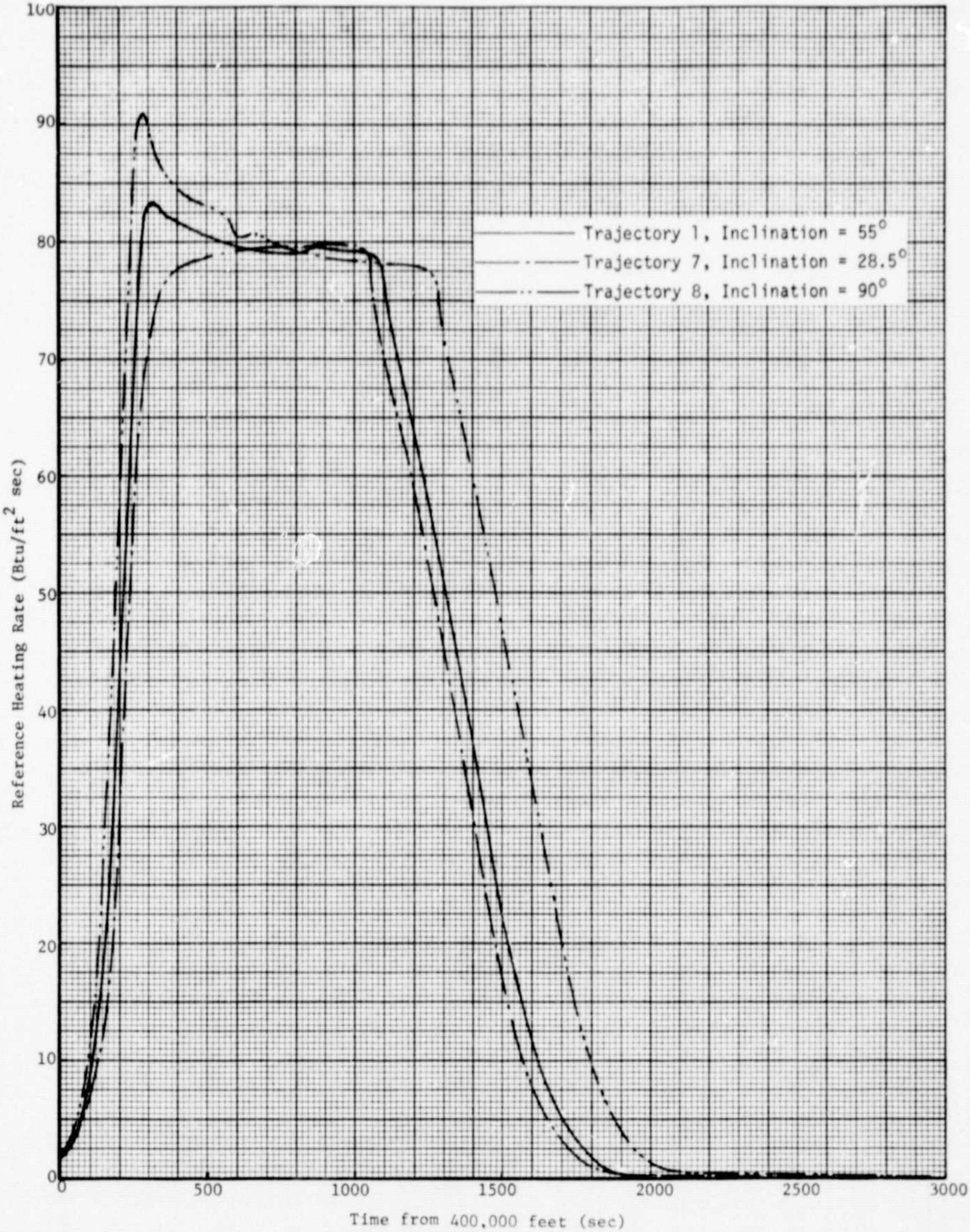


Figure A-7. Reference Heating Rate Histories, Inclination Dispersion

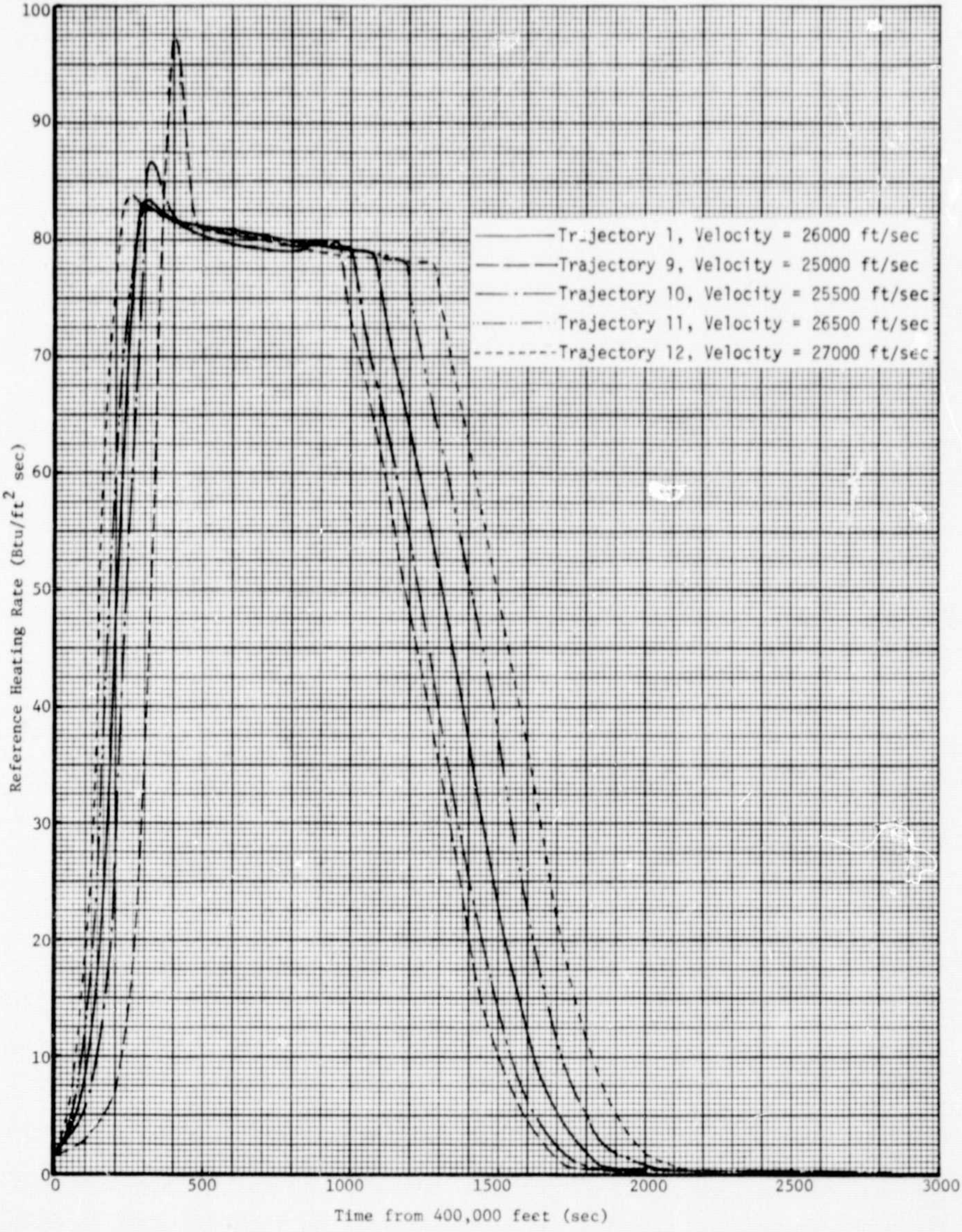


Figure A-8. Reference Heating Rate Histories, Velocity Dispersion

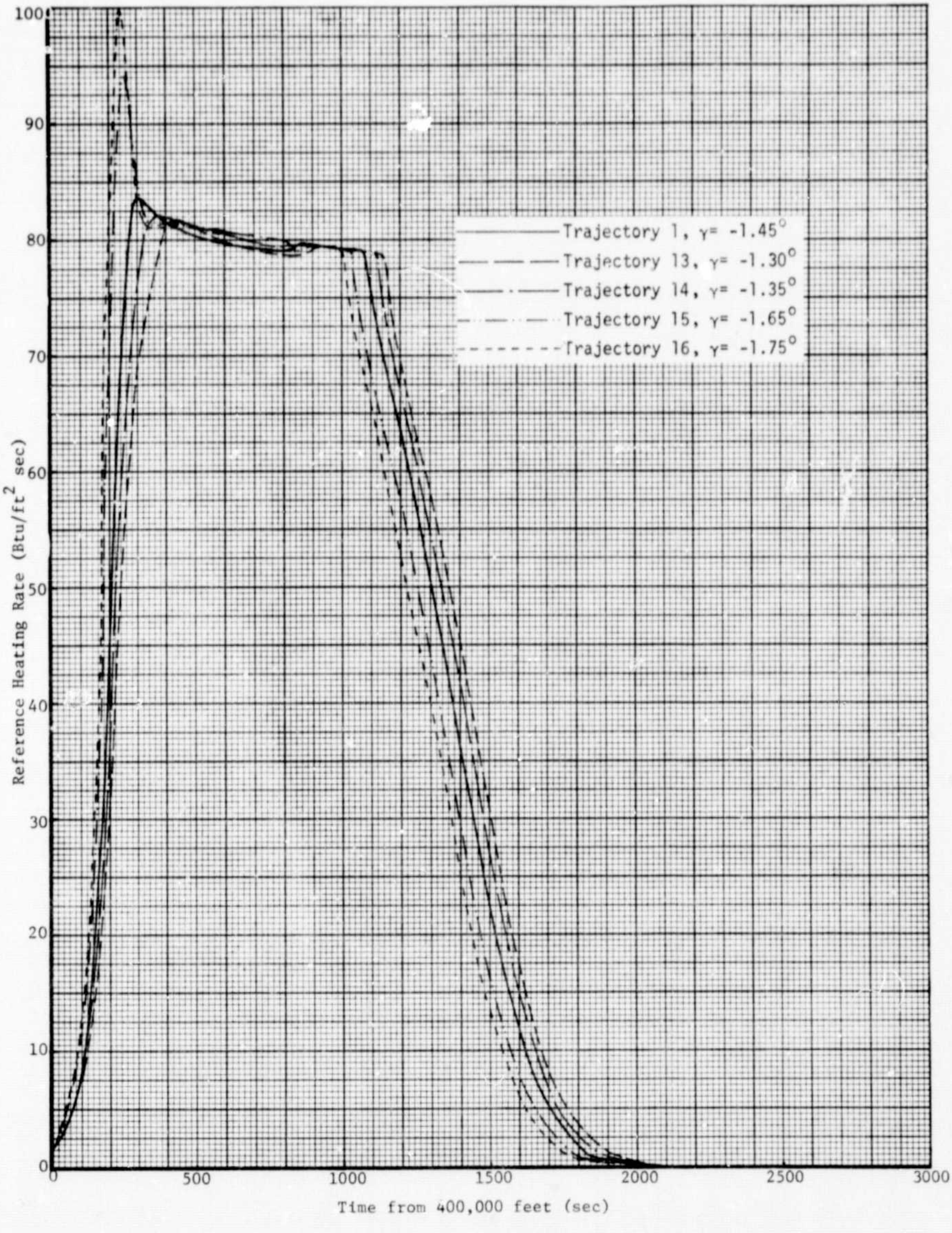


Figure A-9. Reference Heating Rate Histories, Flight Path Angle Dispersion

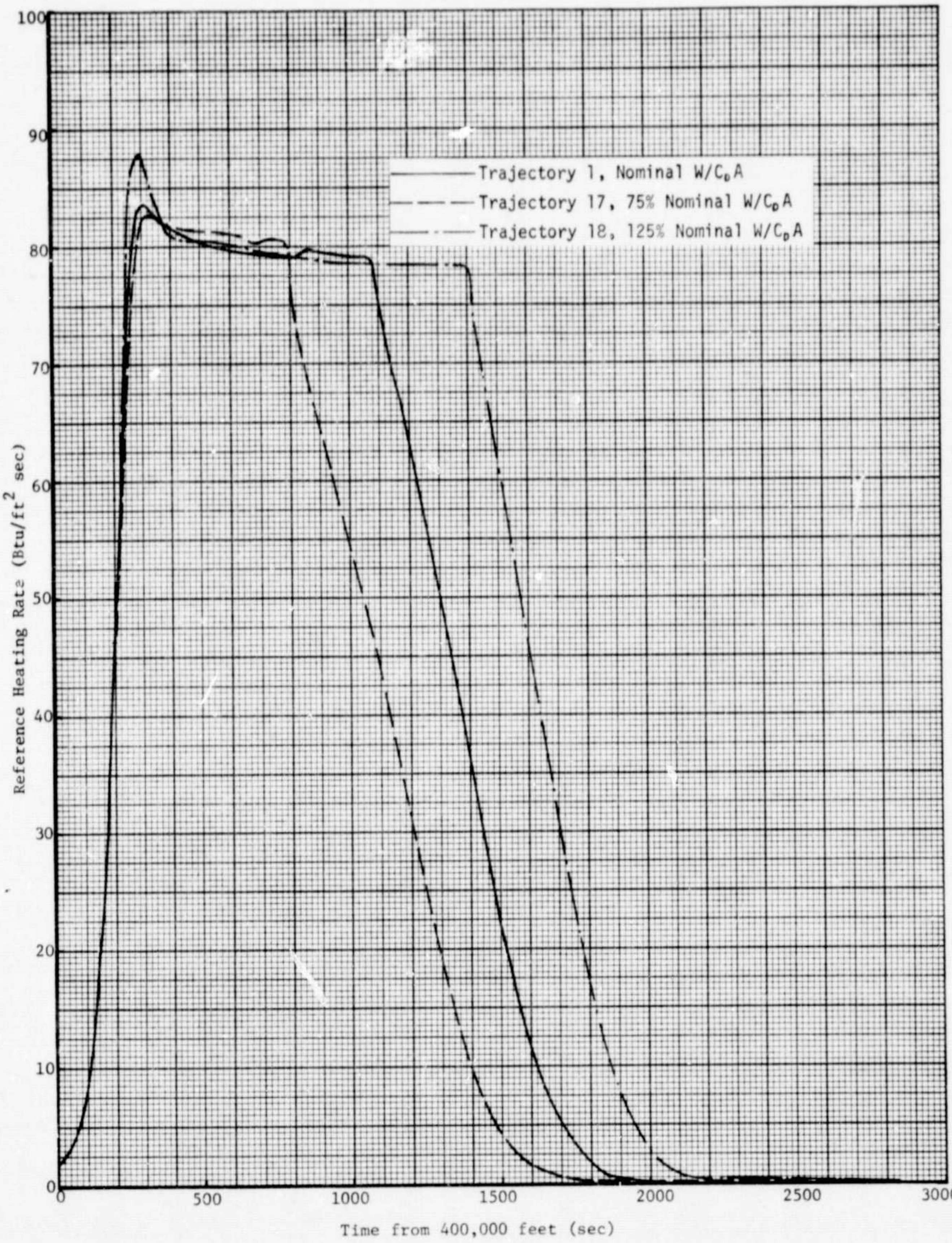


Figure A-10. Reference Heating Rate Histories, Ballistic Coefficient Dispersion

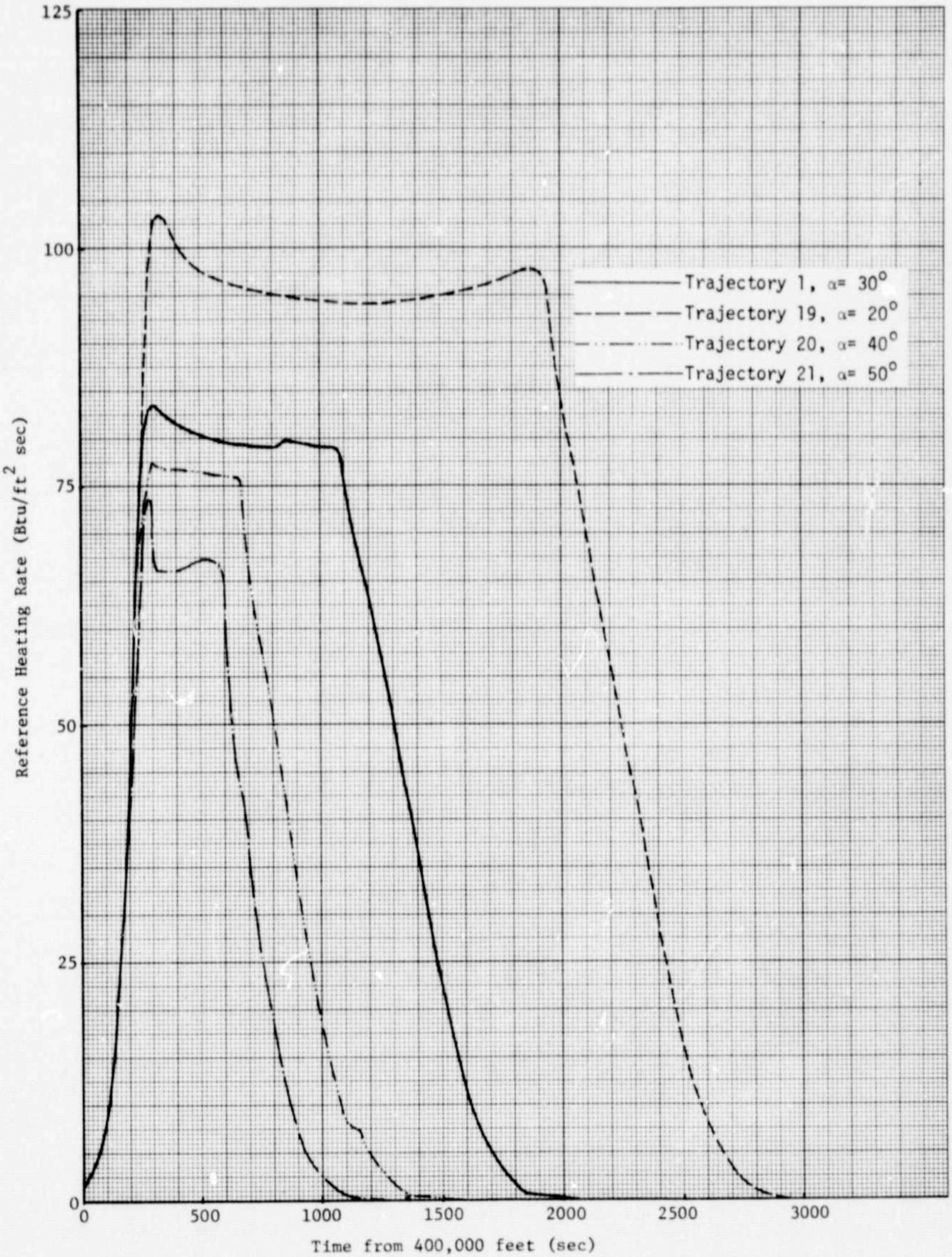


Figure A-11. Reference Heating Rate Histories, Angle of Attack Dispersion

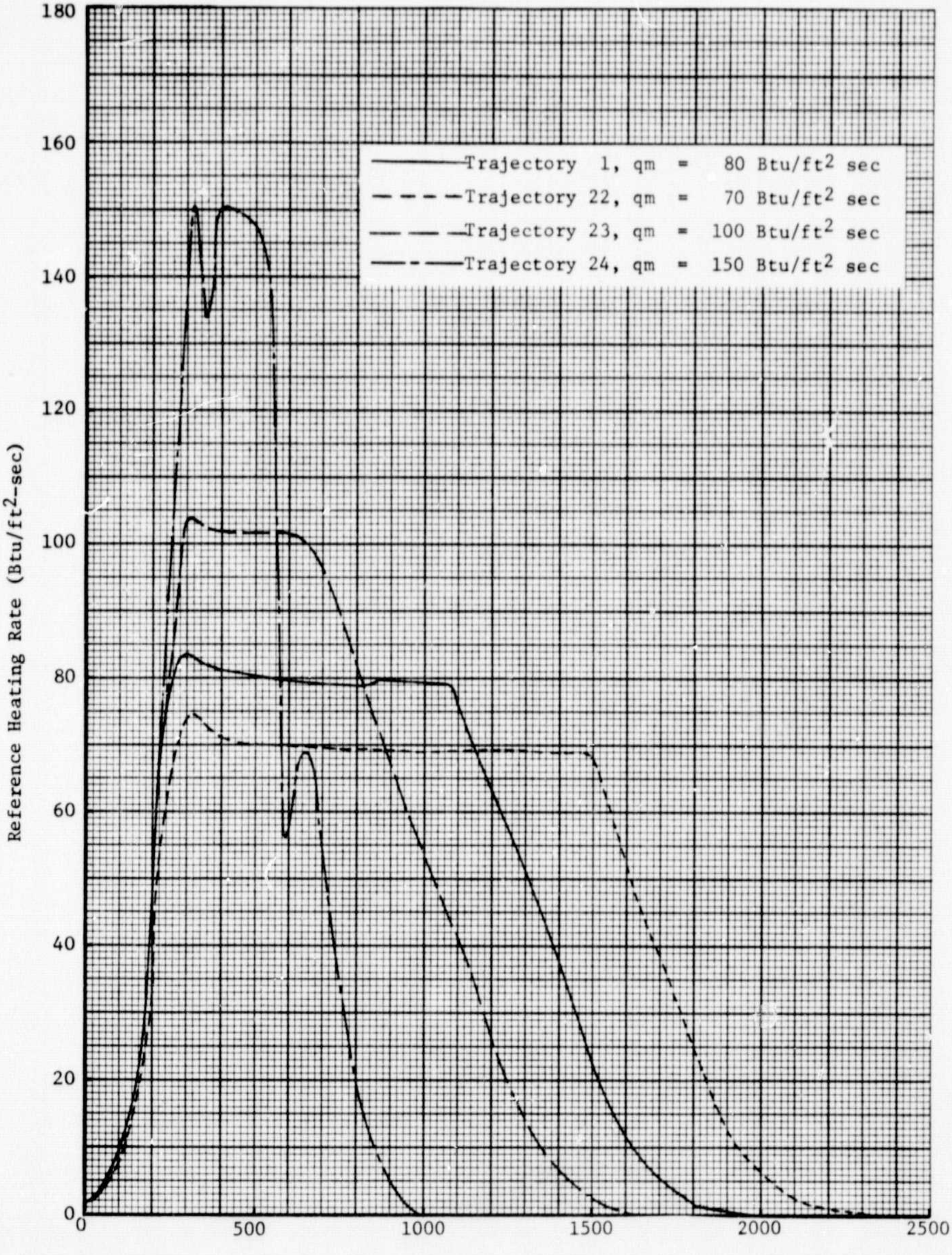


Figure A-12. Reference Heating Rate Histories, Flight Level Dispersion.

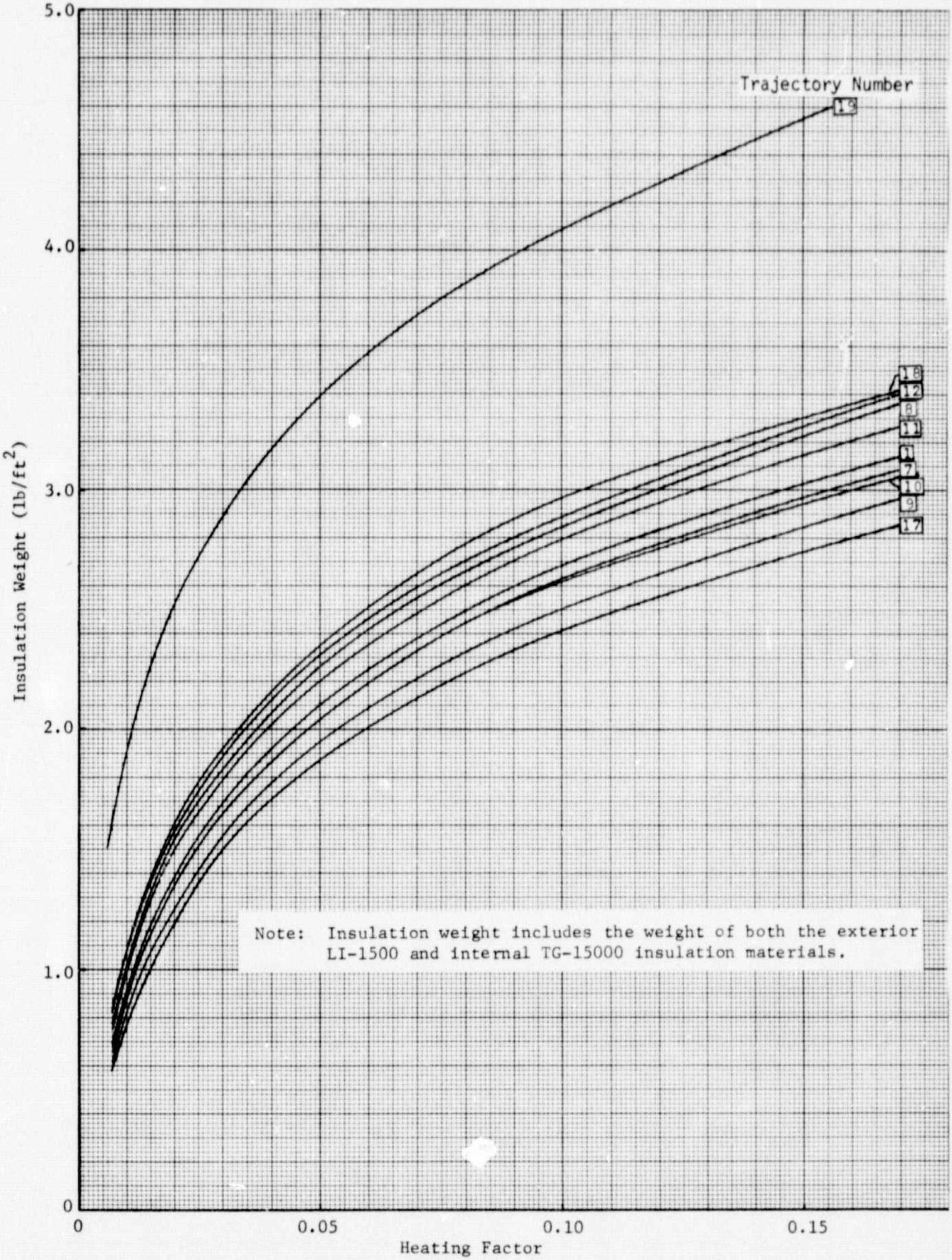


Figure A-13a. Insulation Weight as a Function of Heating Factor, Insulative TPS

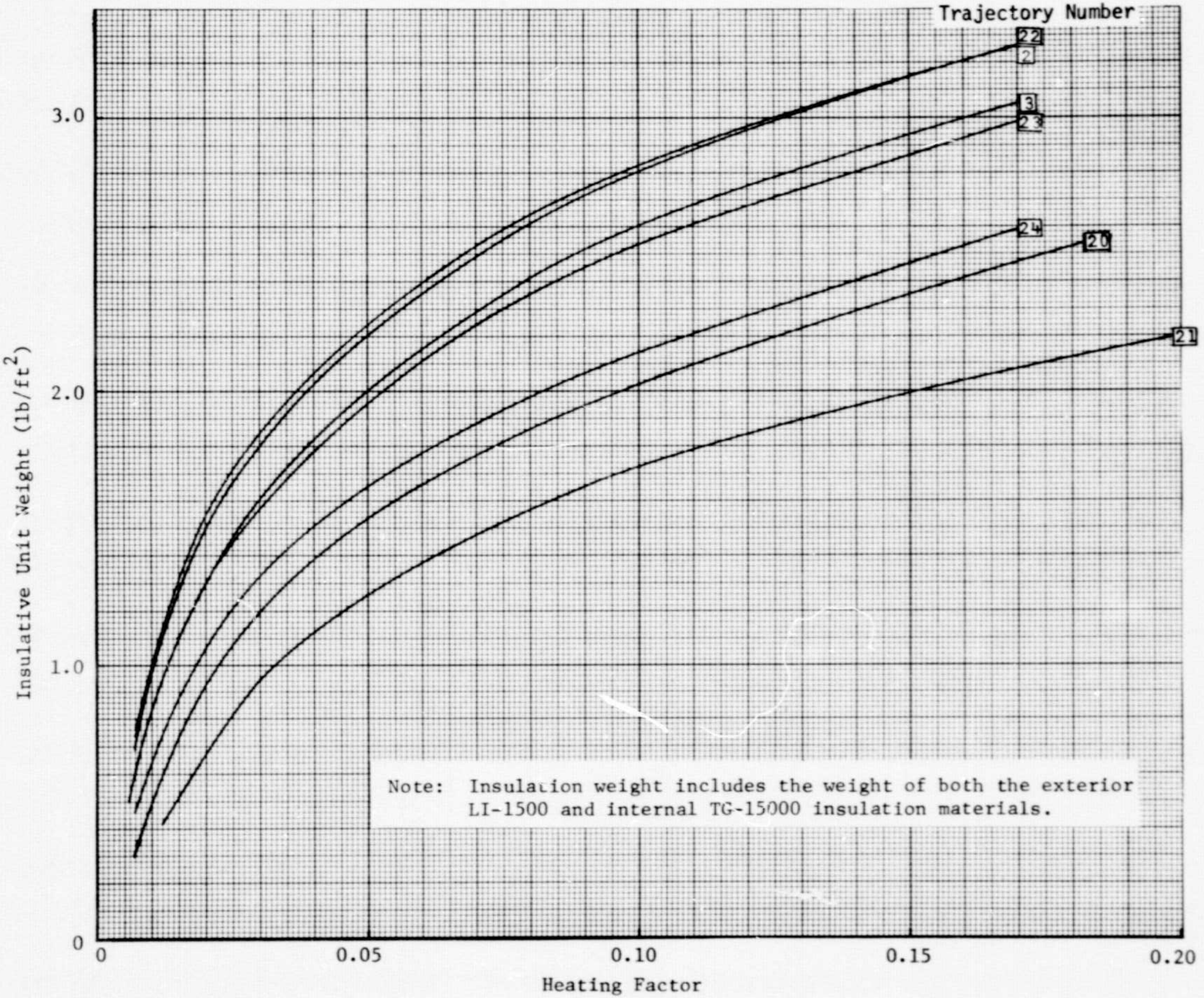


Figure A-13b. Insulation Weights as a Function of Heating Factor, Insulative TPS

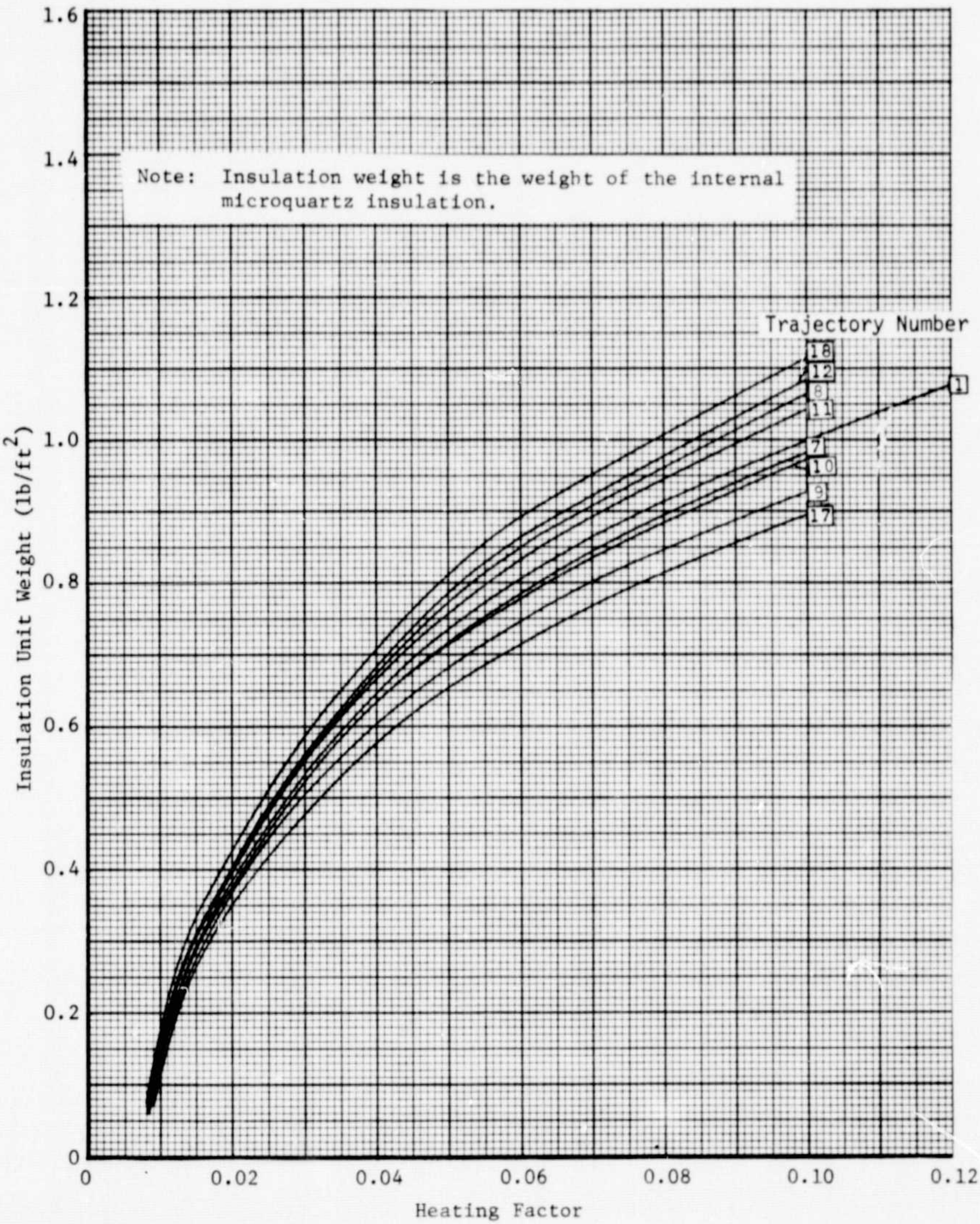


Figure A-14a. Insulation Weight as a Function of Heating Factor, Metallic TPS

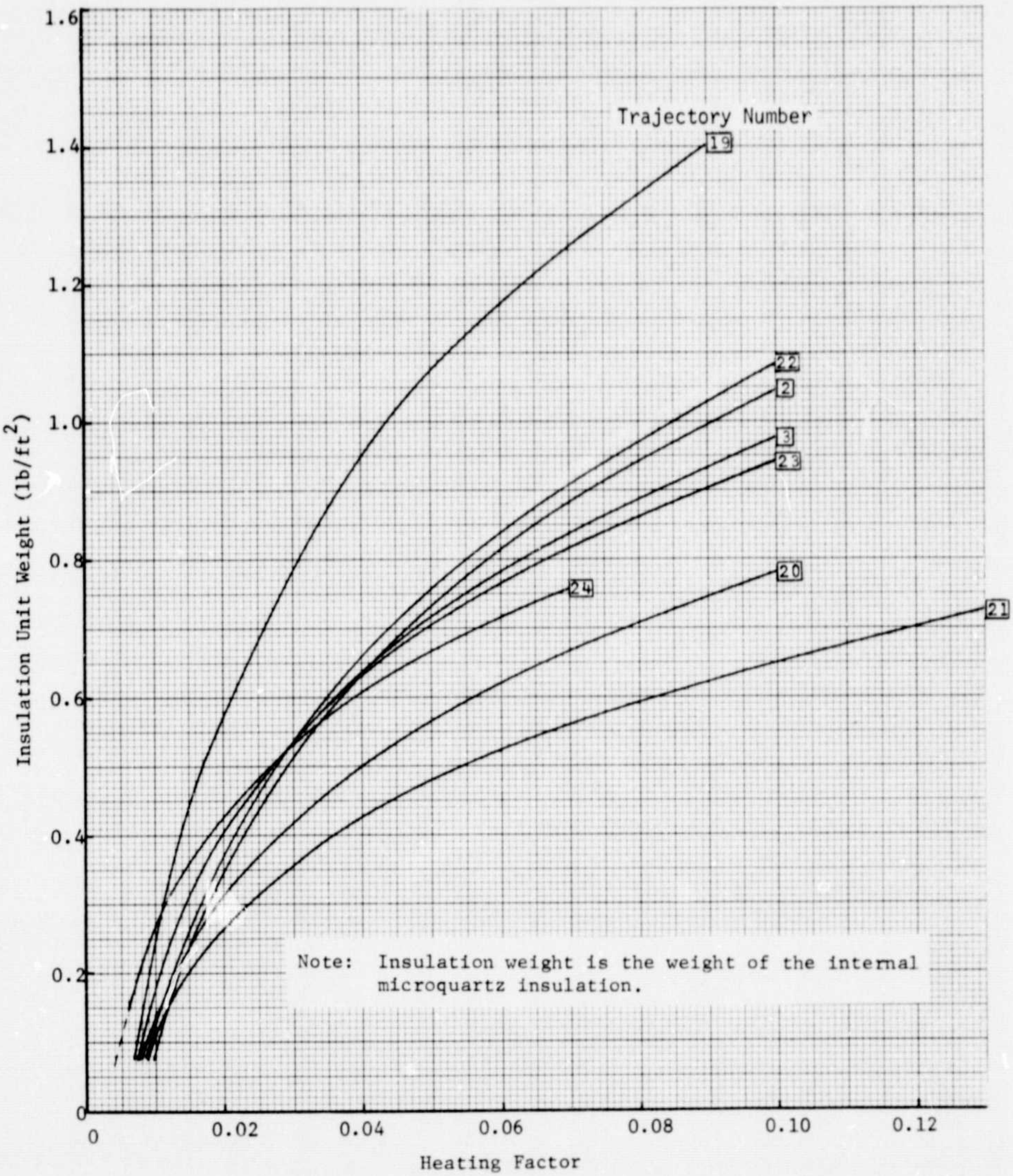


Figure A-14b. Insulation Weight as a Function of Heating Factor, Metallic TPS

REFERENCES

1. Goodrich, Winston. "TPS Optimization Study - Delta Wing Orbiter Heating Rates," NASA/MSC Memorandum ES35/3-18(1), March 1971.

2. Stuckly, Bernard F. Program F144 Apollo Heating Rates. NASA Project No. 3341, January 1966.

3. Detra, R. W., N. H. Kemp and F. R. Riddell. "Addendum to 'Heat Transfer to Satellite Vehicles Re-entering the Atmosphere.'" Jet Propulsion, pp. 1256-1257, December 1957.

4. Curry, D. M. "Local TPS Weight Estimation Methods for Space Shuttle Orbiter Entry Optimization Study." NASA/MSC Memorandum ES 32, 21 June 1971.

5. Smith, James P. SINDA User's Manual. TRW Systems Report No. 14690-H001-RO-00, April 1971.

6. Fogerson, P. E. Optimization of a Thermal Insulation System Using the SINDA Program. Lockheed Electronics Company Document No. 675-44-00201, November 1970.

7. Harpold, Jon C. "Updated SMD Heating Analysis." NASA/MSC Memorandum FM 23 (71-156), 17 August 1971.