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THERMAL DESIGN OF COMPOSITE MATERIALS HIGH TEMPERATURE ATTACHMENTS

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PREFACE

This is the final report on the program entitled, "Thermal Design of Composite Material High Temperature Attachments". This study was conducted by North American Rockwell Corporation under the direction of the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, under Contract NAS8-27041. Mr. F. Huneidi was the principal Contracting Officer Representative.

The general purpose of the study was to evaluate the thermal aspects of utilizing advanced filamentary composite materials as primary structure on the Space Shuttle vehicle. The technical objectives of this study were to: (1) establish and design concepts for maintaining composite material temperatures within allowable limits at TPS attachments and/or penetrations applicable to the Space Shuttle; and (2) verify the thermal design analysis by testing selected concepts. The technical activity on this program covered a ten month period from May 6, 1971 to March 6, 1972.

The study was conducted under the direction of W. E. Neuenschwander. Significant contributions to this report were made by G. W. Mauss and M. A. Nadler. Other contributions to this study were made by Members of the Technical Staff of the Structural Systems & Mechanisms and Laboratories & Test Departments of the North American Rockwell Space Division.

SUMMARY

The thermal aspects of using filamentary composite materials as primary airframe structure on advanced atmospheric entry spacecraft such as the Space Shuttle Vehicle have been investigated to identify and evaluate potential design approaches for maintaining composite structures within allowable temperature limits at Thermal Protection System (TPS) attachments and/or penetrations. The technical scope of this investigation included: definition of thermophysical property data for composite material structures; parametric characterization and identification of the influence of the aerodynamic heating and attachment design parameters on composite material temperatures; conceptual design, evaluation, and detailed thermal analyses of temperature limiting design concepts; the development of experimental data for assessment of the thermal design methodologies and data used for evaluation of the temperature limiting design concepts.

The general identification and relationship of the various inputs and activities to this investigation are schematically illustrated by the logic diagram as presented by Figure 1. As indicated by this diagram, Phase B Space Shuttle design/study results, Reference 1, and data from other North American Rockwell contracts and the literature were utilized to maximize the availability of effort directed to the specific objectives of this study.

A full compliment of temperature suppression attachment concepts (e.g., heat sinks, active cooling, isolators) were examined as to relative merit; the simple isolator was identified as the most weight effective concept and was selected for detail design, thermal analysis, and testing. Tests were performed on TPS standoff attachments to Boron/Aluminum, Boron/Polyimide and Graphite/Epoxy composite structures; the test results verified the adequacy of the thermal modeling techniques used in the concept development and evaluation phase of this study.

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INTRODUCTION

The general purpose of the study was to evaluate the thermal aspects of utilizing advanced filamentary composite materials as primary structure on the shuttle vehicle. The technical objectives of this study were to: (1) establish and design concepts for maintaining composite material temperatures within allowable limits at TPS attachments and/or penetrations applicable to the Space Shuttle Orbiter Vehicle; and (2) verify the thermal design analysis by testing selected concepts. Specific composite materials evaluated were Boron/Epoxy (B/E), Graphite/Epoxy (G/E), Boron/Polyimide (B/PI), Boron/Aluminum (B/Al) and Graphite/Polyimide (G/PI). Calculations and measurements were made in U. S. Customary Units; however, the data are reported in the International System of Units and U. S. Customary Units where useful for communication.

The TPS standoff/composite structure attachment over-temperature problem is directly related to TPS maximum surface temperature; to provide a thermally comprehensive evaluation of attachment concepts, maximum surface temperatures of 755°K, 920°K, 1255°K, 1645°K, and 1920°K (900°F, 1200°F, 1800°F, 2500°F, and 3000°F) have been considered in this study. Figure 2 depicts maximum surface temperatures on the reference vehicle used in this study. This range of surface temperatures and the high and low maximum temperature capability of the selected composite materials provided the basis for the identification of a wide range of thermal design requirements for composite/TPS standoff attachments.

The approach to realizing the objectives of this study was to accomplish the following specific tasks:

(1) Thermal property determination - define the thermophysical properties of the advanced composite materials;

(2) Thermal requirements definition - perform parametric analysis to identify the nature of the attachment temperature problem as functions of the thermal parameters of typical TPS standoffs;

(3) Concept development - conceive composite/standoff attachment designs to keep the composite material structure within acceptable temperature limits and perform detailed thermal analysis to obtain entry thermal response and temperature gradients for the selected concepts;

(4) Model assembly and testing - construct and test standoff to composite attachments to verify the detailed thermal analysis.

Figure 1 identifies the relationships of these specific tasks and Figure 3 illustrates the time phasing of these various activities related to the accomplishment of these tasks.

THERMAL CHARACTERISTICS OF FILAMENTARY COMPOSITE MATERIALS

The thermophysical property data on advanced filamentary composite materials was determined, for design analysis purposes, from critical evaluation of data on the materials of interest. Available data was excerpted from the literature, material suppliers and government sponsored programs. The data availability is summarized by Table I and a listing of the data sources located are referenced (References 2 through 19). The available data, as reported by the sources, are catalogued in Appendix A; pertinent information necessary to interpret and analyze these data is also included in the Appendix A data summary. In many cases pertinent experimental information (e.g., fiber content, composite array, test direction and temperature) is not reported by the data sources and the useability of the reported data is compromised.

Results from the thermophysical property data location and collation effort evidence a lack of the type of property data (thermal conductivity and specific heat) that has primary influence on the results of this study. For example, there were no conductivity data located for three out of the five classes of composite material systems being considered in this study (data were not located on the B/PI, G/PI, and B/Al composites). For the purpose of this study, estimates of the properties for these materials were made from the constituent property data and or analogy with similar composite material systems. The composite material thermophysical property design values used for thermal analysis in this study, developed from evaluation of available data and the application of engineering judgment, are presented in Table II.

In general, the definition of thermophysical property data is based on the assumption that the composite structures to which the TPS standoff will be attached will require essentially equal stiffness and/or strength in all directions. The relationship between this assumption and the values shown for the various thermophysical design parameters is briefly discussed as follows: whereas, density and specific heat values are independent of fiber orientation as is conductivity in the thickness direction, in-plane conductivity and thermal expansion values are dependent on fiber orientation. For the purpose of this study, the pseudo-isotropic array, i.e., (0°/± 60°) was chosen as sufficiently representative for "equal stiffness" composite structure designs.

The conductivity values for this composite array were synthesized from longitudinal and transverse monolayer properties according to the following relationships:

$$k_{(0°/\pm 60°)} = \frac{k_{0°} + 2\,k_{60°}}{3} \qquad (1)$$

$$k_{60°} = k_{0°} \times \cos^2 60° + k_{90°} \times \sin^2 60° \qquad (2)$$

For cases where no transverse conductivity data existed, $k_{90°}$ was computed from longitudinal conductivity and constituent volume fractions (V) per the following equation:

$$k_{90°} = \frac{k_F \times k_R}{k_F V_R + k_R V_F} \qquad (3)$$

where the subscripts F and R denote fiber and resin respectively.

B/PI was estimated to have similar conductivity as B/E over their respective operating temperature ranges. The lower conductivity of the PI matrix at identical temperatures was assumed to be compensated for by the fact that the operating temperature is higher. Consequently, the effective conductivities for the two resin matrices were assumed to not differ substantially over their respective temperature regimes.

Reasonable confidence exists in the validity of the design values presented for boron filament plastic matrix composites. In the case of graphite filament base materials, the meager composite data reported cannot be brought into consonance with the thermal conductivities given for the "Thornel" family of fibers. It may be that the different fibers do indeed have different conductivities. It is also reasonable to expect that the fiber conductivity will be a function of degree of graphitization and thus could differ between "high strength" and "high modules" fibers which have experienced different thermal histories in production. Other factors which may have an effect on conductivity that have not been considered in depth in arriving at the design values are the effects of resin fillers and voids.

The maximum operating temperatures presented in Table II for the epoxy and polyimide resin composites are generally accepted values. In the case of B/Al, the design value of 617°K(650°F) selected for this study is based on limited test results from Contract NAS8-20295 and is assumed applicable to the pseudo-isotropic composite array structure used as reference for this study.

The thermal expansion coefficient of composites is primarily influenced by the thermal expansion of the fibers. Reference 19 presents an analytical model which permits computation of thermal expansion from constituent properties for any polar direction of any specific laminar array. This program, consistent with the equal stiffness and/or strength requirements assumption, assumes a pseudo-isotropic array. For such an array, however, thermal expansion coefficients can be reasonably estimated from fiber expansion data without the mathematical complexity of multiple matrix equations of the Reference 19 method. For this study, thermal expansion is of secondary importance and the design values presented in Table II were, therefore estimated from fiber thermal expansion coefficient data presented by Appendix A.

PARAMETRIC THERMAL DESIGN ENVIRONMENTS AND REQUIREMENTS

Parametric analyses were performed to identify the nature of the TPS attachment temperature problem as it relates to limiting the composite structure temperature within allowable limits. The reference aerodynamic heating data used in these analyses were developed from Reference 1 study results. Simplified 2-dimensional thermal models representing a range of TPS standoff designs and composite structure substrates were used to develop composite structure temperatures as a function of heating level, standoff design variables, and composite substructure variables. The parametric analysis was organized to provide data that will permit thermal categorization of the standoff to composite structure attachments into three groups: (1) no particular over-temperature problem area; (2) cases where the composite structure temperature can be maintained within limits by relatively simple thermal designs (e.g., isolators and/or standoff design control); and, (3) the more complex design group where augmented temperature suppression techniques (e.g., phase change materials, active cooling) may be required to avoid composite structure temperature excursions beyond the design temperature limits. Interpretations of the parametric results were used as guidelines in selecting specific TPS standoff/composite structure problem areas to be considered in the concept development of TPS attachments.

The reference entry heating environments used for developing the parametric temperature data are presented by Figure 4. These heating histories correspond to maximum radiation equilibrium ($\varepsilon = 0.8$) surface temperatures of 755, 920, 1255, 1645, and 1920°K(900, 1200, 1800, 2500 and 3000°F). These profiles are characteristic of those encountered during atmospheric entry of a high cross-range shuttle vehicle. Calculated heating profiles were scaled to give peak heating rates corresponding to the selected maximum surface temperatures. The Reference 1 TPS study results indicate that the maximum substructure temperature is relatively insensitive to variations in the shape of the heating profile for the same entry heat load; therefore, the parametric results developed using these histories are applicable to those cases where variations from the reference heating profiles exist.

The parametric thermal analysis was performed using TPS standoff and composite structure parameters that have physical relationships to actual TPS and structure designs applicable to shuttle. TPS standoff materials, standoff thickness to height ratios, standoff height, and effective composite structural thickness ranges considered in the analysis were based on shuttle TPS design data, Reference 1. The general thermal models used in the analysis, presented by Figure 5, were developed to thermally represent typical TPS standoff designs. The TPS standoff materials were selected according to their design temperature capabilities as related to maximum surface temperature experienced during entry. Figure 6 illustrates the material-temperature relationships that may be considered in practical shuttle applications and those selected for the parametric analyses. In some cases, Figure 6 indicates the use of a material at surface temperatures higher than the generally accepted material limit (e.g., TD Nichrome at 1645°K). This, however, only means that when a multi-material standoff is considered as a means of limiting heat transfer to the composite structure, a lower temperature capability material can be used if the temperature drop in the outboard standoff segment is sufficient to limit the temperature at the inner segment within allowable limits (reference Figure 5 Model III). Thermal properties for the standoff materials used in the parametric analysis are presented by Appendix B; it is noted that, in terms of diffusivity level, there are two distinct level groups for seven of the materials shown (excepting carbon-carbon): in the order of .0258 cm^2/sec (0.1 ft^2/hr) for Titanium 6Al-4V, Inconel 718, Rene' 41, Haynes 188, and TD Nichrome; and in the order of .258 cm^2/sec (1.0 ft^2/hr) for columbium and tantalum. With this similarity within groups of materials and the distinct separation between groups, it is reasonable to expect that the thermal isolation characteristics between the surface and composite substrate will be "continuous" between 755 and 1370°K (900 and 2000°F) surface temperatures with "discontinuities" occurring as columbium and carbon-carbon are introduced as standoff elements as dictated by surface temperatures of approximately 1370°K and 1645°K (2000°F and 2500°F), respectively.

Another standoff variable that affects the composite structure temperature is the thickness to height ratio (t/h) of the standoff. The standoff height was selected, for this parametric study, to have a minimum value equal to an outer insulation blanket thickness plus 1.27 cm (0.5 in) for clearance and purge/vent spacing. Representative estimates of insulation blanket thicknesses are presented as a function of surface temperature for typical substructures with 420°K (300°F) and 617°K (650°F) maximum temperature capability by Figure 7. These insulation thicknesses are based on correlations (Reference 1) of heat load-maximum surface temperature data characteristic of high cross-range entry TPS requirements; the insulation blankets are assumed to consist of 96 kg/m^3 (6 lbs/ft^3) Dynaflex operating from the upper temperature limit to 617°K (650°F) with 48 kg/m^3 (3 lb/ft^3) TG-15000 at temperatures less than 617°K (650°F). With recognition that insulation thickness is not a unique function of temperature and that the reuseable temperature limit for Dynaflex is less than 1920°K (3000°F), this method for estimating the practical range for standoff height provides reasonable guidelines for selecting parameter ranges for the generalized analysis.

In addition to the standoff design parameters, the effective thicknessess ($\bar{t}_c$) of the composite substrates required typical definition to perform the parametric analysis. Composite structure $\bar{t}_c$'s were calculated as a function of compressive load intensity for the composite structure materials of interest. These data, for a skin-stringer design, are presented by Figure 8. These sizing data were used in conjunction with the Reference 1 developed structural loadings data to develop typical composite material structural designs as may be applied to the Space Shuttle Orbiter Vehicle. The results from this development are presented as Figure 9. These data were used to establish the range of thermal capacitance of the composite substructures considered in the development of the parametric data presented.

The general analysis matrix for identifying and categorizing the nature of composite structure over-temperature problem is presented by the Figure 5 table insert; the combination and values of parameters varied is best illustrated by Figures 10 and 11 which summarize the results from the parametric analysis. The analysis matrix consists of five basic data groups that provide the following information:

(1) Effect of surface temperature level and composite material properties (Thermal Model I, Figure 5)

(2) Effect of standoff height and equivalent cross-section (Thermal Model I, Figure 5)

(3) Effect of composite structure thickness (Thermal Model I, Figure 5)

(4) Effectiveness of isolators for temperature suppression (Thermal Model II, Figure 5)

(5) Effectiveness of multi-material standoffs (Thermal Model III, Figure 5 and multi-material standoffs with isolators (Thermal Model IV, Figure 5 for temperature suppression.

Figures 10 and 11 graphically summarize results from the parametric analysis and identify the attachment/composite structure over-temperature problem. These data were developed using simplified 2-dimensional thermal models (Figure 5) having about twelve thermal nodes per model. Thirty-six transient analyses were performed to establish the data points for the trends and sensitivities illustrated by Figures 10 and 11. The calculated data are identified with symbols on these figures.

Figure 10 illustrates how the maximum temperature of the composite structure at the TPS standoff attachment varies with: (1) surface temperature; (2) composite material; (3) standoff thickness to height ratio (t/h); and (4) effective thickness ($\bar{t}_c$) of the composite structure. These data are for the simplest of TPS standoff/attachment designs (Thermal Model I) that use a single material standoff without isolators or other composite structure temperature suppression techniques. These results and subsequently described interpretations indicate that the attachment point over-temperature (with Model I designs) is minor for maximum entry surface temperatures at or below 920°K (1200°F), but is substantial for all composites at surface temperatures above 1370°K (2000°F) where higher temperature material standoffs (columbium or carbon-carbon) are required. The effectiveness of isolators and multi-material standoff concepts in suppressing the composite structure temperature is shown by Figure 11 for conditions where Figure 10 data indicates a substantial over-temperature problem area (1255 and 1645°K surface temperature conditions.) The multi-material standoff concept was examined only for the 1645°K (2500°F) surface temperature environment since the real thermal design advantage of using multi-material standoffs is attributable to minimizing the length of the high thermal diffusivity columbium material. The effect of thermal diffusivity is illustrated by Figure 10(a) where a substantial increase in composite structure temperature is observed as columbium is introduced as the standoff material; correspondingly, a temperature decrease occurs as the columbium is replaced (at about 1645°K) with the carbon-carbon material with its lower transverse thermal diffusivity.

CONCEPT DEVELOPMENT AND ANALYSIS

Applicable concepts were identified based on interpretations of the parametric data developed. The nature of the composite structure "over-temperature" problem is typically indicated by Figure 12 as being strongly influenced by the configuration of the TPS standoff, standoff thickness to height ratio, as well as the maximum temperature experienced at the TPS outer surface. The hat section standoff configuration is observed to present a substantially more difficult thermal design problem than does the sine wave configuration due to the larger cross-sectional area of the standoff structurally required for the hat section configuration. (It should be noted that the Figure 12 temperature data were developed to identify the nature of the over-temperature problem and do not represent temperatures that would exist if composite structure temperature suppression designs are incorporated.)

Figure 13 illustrates the degree of composite structure over-temperature for the hat section standoff as used with the five composites of interest to this study. These results and the previously reported parametric data are interpreted to suggest the following conclusions:

(a) There is no particular thermal design problem for either the low (450°K) or high temperature (590°K) composites for maximum surface temperature conditions of 755°K and 920°K (900°F and 1200°F).

(b) Hat section standoffs present a difficult thermal design problem for the 1255°K (1800°F) maximum surface temperature conditions and low temperature (450°K) capability composites; only a minor problem exists for the high temperature composites. At the 1645°K (2500°F) maximum surface temperature condition, hat section standoffs present a difficult problem for the high temperature composites as well as the low temperature capability materials.

(c) The sine wave standoff designs are much better from a thermal design perspective. The thermal design problems for 1255°K (1800°F) maximum surface temperature condition is insignificant even for the low temperature composites. Only a minor problem exists for the high temperature materials at a maximum surface temperature of 1645°K (2500°F), and the problem with the low temperature composites is about the same as experienced with the hat section standoff at 1255°K (1800°F).

(d) The post-type standoff designs would have thermal cross-sections similar to the sine wave configurations and would present similar thermal design problems.

Based on these indicated guidelines, the more thermally difficult hat section design, the low temperature capability composites, and the 1255°K and 1645°K (1800°F and 2500°F) maximum surface temperature conditions were selected for emphasis in subsequent concept development and design activities. TPS attachments to composite structures at locations where the TPS surface temperature would reach 1920°K (3000°F) was not selected for emphasis since the thermal design problem using carbon-carbon material standoffs at the

1920°K (3000°F) environment is less severe than that using columbium hat section standoffs at the 1645°K (2500°F) environment (reference Figures 10 and 12). The applicability of temperature suppression design concepts was examined by conceptual development of forty-seven TPS standoff and/or attachment concepts. A relatively full complement of thermal design concepts (Table III) was formulated with major emphasis placed on the conditions where the more severe thermal design problems exist as discussed. These concepts (presented by Figures 14 through 17) included phase-change materials, isolators, substrate heat sinks, active cooling and various combinations of temperature suppression elements. Table III summarizes the conditions and concepts developed as design schematics with approximate thermal and structural sizings. The thermal requirements were estimated through utilization of the parametric data or through direct computation for those concepts of which applicable parametric data had not been developed. The standoff height, as previously reported, is assumed to be equal to the thickness of the outer insulation blanket plus 1.27 cm (0.5 in) for clearance and purge/vent spacing (Figure 7). The standoff heights derived for this evaluation range from 2.54 to 12.7 cm (one to five inches). Thicknesses (t) for the hat-type standoffs were determined as unique functions of standoff height (h) from column buckling formulations as follows:

$t = .0247\ h^{2/3}$ for Titanium 6 Al-4V ($T_{surface\ max} \leq 755°K$)

$t = .0202\ h^{2/3}$ for Inconel 718 ($T_{surface\ max} \leq 920°K$)

$t = .0198\ h^{2/3}$ for Haynes 188 ($T_{surface\ max} \leq 1255°K$)

$t = .025\ h^{2/3}$ for Columbium 752 ($T_{surface\ max} \leq 1645°K$)

A minimum gauge thickness of .0254 cm (.010 in) was considered for the sine wave and post TPS standoffs. It is understood that exact requirements for each concept are not obtained in this analysis method, but the approximation obtained is sufficient to identify advantages and disadvantages of the basic TPS attachment/composite structure concepts augmented with temperature suppression devices.

The design schematics of the forty-seven concepts developed (Table III) were quantitatively and qualitatively evaluated to identify the advantages and disadvantages of the various thermal concepts formulated. The results of this evaluation are presented in Tables IV and V. Table IV presents weight comparisons of various concepts which limits composite structure temperatures within the maximum design allowables. These concepts included isolators, phase change materials, active cooling and heat sinks. The simple isolator concept was identified as the most weight efficient design for both the high and low temperature capability composites with attachment to both the hat section and sine wave TPS standoffs for the 1255°K and 1645°K (1800°F and 2500°F) maximum surface temperature environments. The relative advantages and disadvantages of the evaluated concepts were quantitatively rated according to weight, design simplicity, cost, and technology status as shown by Table V. Isolators and heat sinks are shown to have the definite advantage of design simplicity. However, conventional heat sink materials (e.g., copper, beryllium) show a substantial weight penalty compared with the more thermally efficient isolator materials. A more advanced heat sink concept, such as polyethylene, which has a solid to solid crystalline transition phase change, is only slightly heavier than the efficient isolator materials. In terms of relative weight advantage, the Marinite-23 and Syntactic PBI isolators rate first and second, respectively, and the polyethylene phase change material rated third for the concepts and materials evaluated (Table IV). In summary, these evaluations indicate that the simple isolator concept will satisfy the thermal requirements with a relatively low weight penalty compared to other concepts even for the more thermally difficult hat section standoff configuration.

The results from the concept screening, and the previously discussed identification of the major thermal design problems as related to maximum surface temperature, standoff configuration, and composite structure material were the basis for selecting standoff, material, and environment combinations for preliminary design and detailed thermal analyses as follows:

Preliminary Design Matrix

TPS Standoff Configuration	Max. Surface Temperature	Primary Structure Material
Hat Section with Isolator	1255°K (1800°F)	G/E B/E G/PI B/PI B/Al
	1645°K (2500°F)	G/E G/PI
Sine Wave with Isolator	1645°K (2500°F)	G/E G/PI

This matrix defines the impact of standoff configuration, heating environment, and composite material structure on detail design requirements for TPS attachments to composite material structures. The isolator materials considered in developing the detail designs were limited to thermally efficient materials having expected multi-reuse and maximum temperature capabilities within the limit requirements indicated by the concept screening analyses. The thermally efficient, high temperature capability Marinite-23 was eliminated as a primary candidate because of its moisture absorption characteristic which results in degraded structural integrity. Foamed PI (polyimide) and PBI (polybenzimidazole) were identified as being primary candidates as isolator materials for use with the 450°K (350°F) capability composites; these materials have good thermal efficiency and upper temperature capability in the 590°K (600°F) range required for this application.

PBI was selected for this design application because of its slight advantage in temperature capability. When applied as an insulator to the high temperature capability composites, (G/PI, B/PI, and B/Al), the PBI would exceed its multi-reuse temperature at the standoff/isolator interface; Chem Ceram, a Whittaker Research molded aluminum phosphate ceramic with a temperature capability greater than 810°K (1000°F), was selected as the isolator for use with the G/PI, B/PI and B/Al composites due to its good thermal efficiency as compared with other higher temperature capability materials (e.g., Pyroceram). Molded polyimide and Chem Ceram were selected as bushing materials. Complete design details of the TPS standoff to composite material attachment designs for the nine configurations identified in the "Preliminary Design Matrix" are presented in Figures 18 through 21 and Table VI.

Doublers on the composite material structure were selected as the means by which the composite skin would be strengthened at the attachment bolt locations. (The design options considered to provide strength at the bolt locations are shown by Figure 18.) The preliminary design drawings for the hat section and sine wave standoff configuration are presented as Figures 19 and 20, respectively. Detail dimensions and materials for these drawings are given in Figure 21 and Table VI. Table VI delineates details of the standoffs, isolators, and fibrous insulation. Detail dimensions of the skin-stringer design composite material structure are given in Figure 21. These designs were developed with specific emphasis on the thermal design requirements related to TPS attachments to composite structures. The designs were individually analyzed to establish fibrous insulation and corresponding standoff t/h ($h = \delta_{ins} + 1.27$ cm), and isolator thickness requirements to satisfy the maximum temperature limits on the substructure.

Detailed thermal analyses were performed to develop temperature and temperature gradient histories for standoff and attachment configurations for each of the five composite material structures of interest to this study. The general thermal model developed for these analyses is shown by Figure 22. The fibrous insulation thickness, standoff t/h, isolator thickness, and composite structure definition was different for each composite material as required to satisfy the thermal and structural design requirements. These analyses were performed for the hat section standoff design for the 1255°K (1800°F) maximum entry surface temperature environment. Thermophysical properties utilized for the thermal isolator blocks (PBI and Chem Ceram Foam) and bushings (molded PI and Chem Ceram) are given in Appendix B. These materials were selected for preliminary design as being appropriate for the expected maximum temperatures and for their relatively low thermal diffusivity. The results are summarized by Figure 23. Temperature histories at selected locations are shown by Figures 23a through 23e; the points selected for graphical presentation provide a reasonable representation of the temperature gradients through the standoffs and composite material structures.

EXPERIMENTAL VERIFICATION OF DESIGN METHODS

Testing was performed on three of the five attachment/structure designs on which detailed thermal design analyses were performed. G/E, B/PI, and B/Al composite systems were selected as those to be tested for thermal design methods verification. These composites encompass the full range of design temperature capability and thermal conductivities as defined for the analytical thermal evaluation effort of this study, thereby creating a range of thermal design problems at the TPS attachment. G/E, with a relatively low maximum temperature capability (450°K), possesses a moderately high transverse thermal conductivity (k = 7.6 W/m-°K). B/Al, with a relatively high maximum temperature capability (617°K), possesses a high transverse thermal conductivity (k = 44.8 W/m-°K) and B/PI, expected to be the best insulator of the three selected (k = 1.225 W/m-°K), has a relatively high maximum temperature capability (590°K). The tests were performed per the detailed test plan included as Appendix C.

The test articles were designed to closely approximate the detail configurations on which the previously described detail thermal design analyses for the 1255°K (1800°F) surface temperature environment were performed. Pertinent dimensions of each test article component were obtained from these design analyses. (Appendix C presents detail data on each test article component). The only hardware simulation that was introduced into the test article designs was the substitution of stainless steel for the Haynes 188 standoffs; this was a cost effectiveness measure that could be introduced without compromising test objectives since stainless steel has very similar thermal diffusivity properties as the Haynes 188 "design" material. The stainless steel standoffs were fabricated to the same thickness to height ratio as the Haynes 188 standoffs, which completed the thermal simulation of the test article designs.

Each of the assembled test articles was instrumented with seven thermocouples. Three Chromel-Alumel thermocouples were spot-welded to the standoff: in the center of the standoff cap (location #1), halfway down the standoff height (location #2), and at the edge of the standoff leg (location #3). Four Chromel-Alumel thermocouples were bonded to the composite panel: on the composite panel lengthwise centerline directly below the location #3 (location #4); along the lengthwise centerline, 1.905 cm (.75 in) from location #4 (location #5); along the centerline at the edge of the panel (location #6); and in direction perpendicular to the lengthwise centerline, 3.81 cm (1.5 in) from location #4 (location #7). Refer to Figure 4 of Test Plan (Appendix C) for a pictorial representation of the thermocouple installation. The thermocouples at locations #1, #2, and #3 provide temperature gradient data in the standoff; the thermocouples at locations #4, #5, and #6 provide measurement of temperature gradients produced by the particular fiber orientations of each composite panel. A thermocouple was installed at location #7 as an aid in the evaluation of acquired data and potential data anomalies.

After completion of the thermocouple installation, 96 kg/m^3 (6 lb/ft^3) Dynaflex insulation was built up within and surrounding the standoffs, completing a 48 x 56 cm (19 x 22 in) package. At this point in the assembly, only the cap of each test article standoff was visible (refer to Figure 2 of Test Plan, Appendix C). The thermocouple leads for each specimen were routed to the side of the test assembly, bundled together, and routed to a junction. Irish Refrasil cloth was placed on top and around the edges of the assembly, and Refrasil fabric was used to sew the cloth to the standoff caps to assure contact between the cloth and standoff. A Chromel-

Alumel thermocouple was placed in the center of the test area below the cloth and sewn to it to hold it in place. The two radiant heating environments, corresponding to a 920°K and 1255°K (1200°F and 1800°F) maximum surface temperature condition, were to be controlled by a pre-programmed surface temperature measured by the control thermocouple.

Detailed pre-test thermal analyses were performed to define the two test environments (920°K and 1255°K maximum surface temperatures) that would result in the composite structure temperatures reaching a maximum of approximately two-thirds of design limit on the first test exposure (920°K), and 90 - 95% of design limit on the second test exposure (1255°K). Uncertainty in the design property data of test article components (composite structure panels, foamed isolator blocks, and molded bushings) was the reason for limiting the maximum composite structure temperatures to less than the maximum design values (450°K for G/E, 617°K for B/Al, and 590°K for B/PI). The 920°K and 1255°K (1200°F and 1800°F) maximum surface temperature test environments show a great degree of similarity with the 920°K and 1255°K (1200°F and 1800°F) environments used in the detailed design entry thermal analyses. The effect of testing at one atmosphere, where the conductivity of the Dynaflex insulation is higher, is offset by the fact that more insulation was used in the testing, providing a closer representation of composite structure entry thermal response during the tests. The calculated composite structure maximum temperatures for the defined environments shown in Figures 1a and 1b of Test Plan, are: 400°K, 497°K, and 477°K (260°F, 435°F, and 400°F) for the G/E, B/Al, and B/PI panels during the first exposure (920°K), and 439°K, 575°K and 559°K (330°F, 575°F, and 545°F) for the G/E, B/Al, and B/PI panels during the second exposure (1255°K).

During the first heating exposure (920°K maximum surface temperature condition) it was noted that the control thermocouple was not following the programmed surface temperature, and the test was aborted after 480 seconds. The control thermocouple was replaced and found to be operating well after a short duration calibration run. The test assembly was then exposed to the two test environments (920°K and 1255°K surface temperatures) and thermal data obtained for all thermocouples. Inspection of the recorded data indicated that a major portion of measured data was suspect although the control thermocouple response during both exposures was as planned. The test assembly was taken apart and inspected. It was found that many of the thermocouple leads had been carbonized by severe heating at the edge of the 48 x 56 cm (19 x 22 inch) test assembly. This carbonization of the thermocouple leads effectively created thermocouple junctions at the edge of the assembly which invalidated the temperature measurements obtained. There was evidence of binder condensation within the layers of the Dynaflex insulation material and on the test articles, but the test article assemblies appeared not to have been damaged such that they could not be re-tested after minor modifications to the test setup were made.

The G/E, B/Al, and B/PI test articles were again instrumented with Chromel-Alumel thermocouples sheathed in a glass fabric with high temperature capability, and the wires were run down through the bottom of the test assembly as a precaution. Aluminum tape was used this time to hold the composite structure thermocouples in place as the bonding material appeared to have lifted from the panels at some locations. The Dynaflex insulation was conditioned in a 920°K (1200°F) oven to bake out the rest of the binder as a further precaution to avoid extraneous test influences.

The following re-tests were performed without difficulty: The thermocouple data obtained for both the 920°K and 1255°K (1200°F and 1800°F) maximum surface temperature test exposures was of good quality, suitable for comparison with the data developed in the pre-test thermal analyses for verification of thermal analysis methods and thermal property data utilized in the design evaluation of high temperature TPS attachments to composite structures. The agreement between pre-test predicted and measured composite structure maximum temperatures is presented in Figure 24. Although lower than predicted in the pre-test analyses, measured composite maximum temperatures show consistency with pre-test expectations for both test conditions.

Maximum temperatures measured along the standoffs and on the composites during the first and second test exposures are compared with the corresponding pre-test maximum temperature predictions in Tables VII and VIII, respectively. Thermocouple locations for each test article are illustrated in Figure 25. In all cases, thermocouple measurements at every location on each composite panel are over-predicted even though the thermocouple response on the leg of the standoff (T/C #13 for G/E, #23 for B/Al, and #33 for B/PI) is under-predicted for both exposures. The larger temperature drop measured across the PBI and Chem Ceram isolator blocks would indicate much better thermal performance of the isolator than that anticipated and/or existence of some contact resistance at the standoff leg/isolator block and isolator block/composite structure interfaces. Perfect contact was assumed in the pre-test analyses at these interfaces, consistent with the thermal design approach employed in the pre-test analyses and detail design thermal analysis to predict composite structure thermal response. At the temperature levels and response rates measured on the standoff leg (T/C location #3) on each test article, radiation and conduction heat transfer across a "non-perfect" contact interface would tend to compensate for a conductive resistance at the interface. It is conceivable that the diffusivities used in the pre-test analyses for the PBI and Chem Ceram isolator blocks are high since there is a general lack of design thermal property data for these relatively new materials. A constant thermal diffusivity of .00181 cm^2/sec (.007 ft^2/hr) was used for the 496 kg/m^3 (31 lb/ft^3) Syntactic PBI foam (Appendix B), and a temperature dependent thermal diffusivity shown in Appendix B was used for the 400 kg/m^3 (25 lb/ft^3) Chem Ceram foam utilized in the tests. For design purposes, the thermal conductivity of the 400 kg/m^3 (25 lb/ft^3) Chem Ceram foam was conservatively assumed to be 50% higher than that for the 288 kg/m^3 (18 lb/ft^3) Chem Ceram foam; the thermal conductivity of the 288 kg/m^3 (18 lb/ft^3) Chem Ceram foam was originally corrected for atmospheric pressure from test data obtained in vacuum conditions by the manufacturer (Whittaker Research and Development Company). The closer agreement between the measured composite structure thermal response and that predicted for the more severe test environment (second test exposure) would appear to indicate that the modeled thermal diffusivity for the isolator blocks is closer to actual values at the higher isolator block temperatures. Because the composite structure thermal response is driven by the response at the top of the isolator block (T/C location #3), the variances between predicted and measured temperatures on the standoff cap (T/C location #1) are not the cause of the over-prediction of the composite structure maximum temperatures.

Comparative transient temperatures are presented in Figure 26 for the 920°K test and Figure 27 for the 1255°K test. The measured data plotted was extracted from raw thermocouple data tabulations for each thermocouple. An entire set of transient raw thermocouple data is included in this report as Appendix D. Time phasing of both predicted and measured thermocouple response on both the standoff and composite panel of each test article shows close agreement.

Basic standoff and composite analytical and test data has been reformated and presented in terms of maximum temperature differences (gradients) in the standoff and composite structures in Table IX. Higher predicted thermal gradients in the G/E and B/Al than measured are a direct result of the thermal design modeling method employed, whereby analytical maximum gradients in the composite structures, as well as maximum composite structure temperatures, were expected to be on the conservative side of the test data for the composite thermal property data used. It appears, from examination of the predicted and measured transient temperature data for the B/PI composite panel during both test exposures, that the thermal properties (thermal diffusivity) used for this composite were slightly on the high side in the pre-test evaluation; however, the data agreement is quite good considering that the B/PI composite was one of the composite systems for which no thermal property was available and had to be synthesized. Measured thermal response data on the G/E composite, where thermal property data was available, appears consistent with pre-test expectations; and although property data was not available for the B/Al composite, consistent agreement was obtained as a result of B/Al being a very good conductor. Variances in thermal conductivity for high conductive composite structures should not affect composite structure temperature bulk temperatures (no temperature gradients). The assumption of like thermal responses at thermocouple locations #6 and #7, justifying the use of a two-dimensional approach in the modeling of the TPS attachment configuration in the pre-test evaluation, proved to be a valid one since no significant temperature differences between these two thermocouples on any of the pseudo-isotropic composite arrays was noted.

Visual observation of the G/E, B/Al, and B/PI test articles indicated no apparent thermal or mechanical degradation of test article components resulting from the tests. Some discoloration (surface oxidation) of the stainless steel standoffs occurred, as expected, and as mentioned previously, resolidification of the Dynaflex insulation binder condensate on the isolator block and composite surfaces was apparent. The thermocouple and aluminum tape at location #5 on the B/Al composite (T/C #25) was found not to be in contact with the panel, which is the probable cause of suspect temperatures recorded for about 700 seconds during the 1255°K (1800°F) maximum surface temperature exposure. This anomaly is noted in Table VIII and can be observed in the basic raw test data presented by Appendix D.

CONCLUSIONS

The study results indicate that the use of composite materials as primary structure on the Space Shuttle Orbiter Vehicle would not be uniquely restricted by thermal design problems at the TPS to structure attachment points. The thermal designs of attachments to the low temperature capability composite materials (epoxy resins), in fact, would be very similar to those for aluminum structure; and the high temperature capability composite (polyimide resins) thermal designs would be similar to those suitable for titanium structures. It will be noted, however, that any surface to structure "heat short" attachments to low temperature (450°K) capability structures presents a thermally difficult design problem where the local surface temperatures approach or exceed 1255°K (e.g., forward nose of wing leading edge locations), unless the cross-sectional area to height ratio of the "heat short" is small, t/h ~ 0.005, (e.g., similar to that of a sine wave TPS standoff). For the low t/h "heat shorts," attachments to low temperature capability materials can be practically accommodated at locations where the surface maximum temperatures reach 1645°K. "Heat short" attachments to the high temperature capability structures (590°K) appear not to present an unusually difficult thermal design problem for the 1255°K maximum surface temperature condition even for configurations where t/h approaches 0.015; attachments to high temperature capability structures at the 1645°K surface temperature conditions present about the same level of difficulty as using low temperature structures at the 1255°K surface temperature condition. The attachment design problem is thermally insignificant (relatively) for any of the composite material structures investigated where the maximum surface temperatures are less than the 920°K level even for t/h ratios as large as 0.20 to 0.30.

The thermophysical properties data used in the design analysis appear to be quite adequate for preliminary design as evidenced by the agreement between experimental and analytical results. However, if a final design were to be developed, additional data would be required on the polyimide composites, Boron/Aluminum, and attachment isolators (such as the PBI and Chem Ceram materials selected for preliminary design in this study).

The design modeling techniques used in this study appear quite adequate for detail thermal design of attachments to composite material structures. The maximum temperatures measured on the composite structure panels during testing were about 15 percent of design limit less than the pretest calculated values. The measured temperature gradients in the composite material structures were in the order as calculated. It should be noted, however, that composite panels fabricated for testing were fabricated to produce a pseudo-isotropic array and that other arrays, selected for specific structural loading conditions, could result in higher temperature gradients in the composite structures and would require analyses on individual array orientations.

Post test computer analyses were not considered required or warranted since a very close simulation of the planned 920°K and 1255°K (1200°F and 1800°F) test environments was accomplished (Figures 26a and 27a), and because the pre-test predictions of the thermal response of each test article shows good agreement with the experimental data when considering that some of the significant thermophysical property data was approximated. It would appear that excellent agreement with the test data could be realized without thermal modeling changes if updated property data were available (particularly on the isolator block materials).

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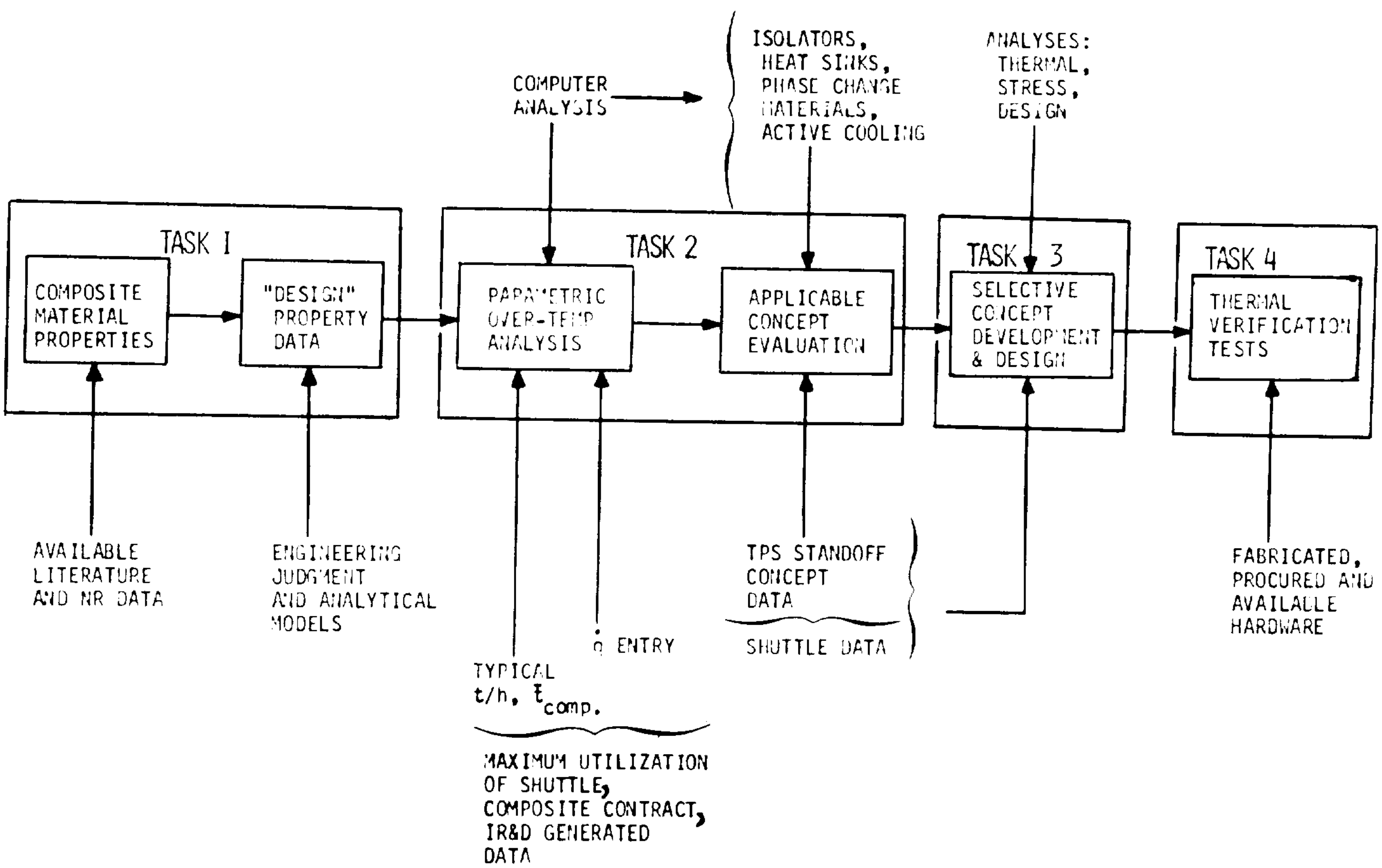


Figure 1. Technical Approach

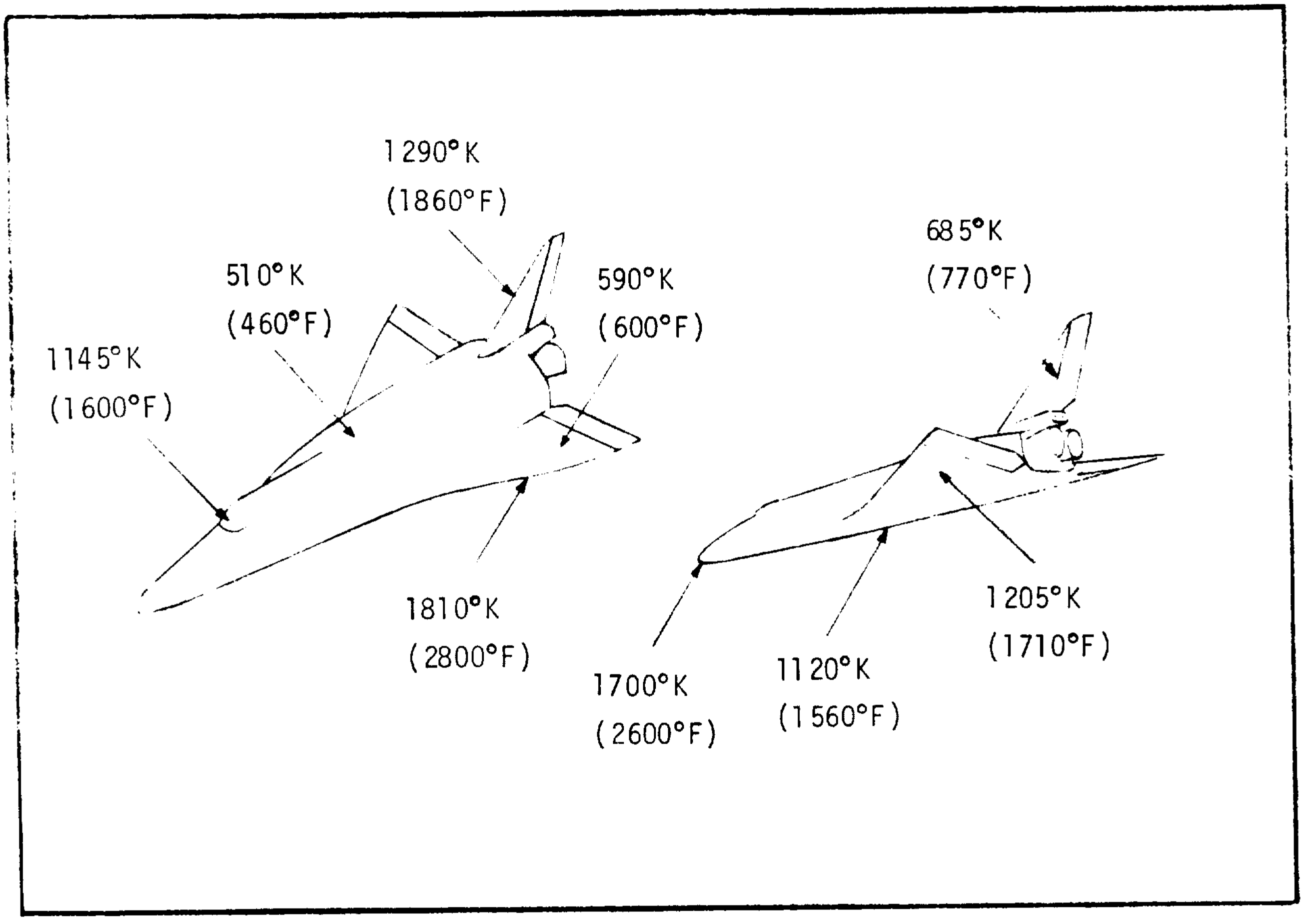


Figure 2. Maximum Surface Temperatures for Reference Vehicle (ε = 0.8)

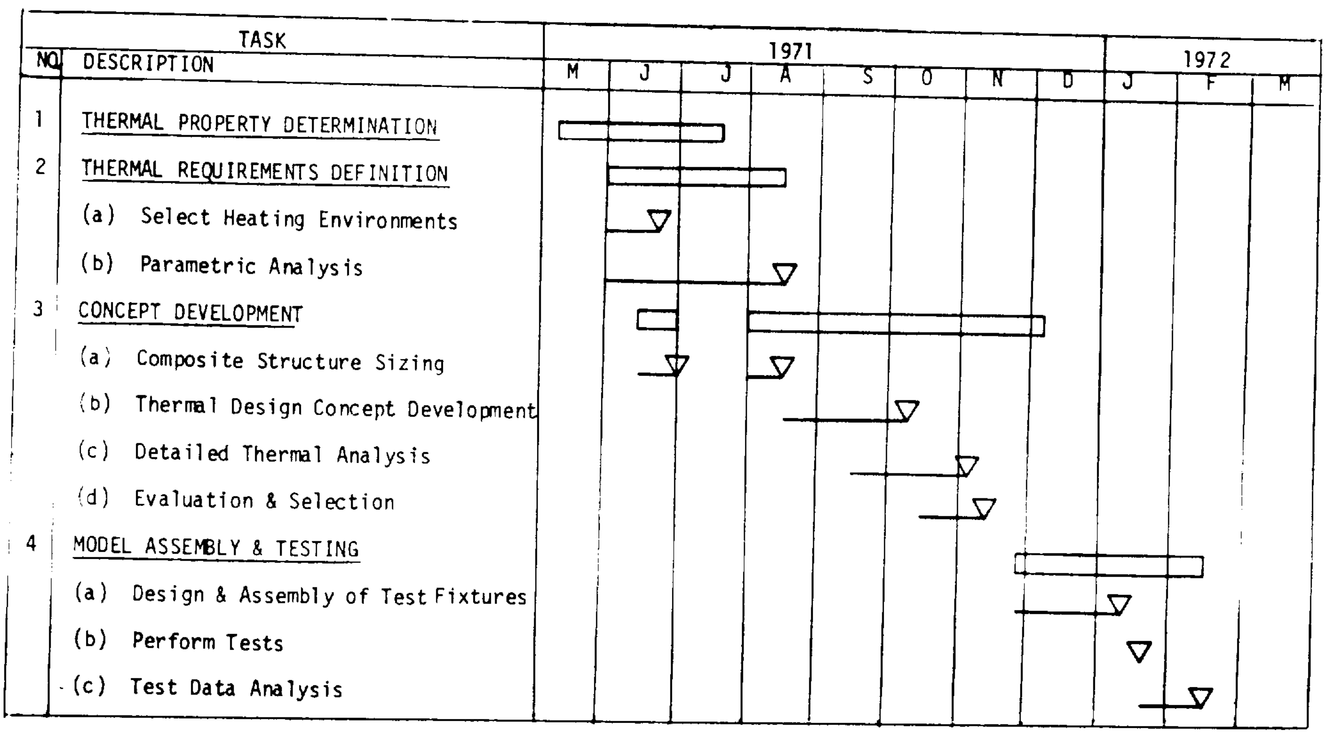


Figure 3. Program Schedule

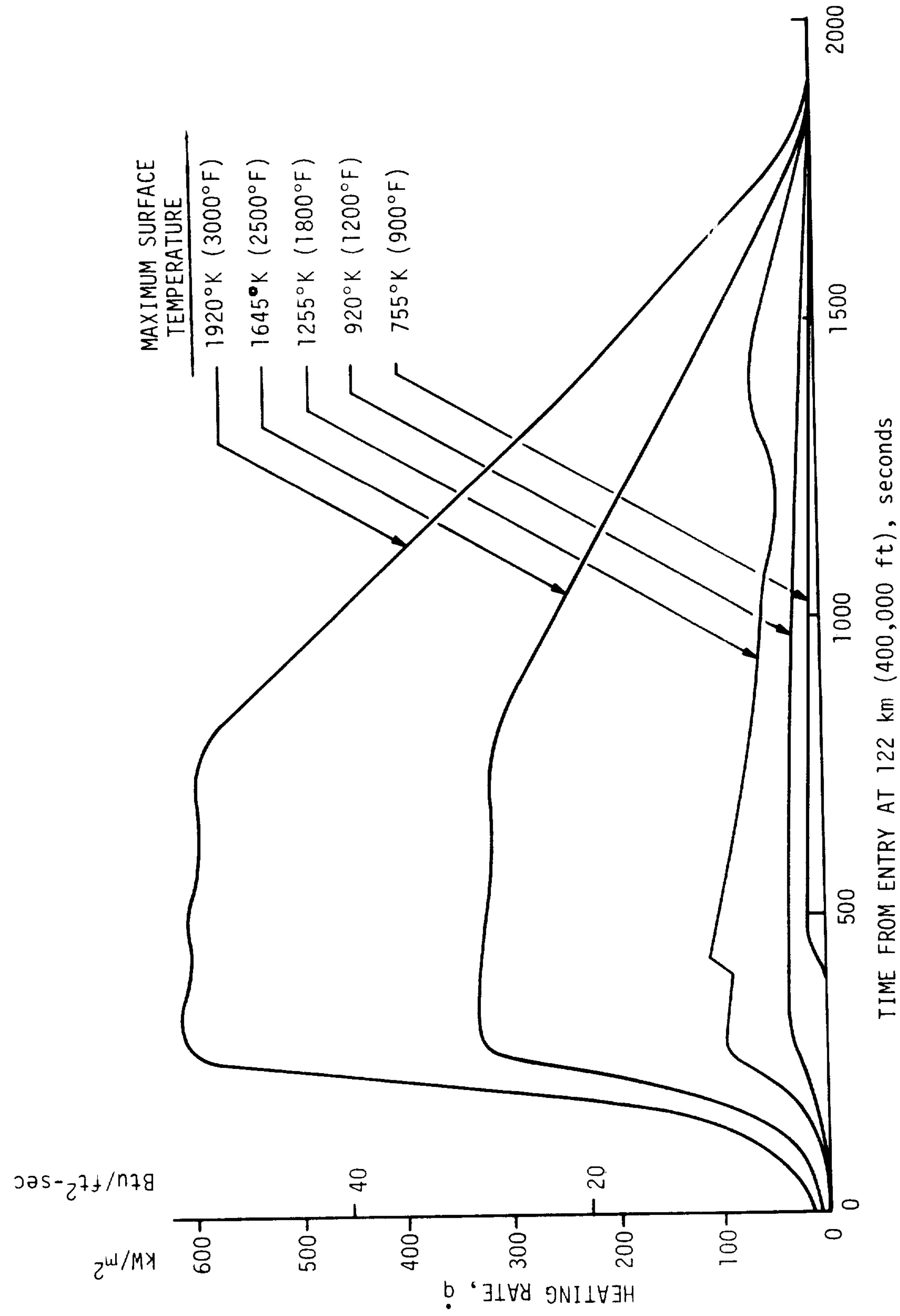
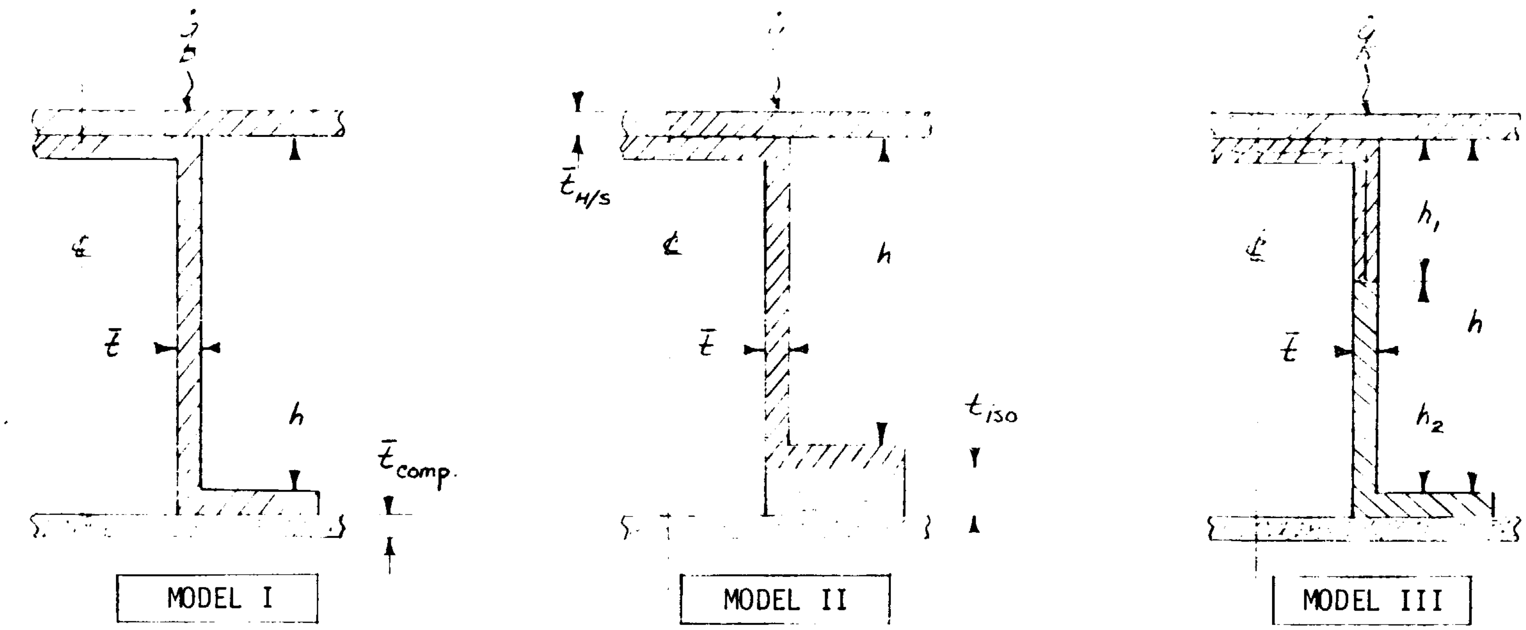
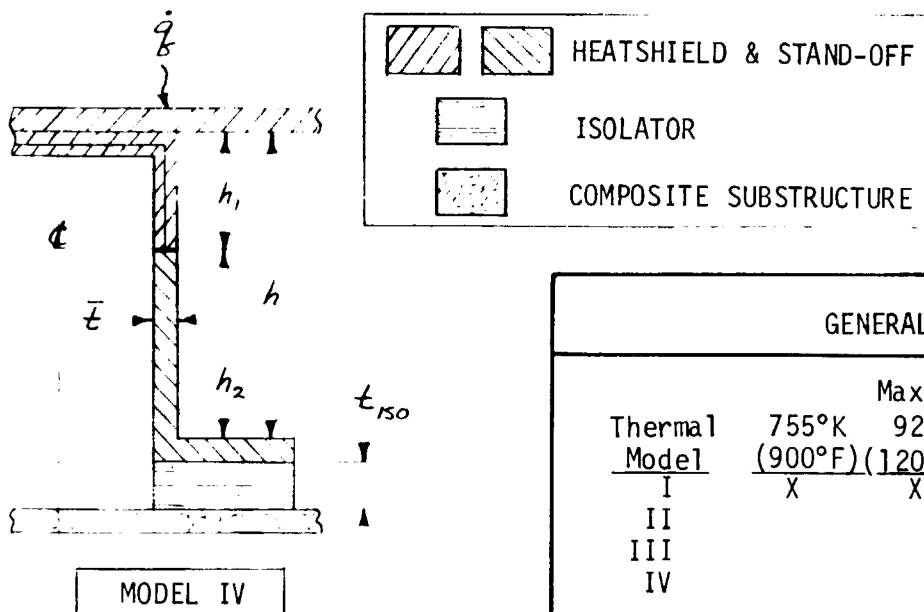


Figure 4. Reference Entry Heating Environments For High Cross-Range Shuttle Orbiter





GENERAL ANALYSIS MATRIX

Thermal Model	Maximum Surface Temperature 755°K (900°F)	920°K (1200°F)	1255°K (1800°F)	1645°K (2500°F)	1920°K (3000°F)
I	X	X	X	X	X
II			X	X	
III				X	
IV				X	

Figure 5. Simplified 2-Dimensional Thermal Models

MATERIAL	TEMPERATURE 755°K (900°F)	920°K (1200°F)	1255°K (1800°F)	1645°K (2500°F)	1920°K (3000°F)
Titanium 6Al-4V	●				
Inconel 718	○	●			
Rene' 41		○	○		
Haynes 188			●		
TD Ni Cr			○	●	
Columbium 752				●	
Carbon-Carbon				○	●
Tantalum T-111					○

○ Materials applicable to TPS stand-off

● Materials selected for parametric analysis

Figure 6. Candidate TPS Standoff Materials

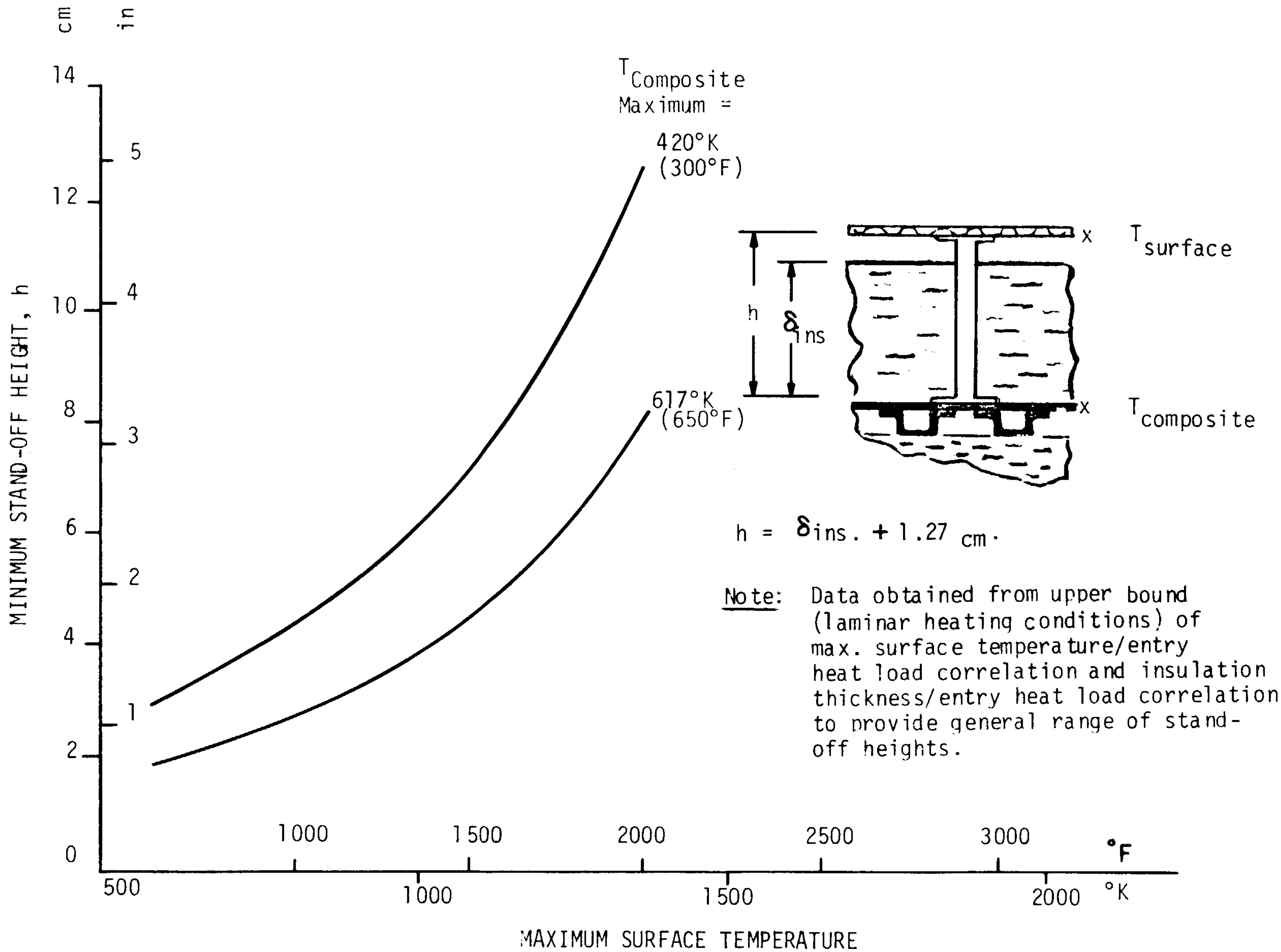


Figure 7. Reference Data For Minimum TPS Standoff Height

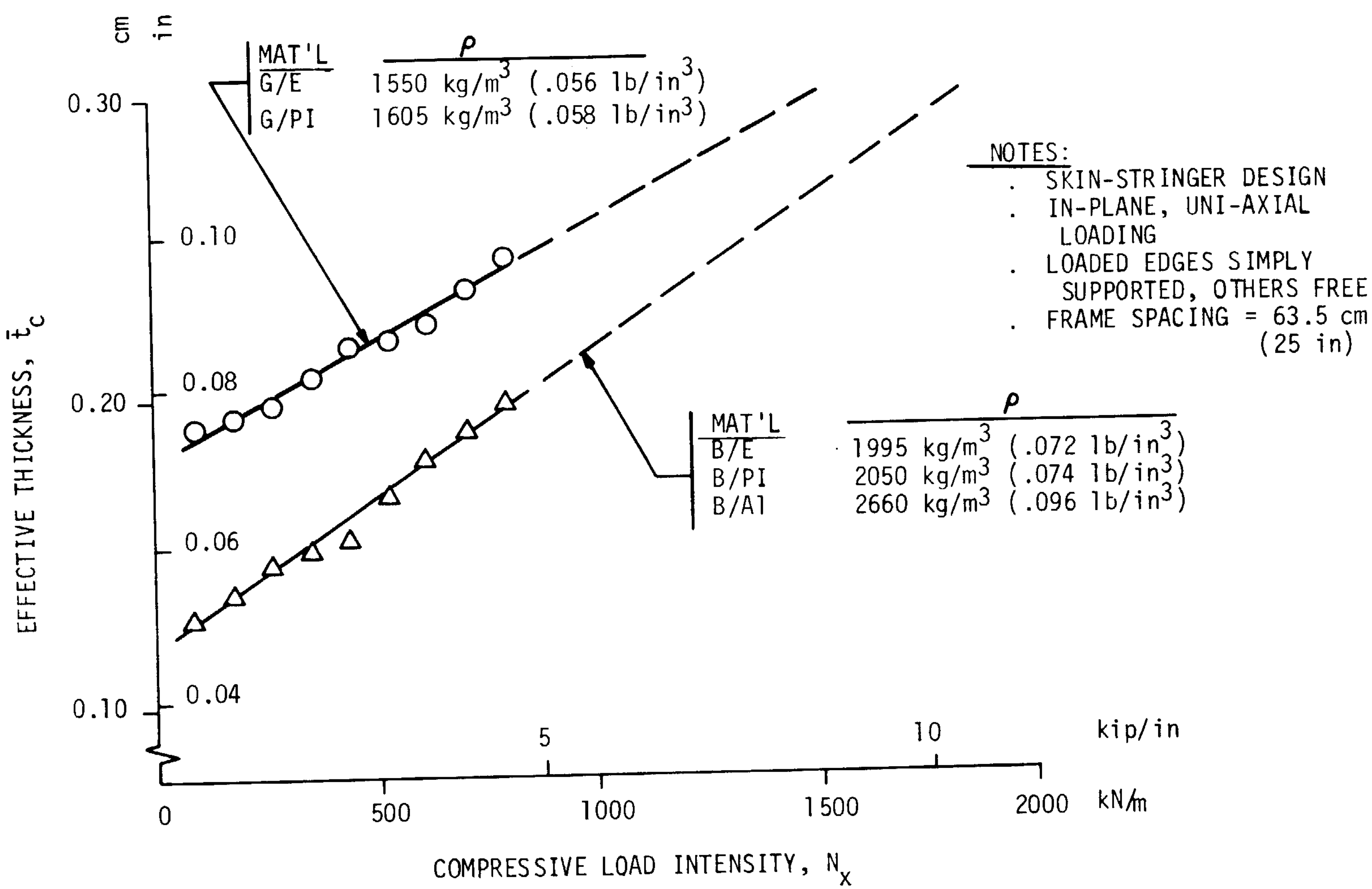
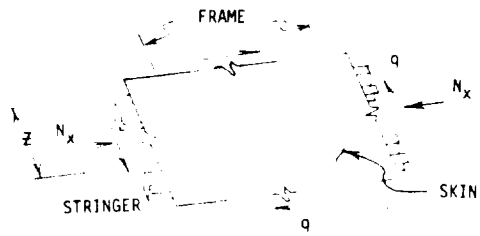


Figure 8. Effective $\bar{t}$ For Composite Panel Structures



STRUCTURE	MAX TEMP deg K (deg F)	COMPOSITE	LOCATION FRAME	LOCATION WP	N_x kN/m (lb/in.)	q kN/m (lb/in.)	$\bar{t}_c$ cm (in.)	t SKIN cm (in.)	z cm (in.)	A_{stgr} cm² (in.²)
AFT [illegible] FUSELAGE (1)	670 (750)	GRAPHITE	1500	400	228 (1300)	52.5 (300)	0.198 (0.078)	0.117 (0.0462)	13.35 (5.25)	1.078 (0.167)
		BORON					0.14 (0.055)	0.0793 (0.0312)	12.05 (4.75)	0.78 (0.121)
VERTICAL STABILIZER (2) TORQUE BOX	755 to 920 (900 to 1200)	GRAPHITE	ROOT	42% CHORD	2190 (12,500)	-----	0.394 (0.155)	0.155 (0.0610)	6.10 (2.40)	1.46 (0.226)
		BORON					0.315 (0.124)	0.124 (0.0490)	5.45 (2.14)	1.045 (0.162)
		GRAPHITE	2/3 UP	42% CHORD	965 (5500)	-----	0.262 (0.103)	0.103 (0.0405)	4.95 (1.95)	0.787 (0.122)
		BORON					0.211 (0.083)	0.083 (0.0327)	4.42 (1.74)	0.574 (0.089)
AFT BOTTOM FUSELAGE (1) OUTBOARD OF LONG'NS	1255 to 1310 (1800 to 1900)	GRAPHITE	1900	---	525 (3000)	-----	0.221 (0.087)	0.117 (0.0462)	12.05 (4.75)	1.245 (0.193)
		BORON					0.17 (0.067)	0.0793 (0.0312)	10.8 (4.25)	0.96 (0.149)
		GRAPHITE			440 (2500)	263 (1500)	0.3 (0.118)	0.203 (0.080)	12.05 (4.75)	1.20 (0.186)
		BORON					0.239 (0.094)	0.155 (0.061)	10.8 (4.25)	0.768 (0.119)
NOSE AND LEADING EDGES	1645 to 1920 (2500 to 3000)	GRAPHITE	N/A		N/A	-----	(4)	0.117 (0.0462)	(4)	(4)
		BORON						0.0793 (0.0312)		

(1) FRAME SPACING = 63.5 cm (25 in.)
(2) FRAME (RIB) SPACING = 38.1 cm (15 in.)
(3) MINIMUM
(4) SIZE FOR THERMAL REQUIREMENTS

Figure 9. Skin-Stringer Composite Panel Parameters

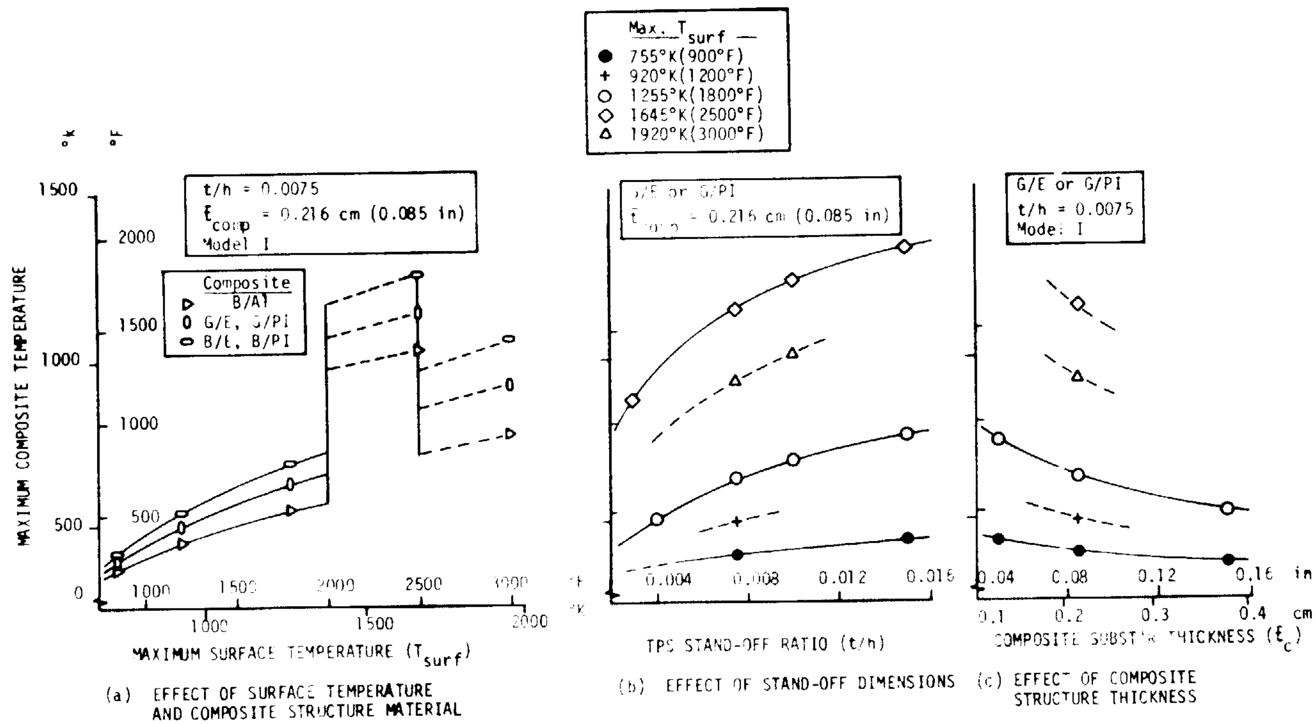
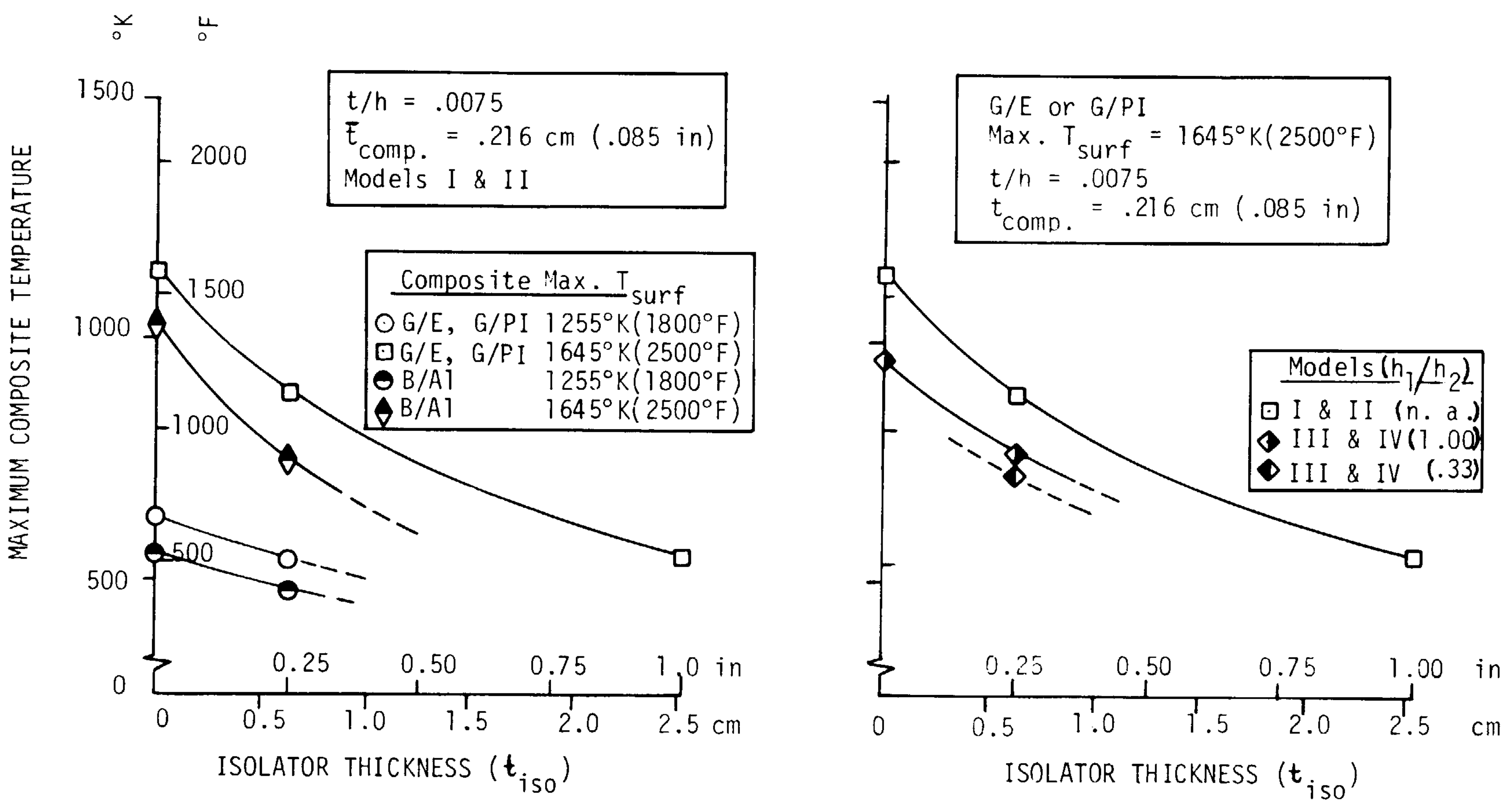


Figure 10. Attachment Point Temperature Variations Without Temperature Suppression



(a) EFFECTIVENESS OF ISOLATORS

(b) EFFECTIVENESS OF MULTI-MATERIAL STAND-OFFS AND ISOLATOR COMBINATIONS

Figure 11. Effectiveness of Simple Temperature Suppression Concepts

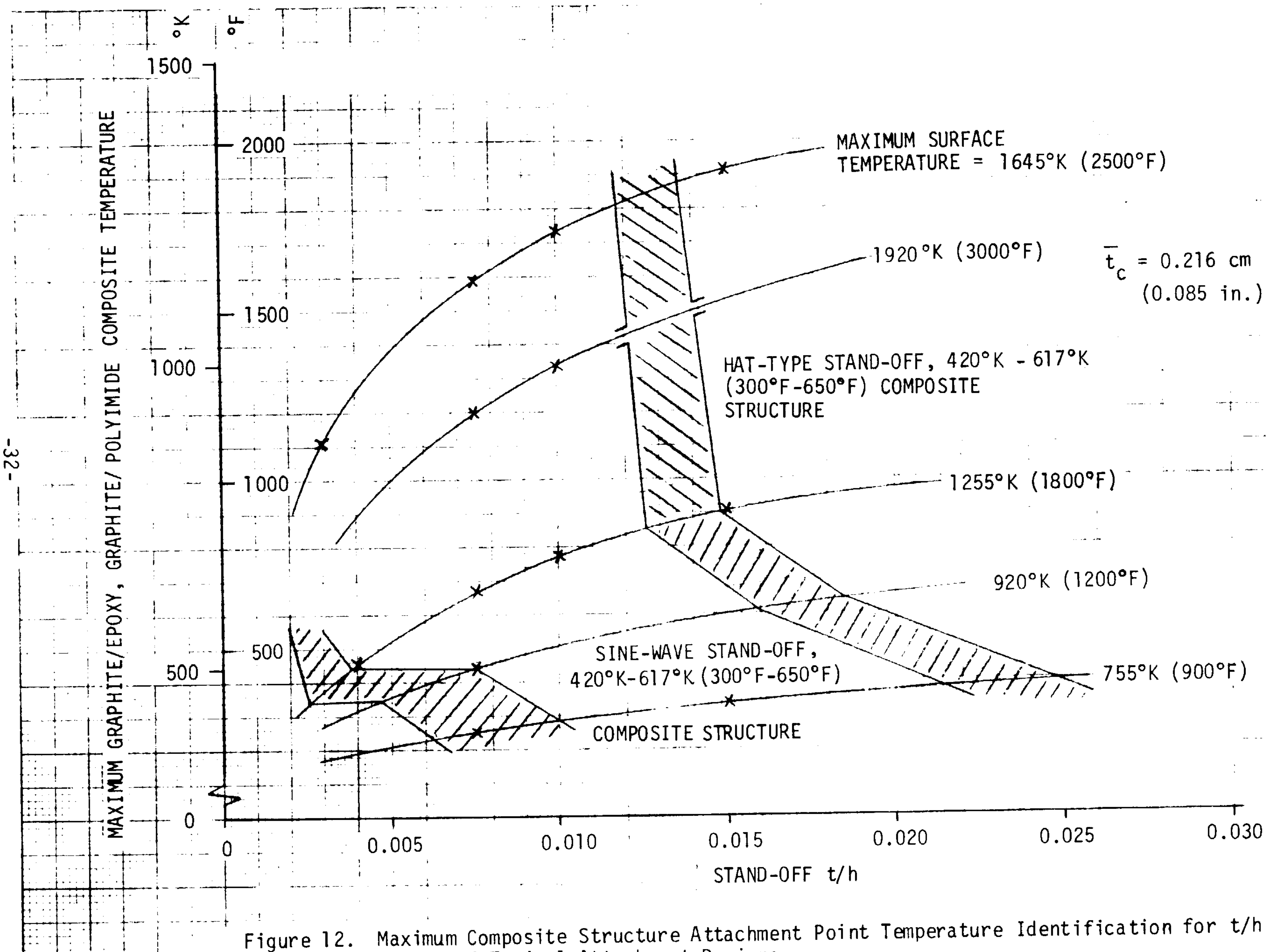


Figure 12. Maximum Composite Structure Attachment Point Temperature Identification for t/h Ranges of Typical Attachment Designs

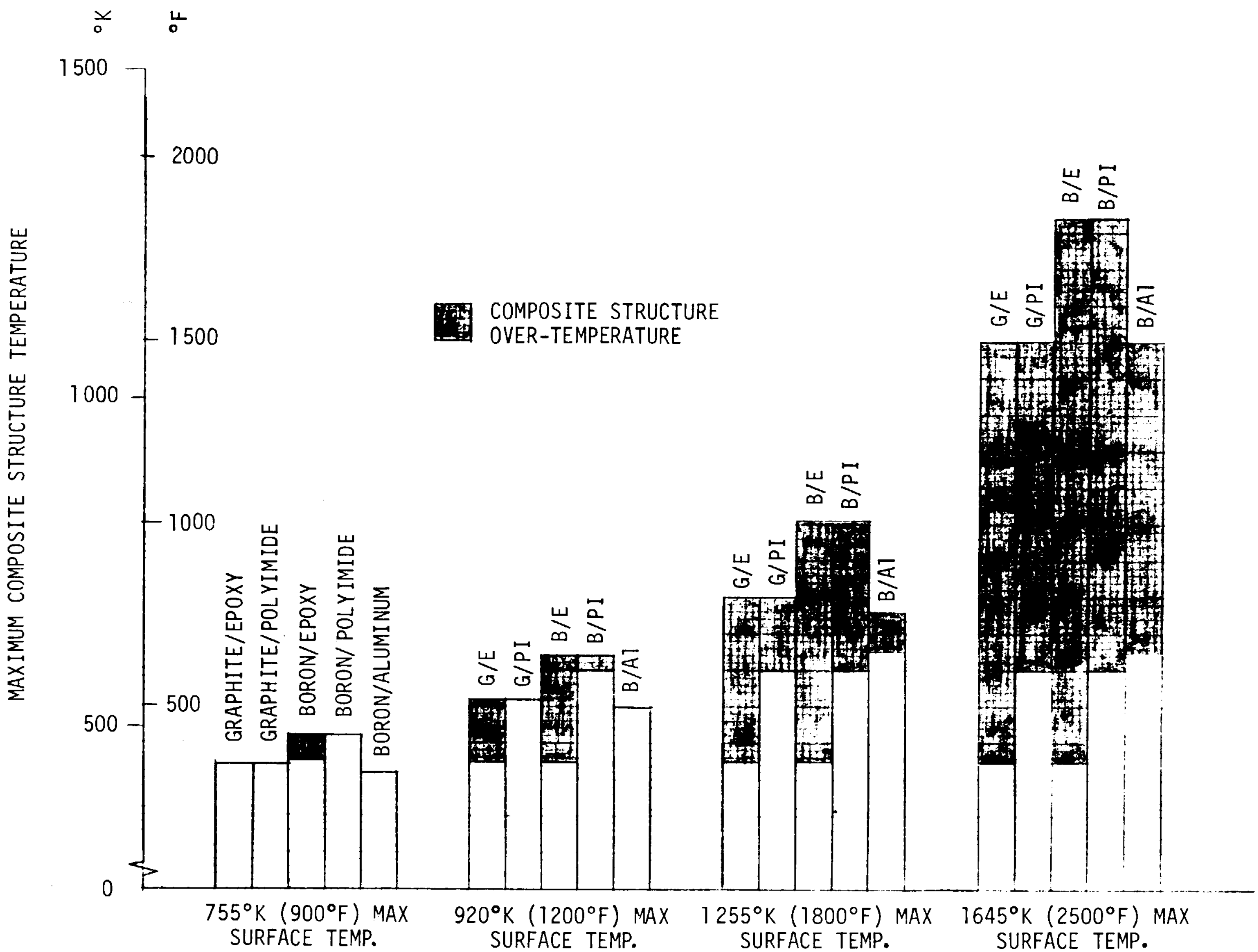


Figure 13. ESTIMATED OVER-TEMPERATURE OF COMPOSITE STRUCTURES FOR APPLICABLE COMPOSITE STRUCTURE THICKNESSES AND HAT-TYPE STANDOFF t/h

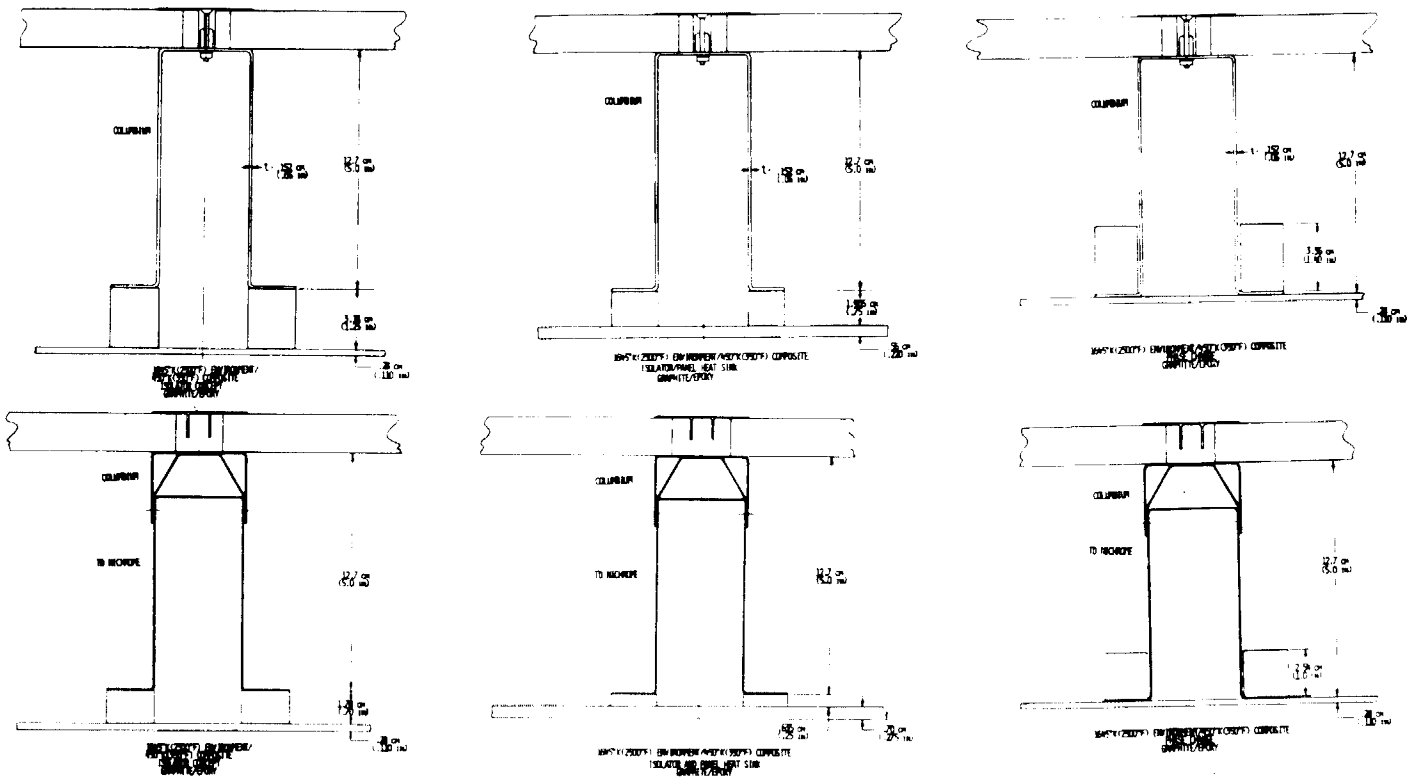


Figure 14a. Composite Structure Attachment Point Temperature Suppression Concepts for Hat-Type TPS Standoffs

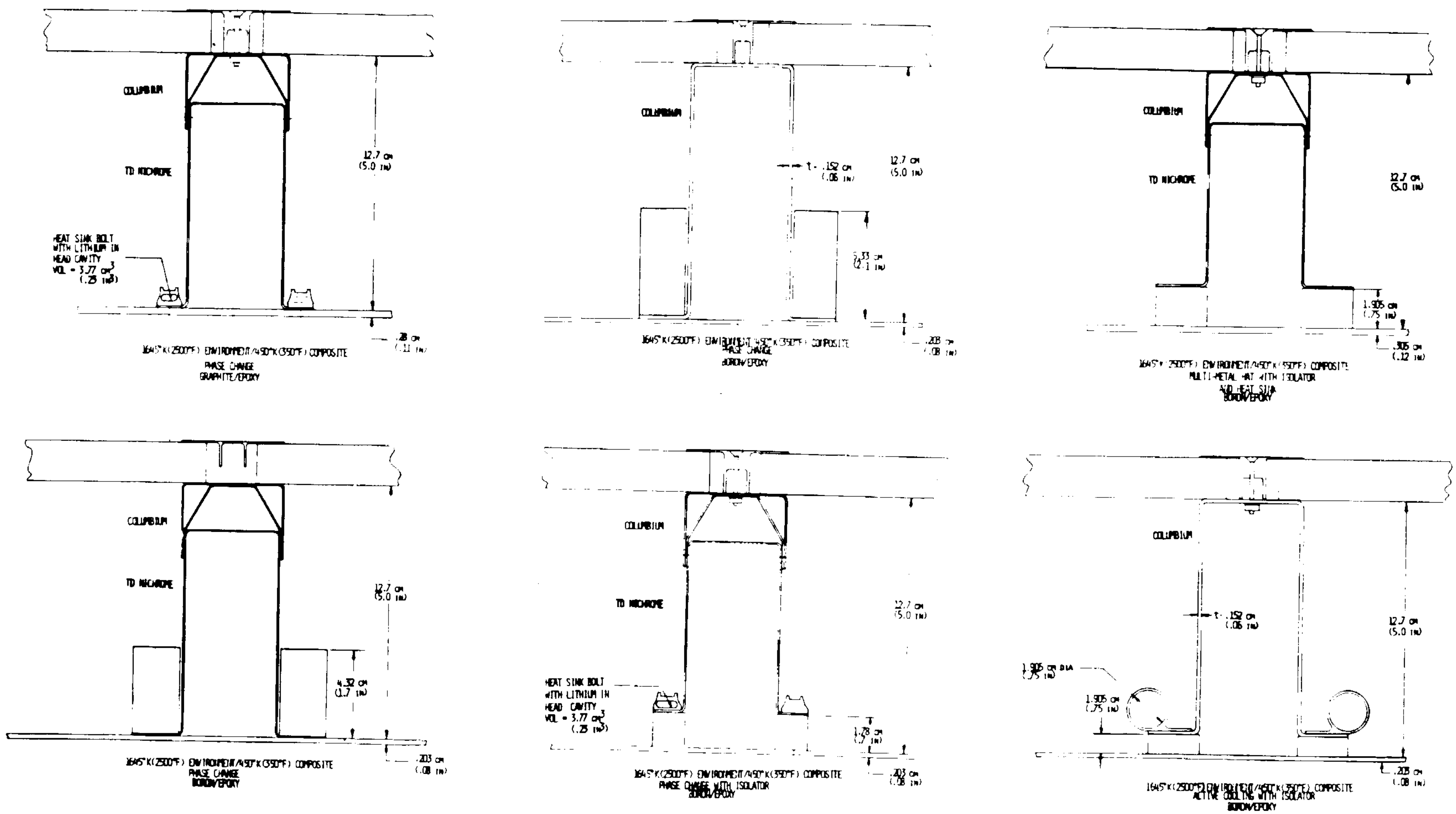


Figure 14b. Composite Structure Attachment Point Temperature Suppression Concepts for Hat-Type TPS Standoffs

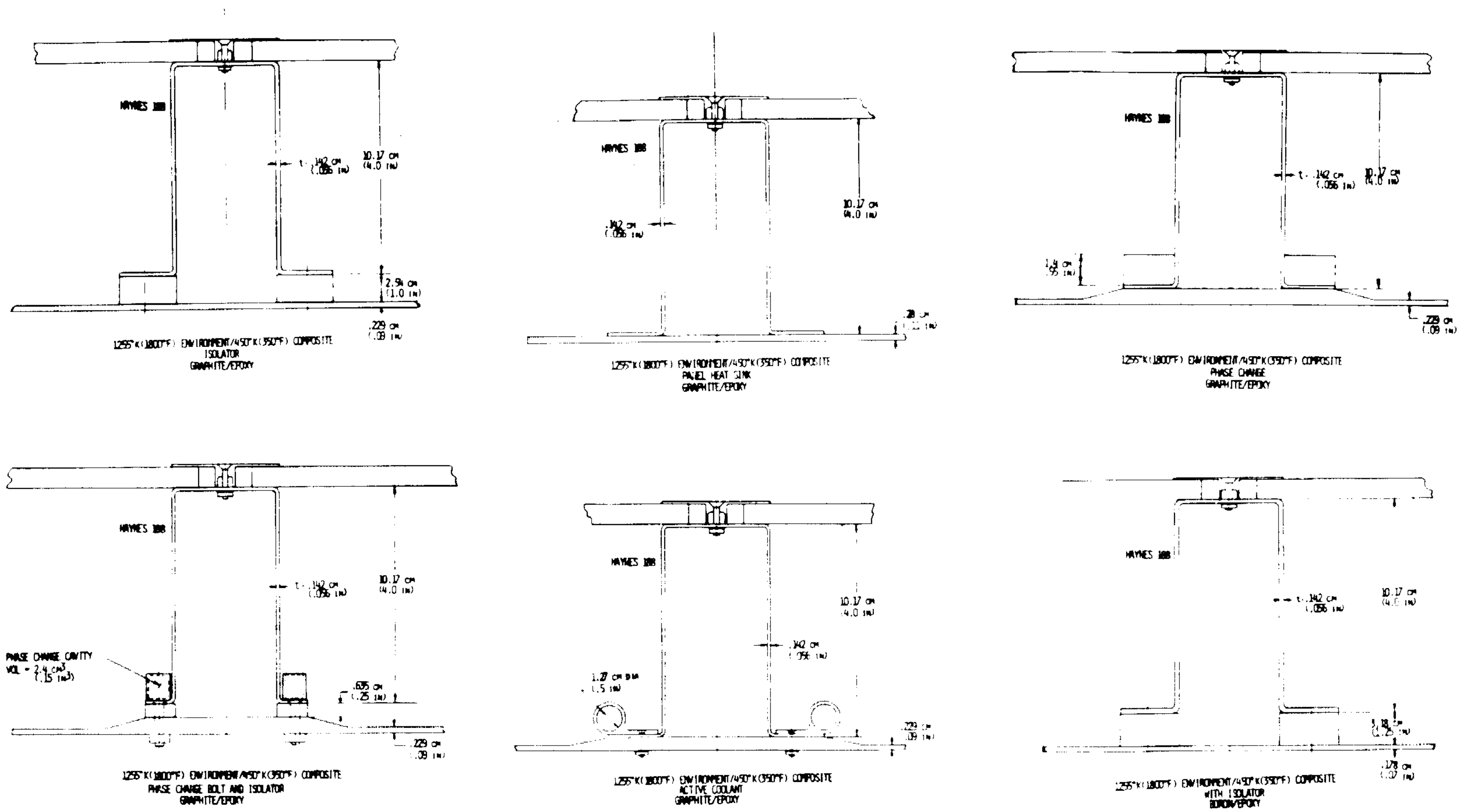


Figure 14c. Composite Structure Attachment Point Temperature Suppression Concepts for Hat-Type TPS Standoffs

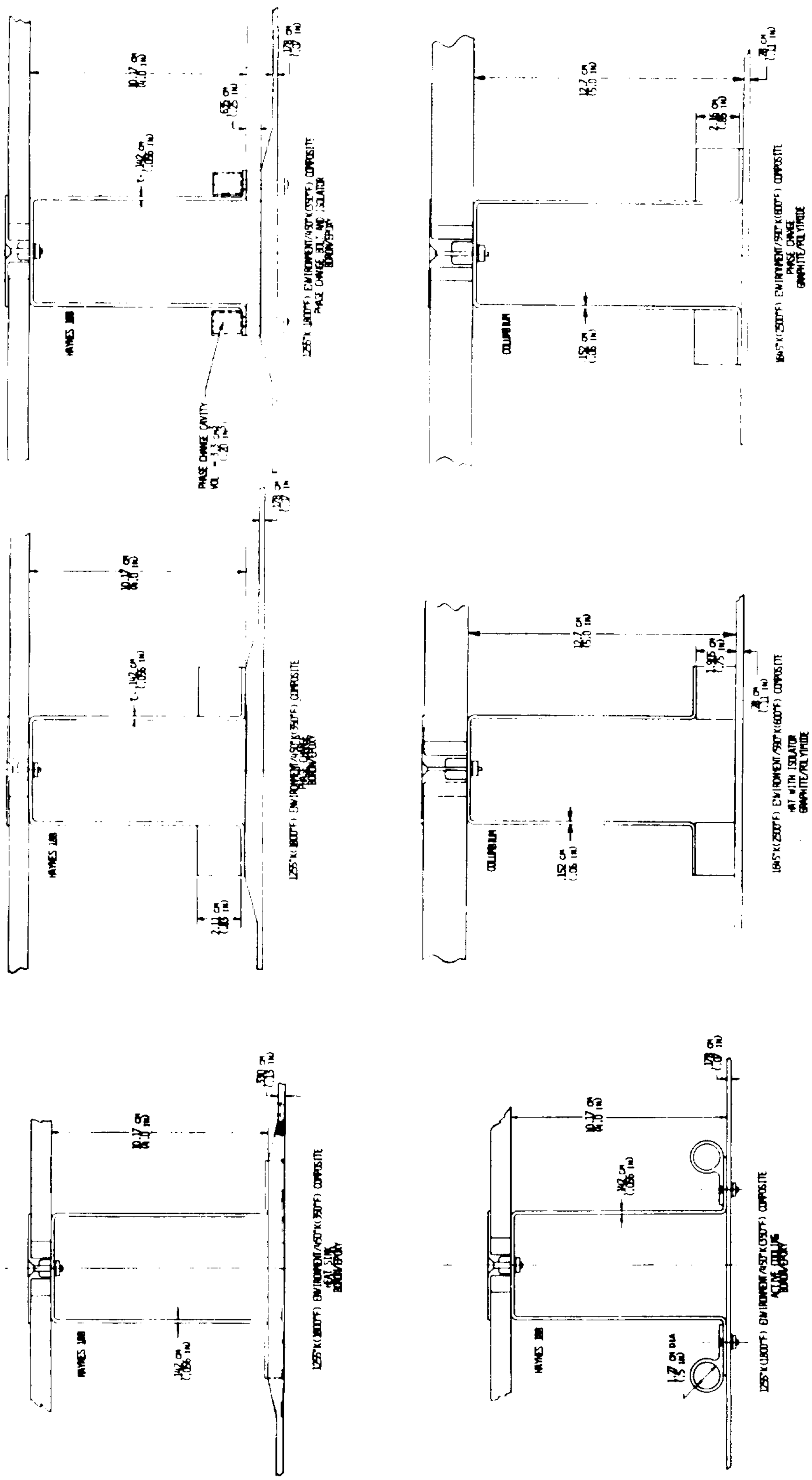


Figure 14d. Composite Structure Attachment Point Temperature Suppression Concepts for Hat-Type TPS Standoffs

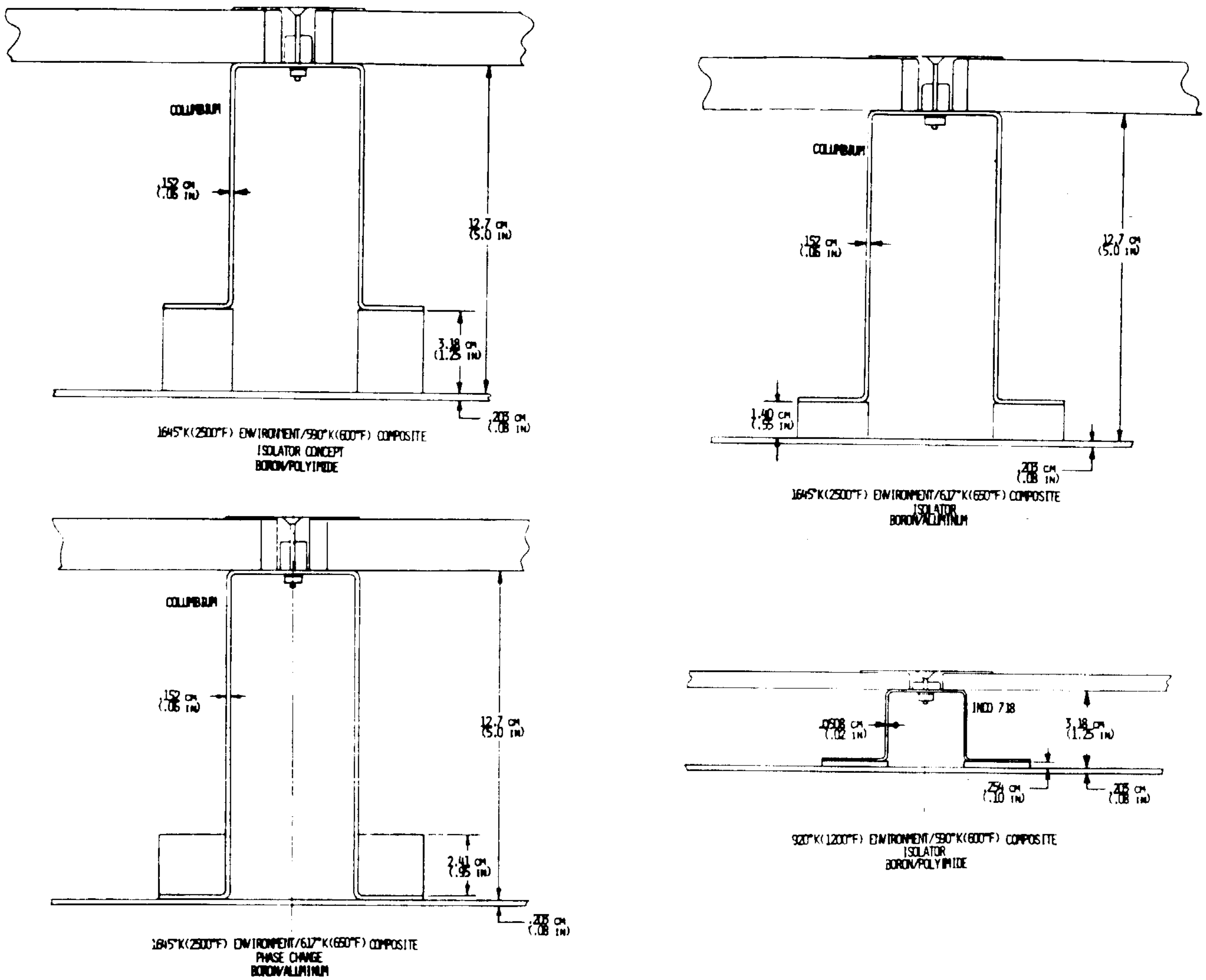


Figure 14e. Composite Structure Attachment Point Temperature Suppression Concepts for Hat-Type TPS Standoffs

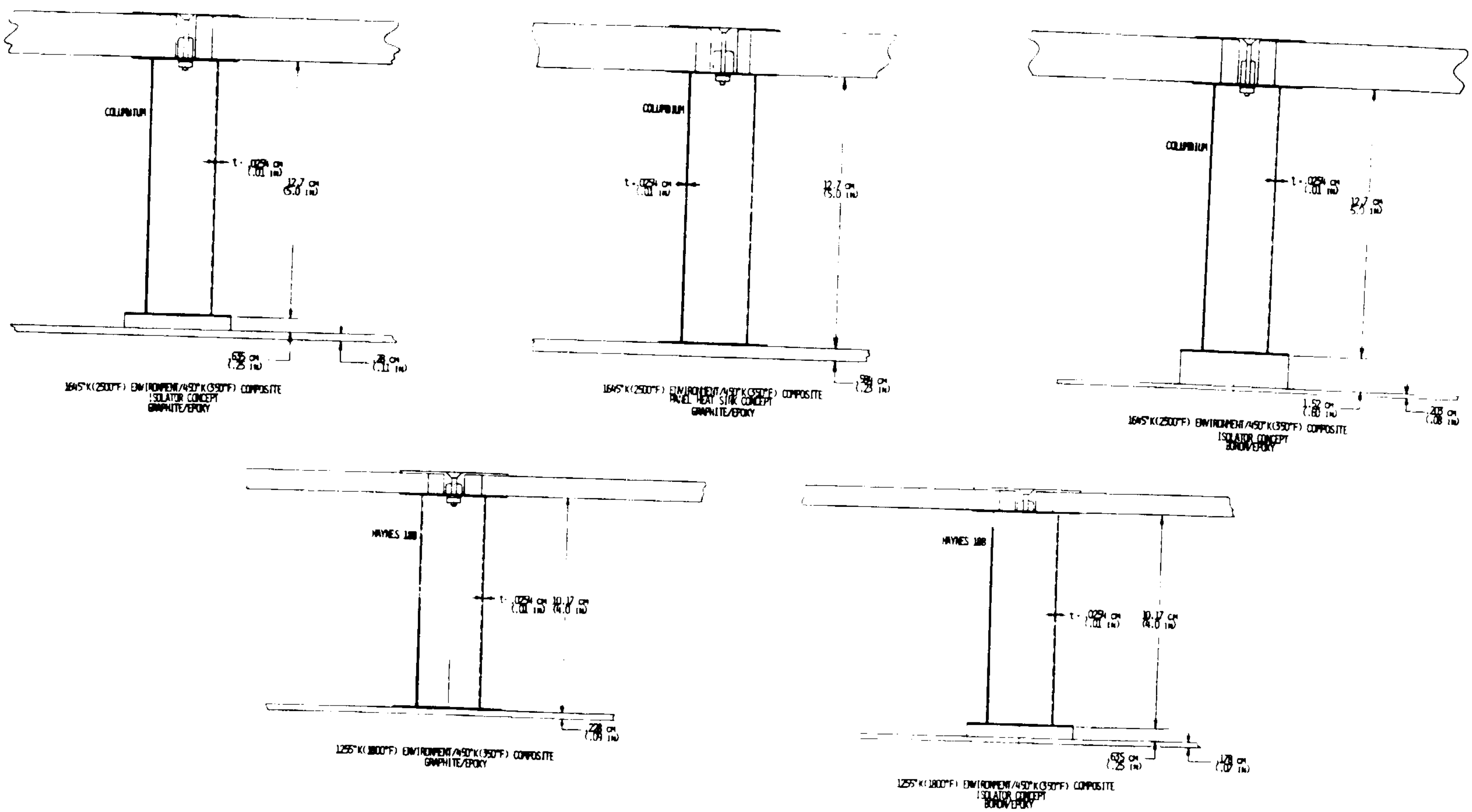


Figure 15a. Composite Structure Attachment Point Temperature Suppression Concepts for Sine-Wave TPS Standoffs

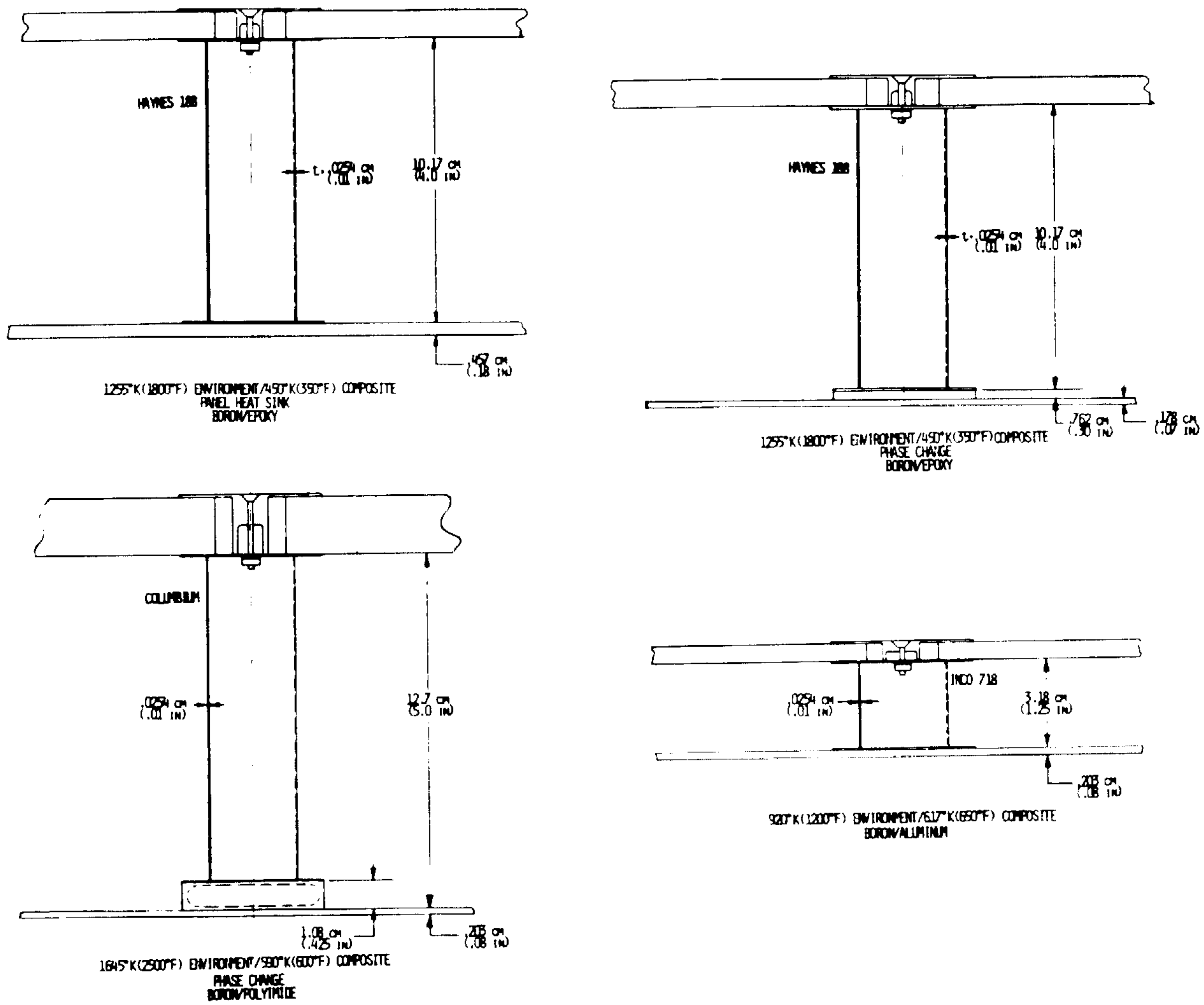


Figure 15b. Composite Structure Attachment Point Temperature Suppression Concepts for Sine-Wave TPS Standoffs

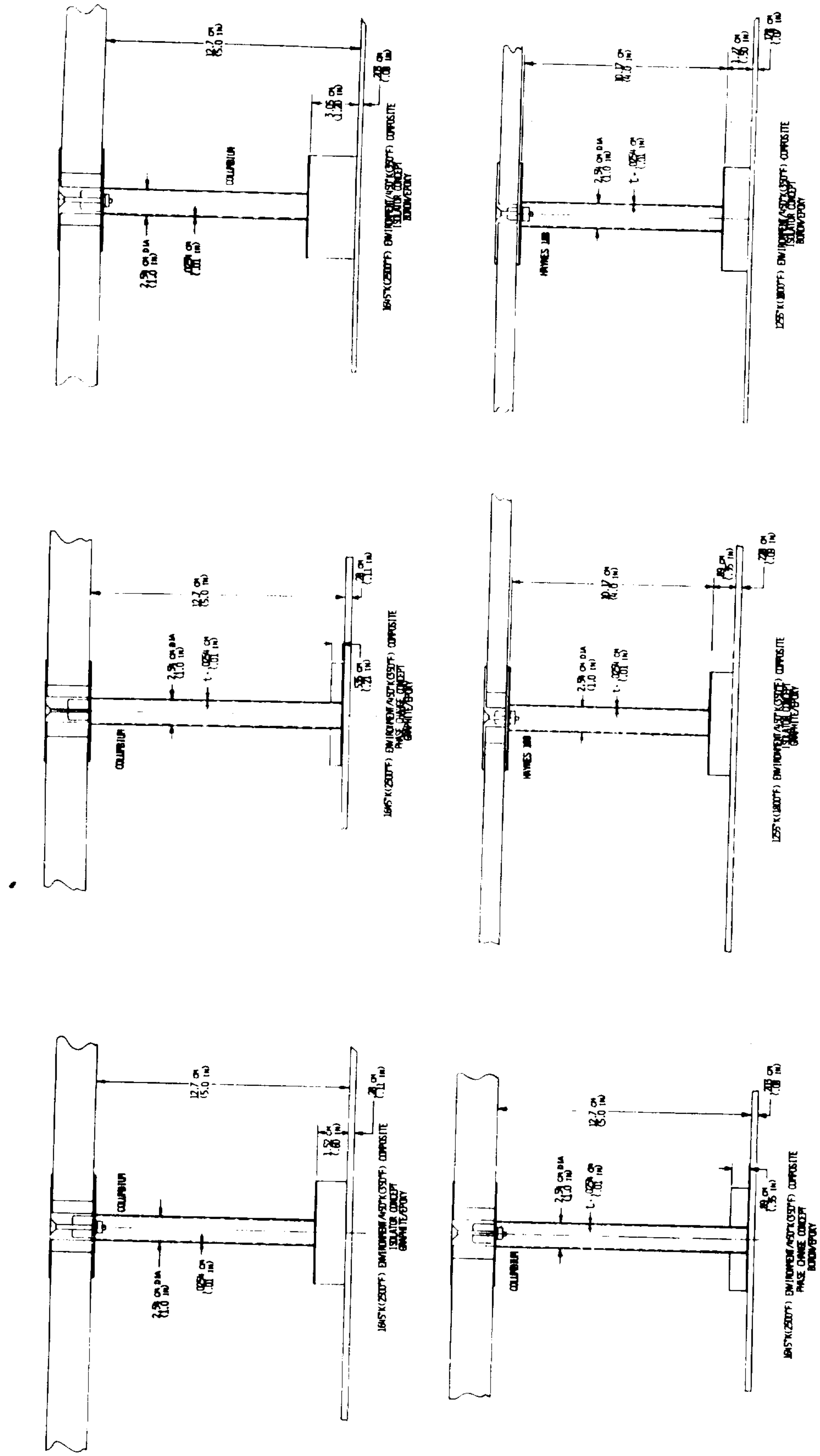


Figure 16. Composite Structure Attachment Point Temperature Suppression Concepts for Post TPS Standoffs

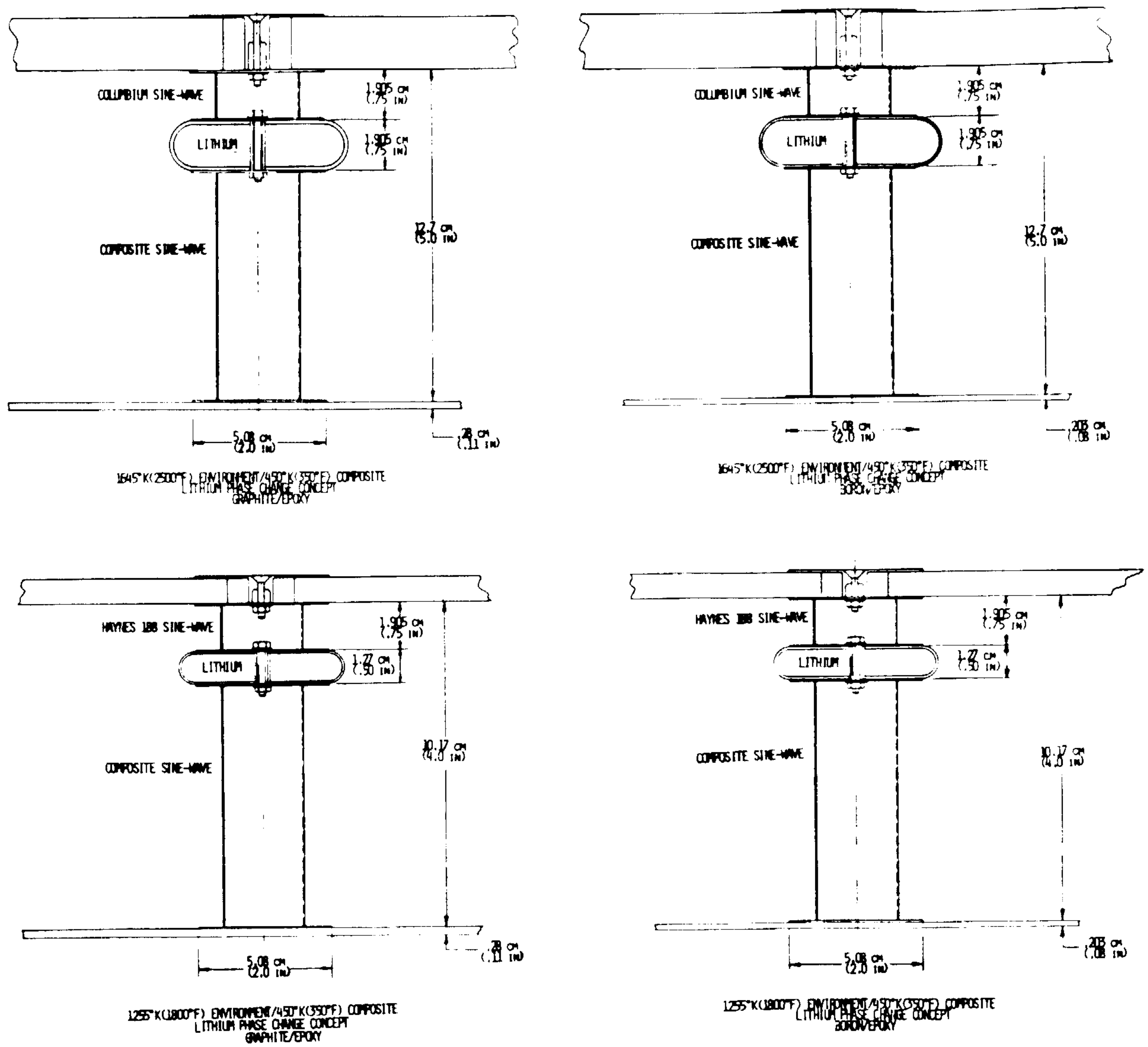
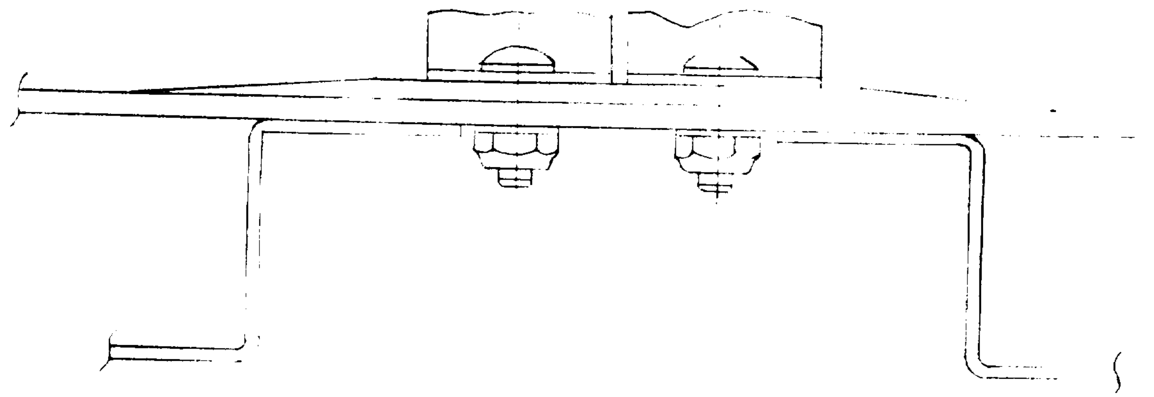
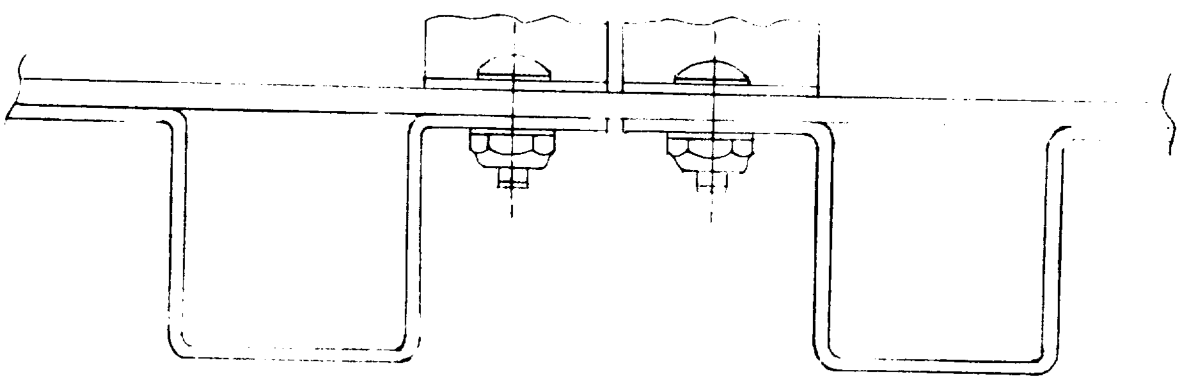


Figure 17. Composite Structure Attachment Point Temperature Suppression Concepts for Metallic/Composite TPS Standoffs

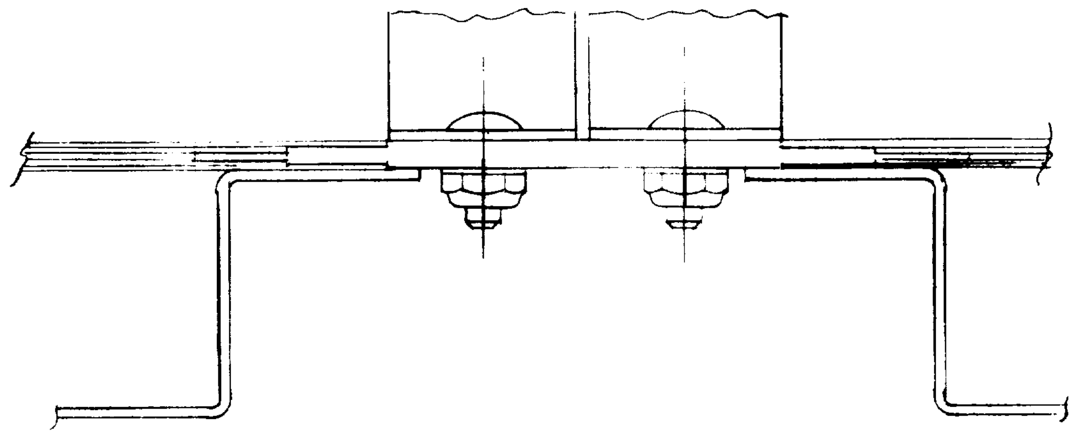


DOUBLER STRENGTHENED

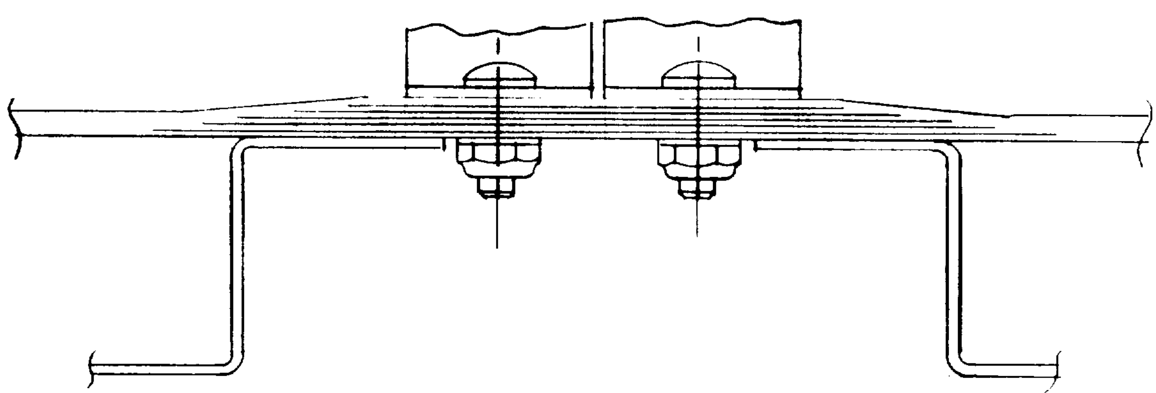


STRINGER STRENGTHENED

Figure 18a. Bolt Attachment Concepts



METALLIC INSERT STRENGTHENED



METALLIC INTERLEAVE STRENGTHENED

Figure 18b. Bolt Attachment Concepts (Continued)

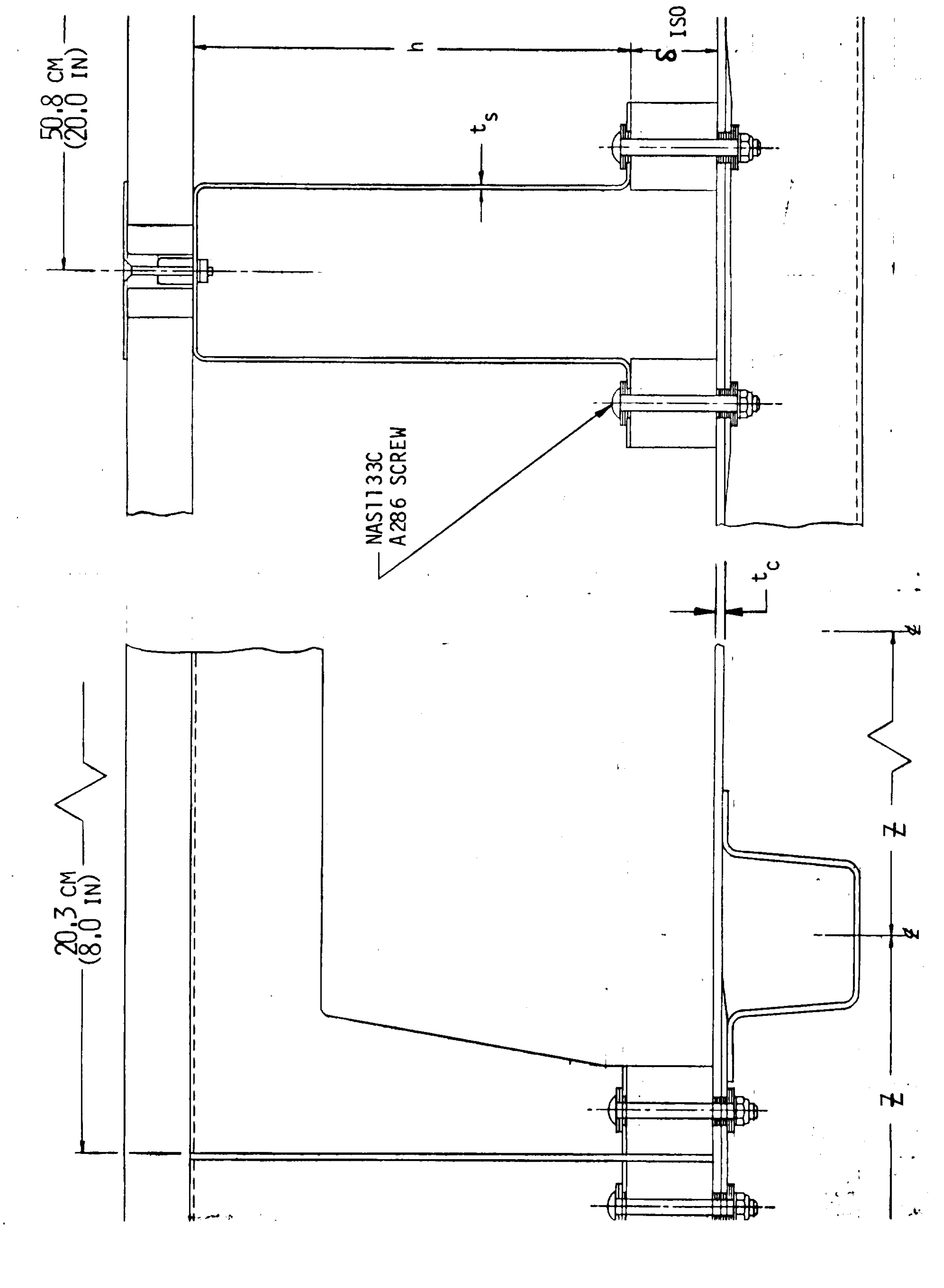


Figure 19. Hat Section Standoff Attachment Design

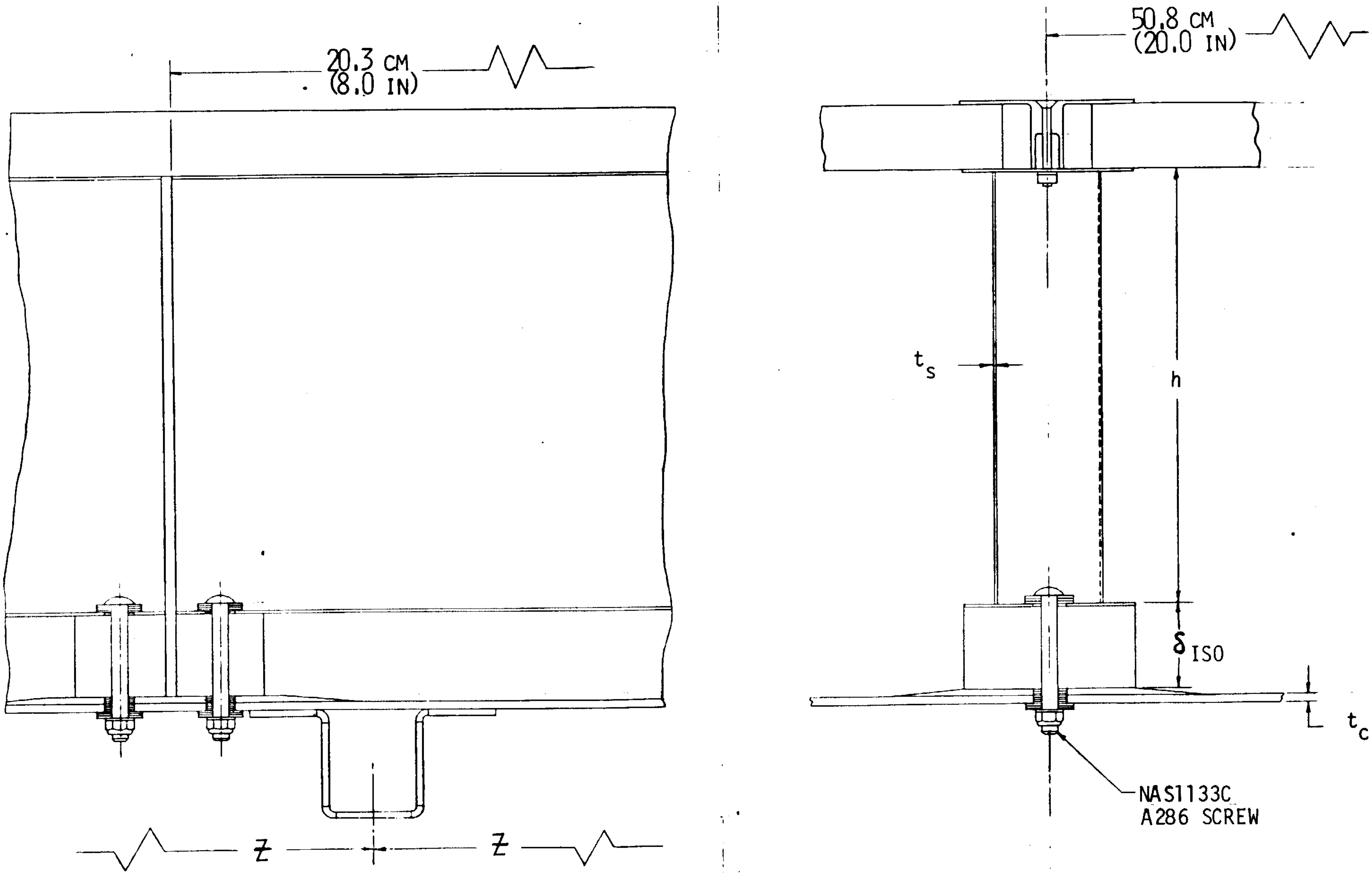
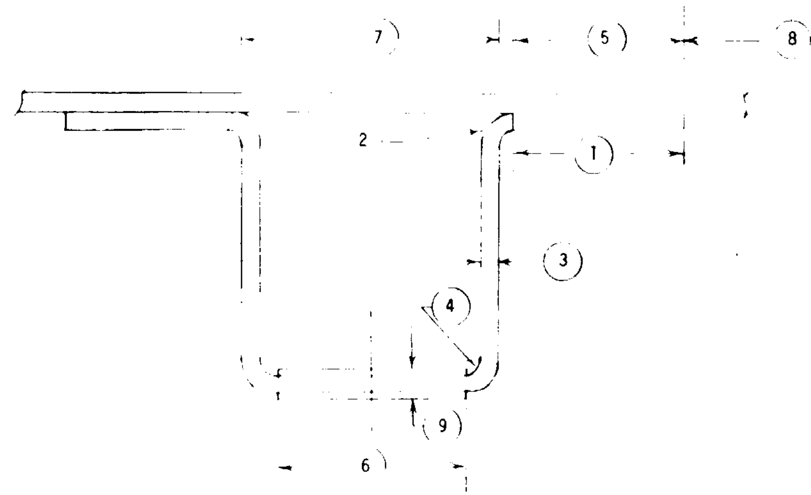


Figure 20. Sine Wave Standoff Attachment Design



	(1255°K) 1800°F			(1645°K) 2500°F	
	G/E and G/PI	B/E and B/PI	B/Al	G/E	B/PI
1	t = .0782 cm (.0308 in) L = 1.905 cm (.75 in)	t = .0529 cm (.0208 in) L = 1.905 cm (.75 in)	t = .0529 cm (.0208 in) L = 1.905 cm (.75 in)	t = .0782 cm (.0308 in) L = 1.905 cm (.75 in)	t = .0529 cm (.0208 in) L = 1.905 cm (.75 in)
2	t = .0782 cm (.0308 in) L = .239 cm (.0942 in)	t = .0529 cm (.0208 in) L = .239 cm (.0942 in)	t = .0529 cm (.0208 in) L = .239 cm (.0942 in)	t = .0782 cm (.0308 in) L = .239 cm (.0942 in)	t = .0529 cm (.0208 in) L = .239 cm (.0942 in)
3	t = .0782 cm (.0308 in) L = 2.87 cm (1.13 in)	t = .0529 cm (.0208 in) L = 2.87 cm (1.13 in)	t = .0529 cm (.0208 in) L = 2.87 cm (1.13 in)	t = .0782 cm (.0308 in) L = 2.87 cm (1.13 in)	t = .0529 cm (.0208 in) L = 2.87 cm (1.13 in)
4	t = .0782 cm (.0308 in) L = .239 cm (.0942 in)	t = .0529 cm (.0208 in) L = .239 cm (.0942 in)	t = .0529 cm (.0208 in) L = .239 cm (.0942 in)	t = .0782 cm (.0308 in) L = .239 cm (.0942 in)	t = .0529 cm (.0208 in) L = .239 cm (.0942 in)
5	t = .117 cm (.0462 in) L = 1.905 cm (.75 in)	t = .0792 cm (.0312 in) L = 1.905 cm (.75 in)	t = .0792 cm (.0312 in) L = 1.905 cm (.75 in)	t = .202 cm (.0795 in) L = 1.905 cm (.75 in)	t = .155 cm (.0612 in) L = 1.905 cm (.75 in)
6	t = .0782 cm (.0308 in) L = 2.14 cm (.84 in)	t = .0529 cm (.0208 in) L = 2.14 cm (.84 in)	t = .0529 cm (.0208 in) L = 2.14 cm (.84 in)	t = .0782 cm (.0308 in) L = 2.14 cm (.84 in)	t = .0529 cm (.0208 in) L = 2.14 cm (.84 in)
7	t = .117 cm (.0462 in) L = 2.74 cm (1.08 in)	t = .0792 cm (.0312 in) L = 2.74 cm (1.08 in)	t = .0792 cm (.0312 in) L = 2.74 cm (1.08 in)	t = .202 cm (.0795 in) L = 2.74 cm (1.08 in)	t = .155 cm (.0612 in) L = 2.74 cm (1.08 in)
8	t = .117 cm (.0462 in) L = 5.51 cm (2.17 in)	t = .0792 cm (.0312 in) L = 4.24 cm (1.67 in)	t = .0792 cm (.0312 in) L = 4.24 cm (1.67 in)	t = .202 cm (.0795 in) L = 5.51 cm (2.17 in)	t = .155 cm (.0612 in) L = 4.24 cm (1.67 in)
9	t = .196 cm (.0770 in)	L = .118 cm (.0468 in)	t = .106 cm (.0416 in)	t = .176 cm (.0693 in)	t = .105 cm (.042 in)

Figure 21. Composite Material Structure Dimensions

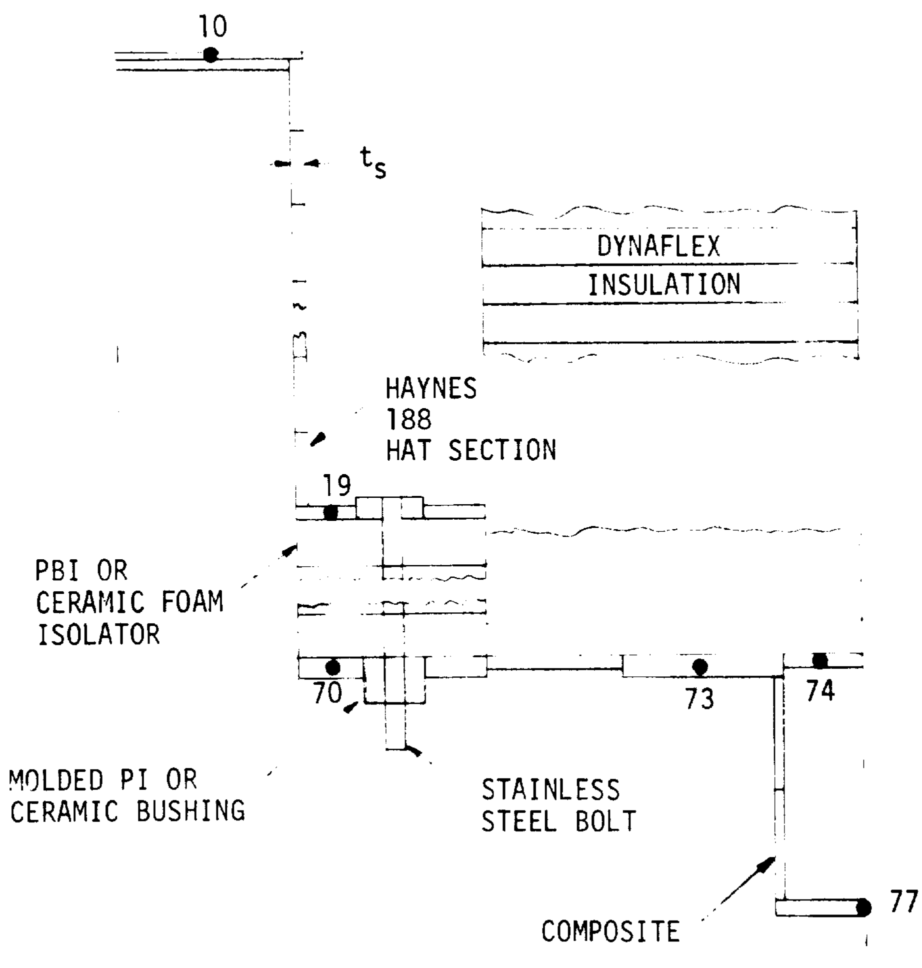


Figure 22. GENERAL THERMAL MODEL FOR DETAILED DESIGN ENTRY THERMAL ANALYSIS

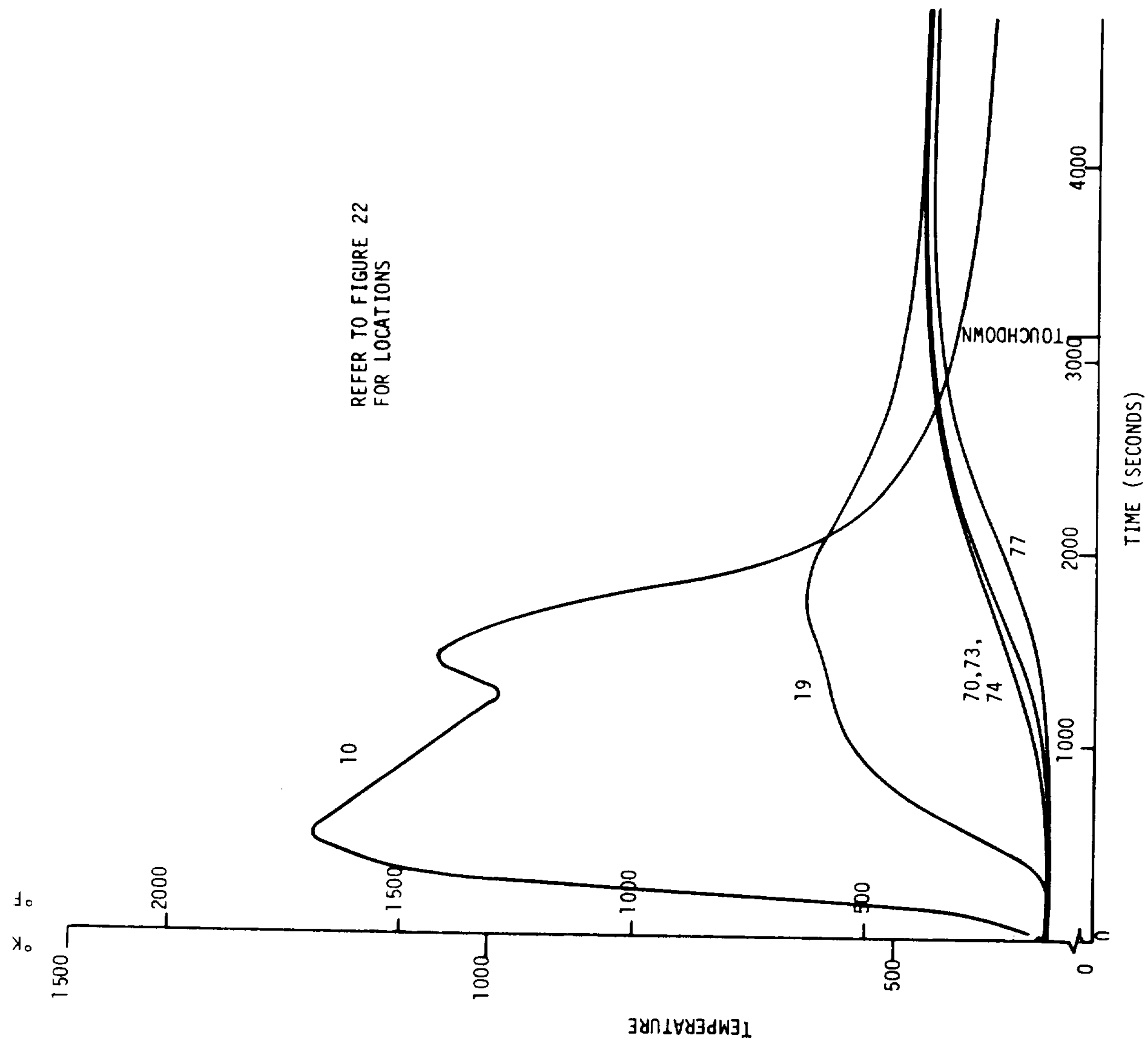


Figure 23a. Temperature Histories for Graphite/Epoxy Composite - Detailed Design Thermal Analysis for 1255°K(1800°F) Entry Environment

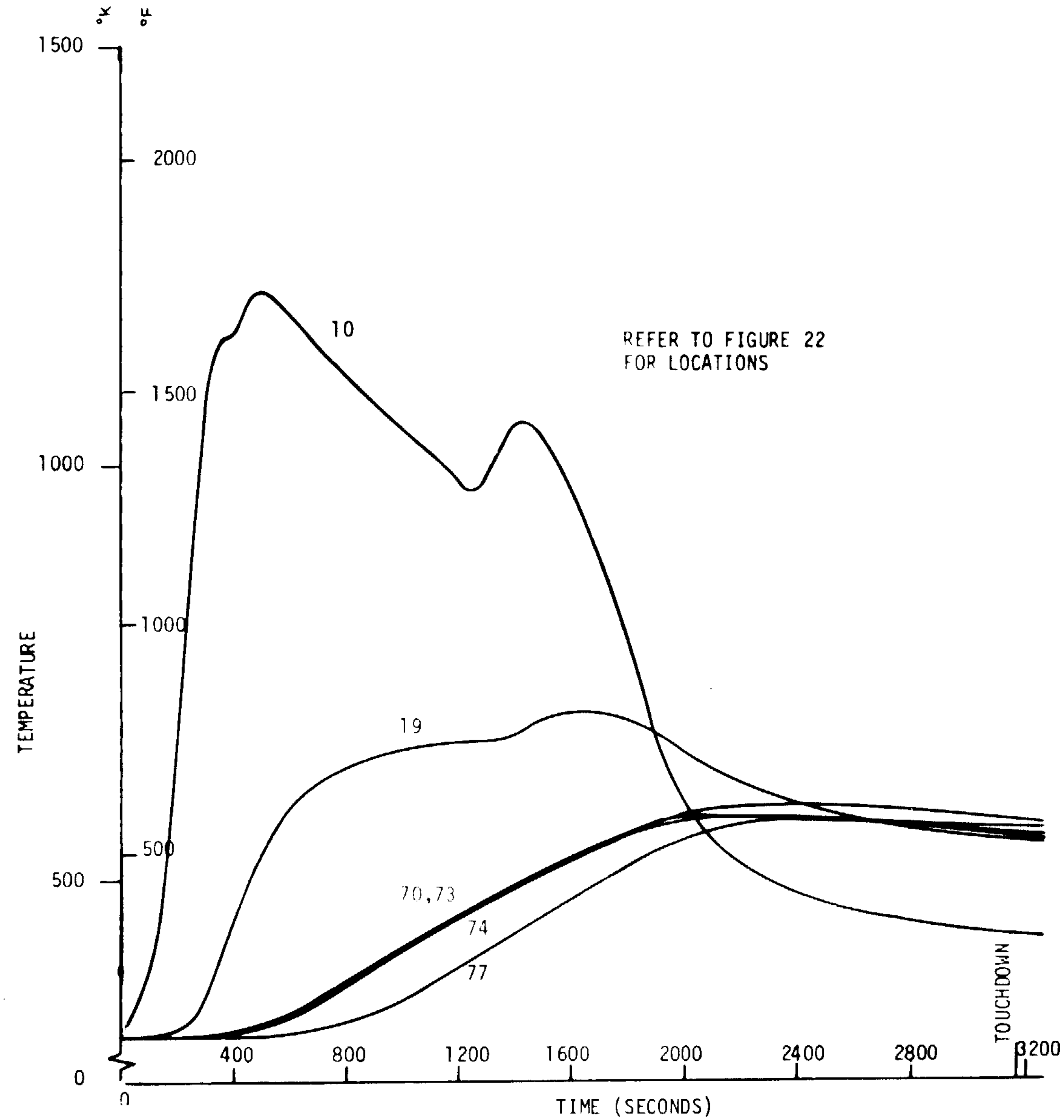


Figure 23b. Temperature Histories for Graphite/Polyimide Composite - Detailed Design Thermal Analysis for 1255°K(1800°F) Entry Environment

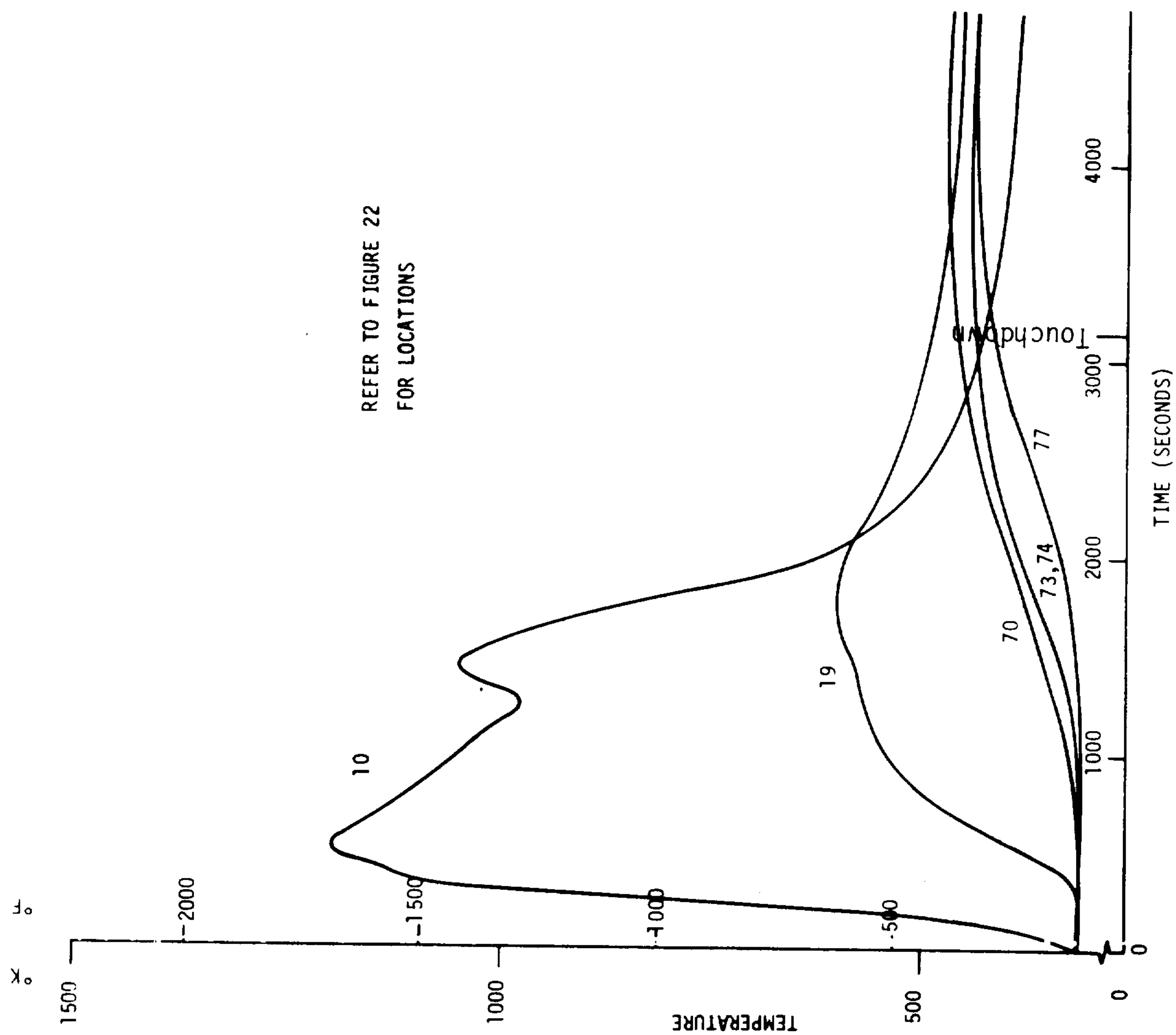


Figure 23c. Temperature Histories for Boron/Epoxy Composite - Detailed Design Thermal Analysis for 1255°K(1800°F) Entry Environment

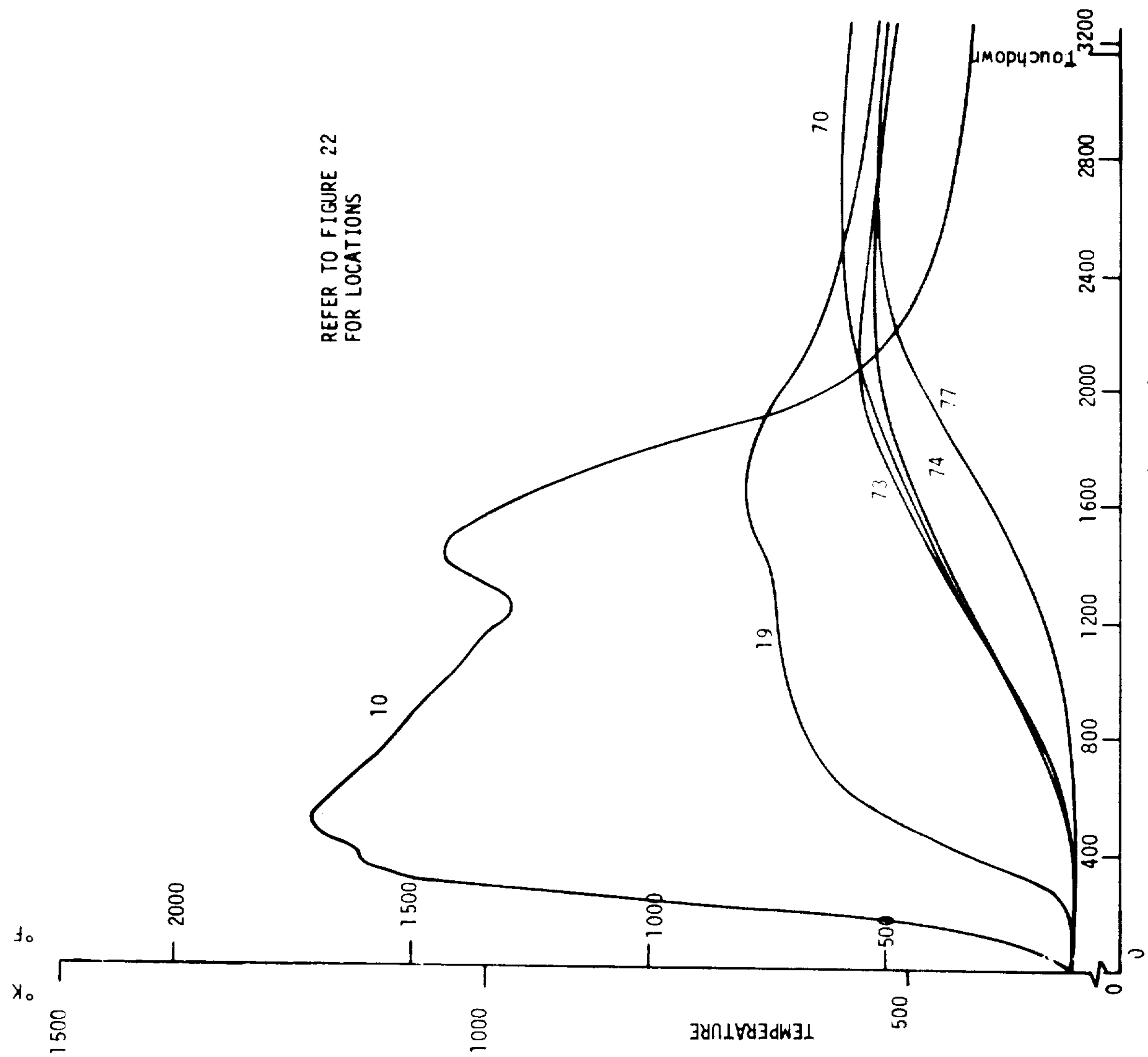


Figure 23d. Temperature Histories for Boron/Polyimide Composite-Detailed Design Thermal Analysis for 1255°K(1800°F) Entry Environment

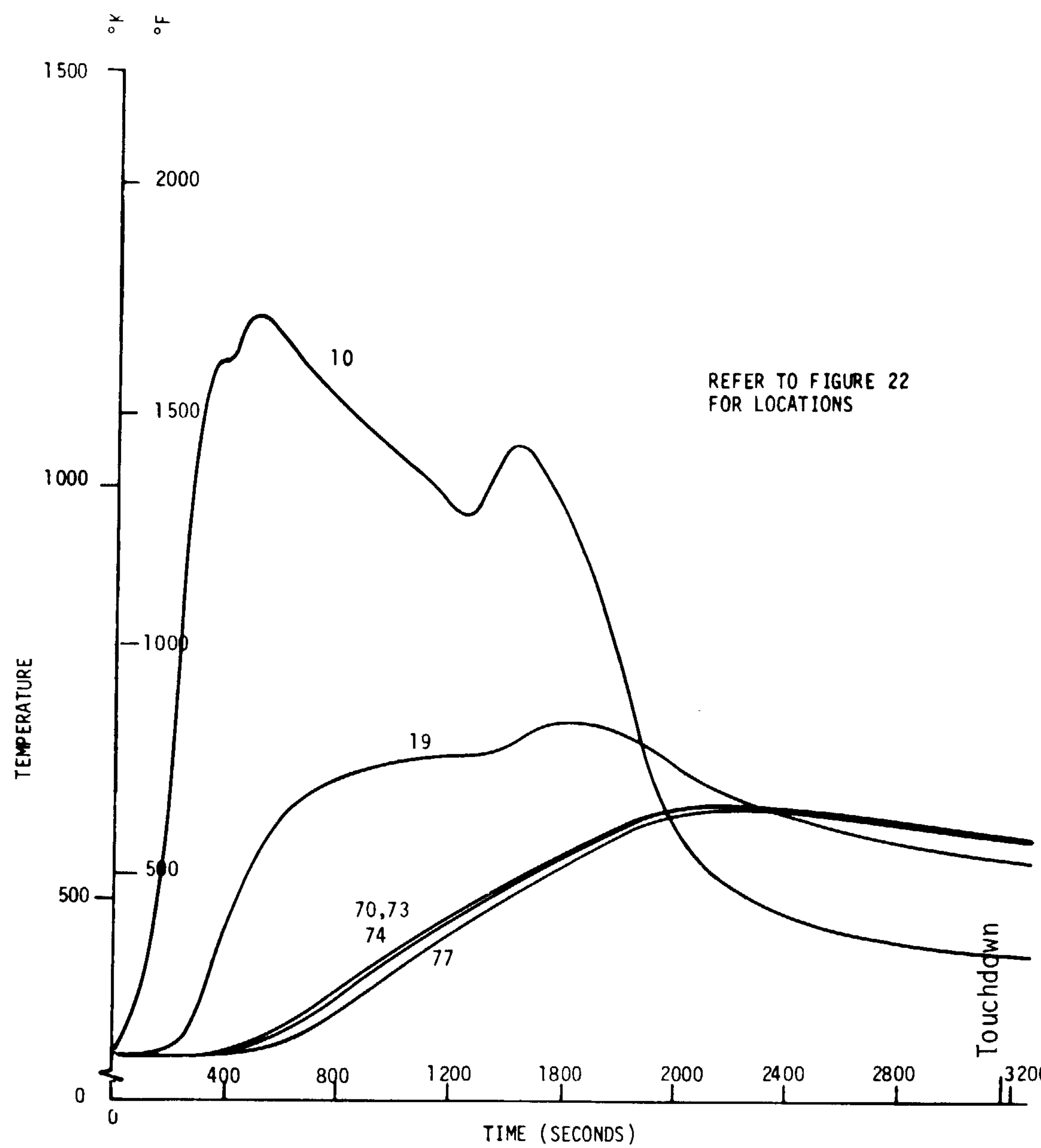


Figure 23e. Temperature Histories for Boron/Aluminum Composite - Detailed Design Thermal Analysis for 1255°K(1800°F) Entry Environment

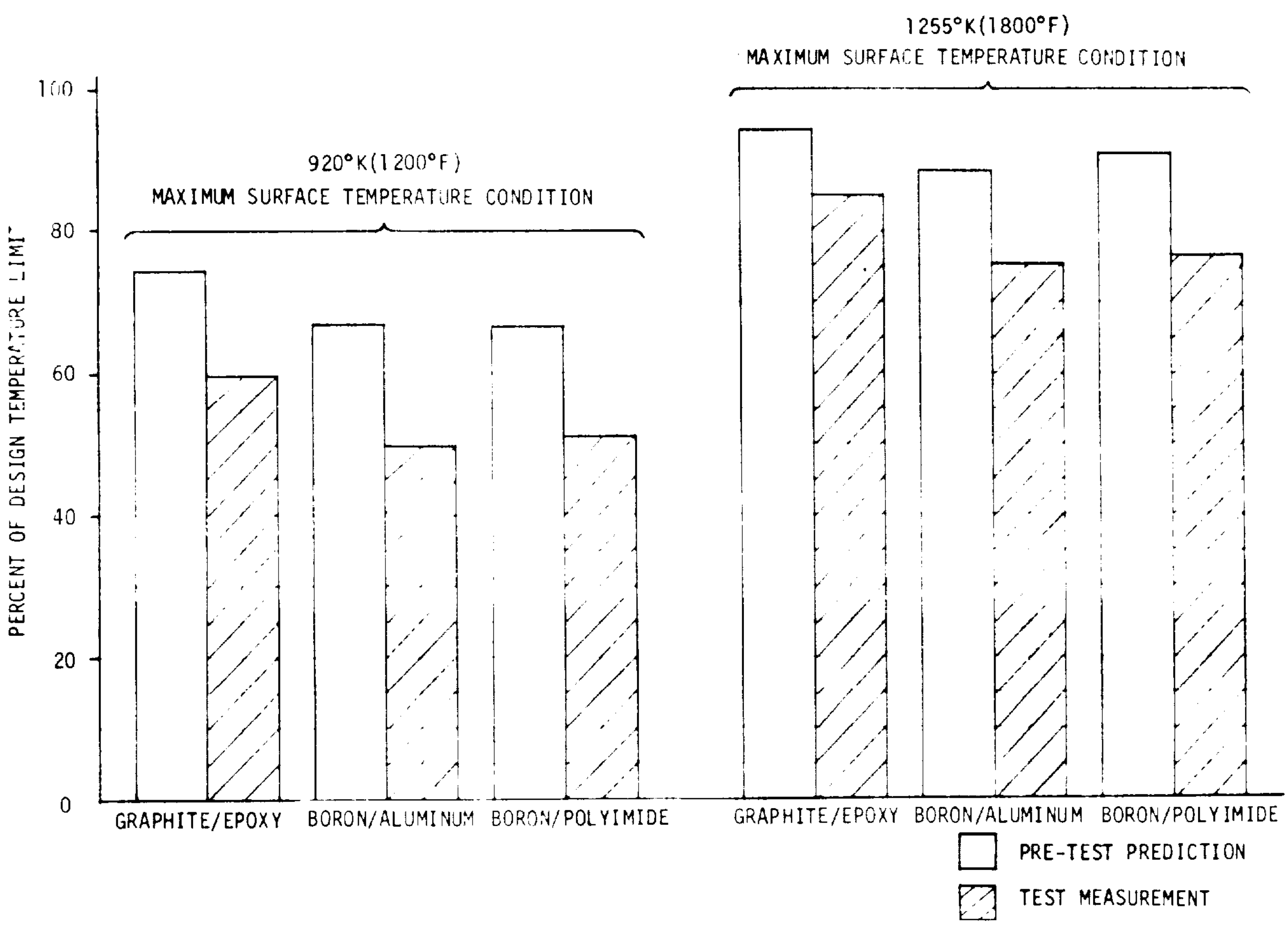


Figure 24. Comparison of Pre-Test Predicted and Measured Composite Thermal Environments for 920°K and 1255°K (1200°F and 1800°F) Maximum Surface Temperature Test Exposures

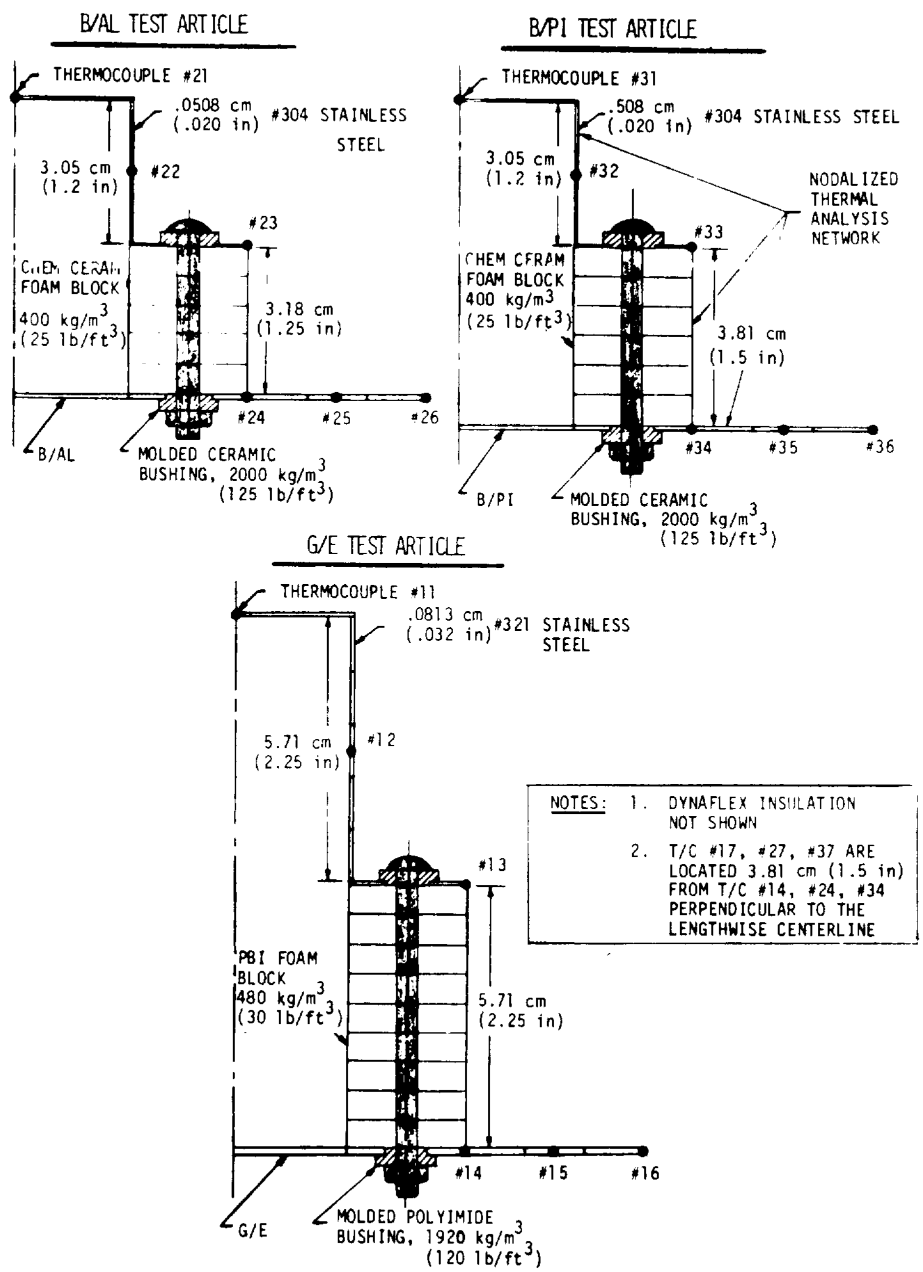


Figure 25. Test Article Assembly/Instrumentation/
Thermal Analysis Model

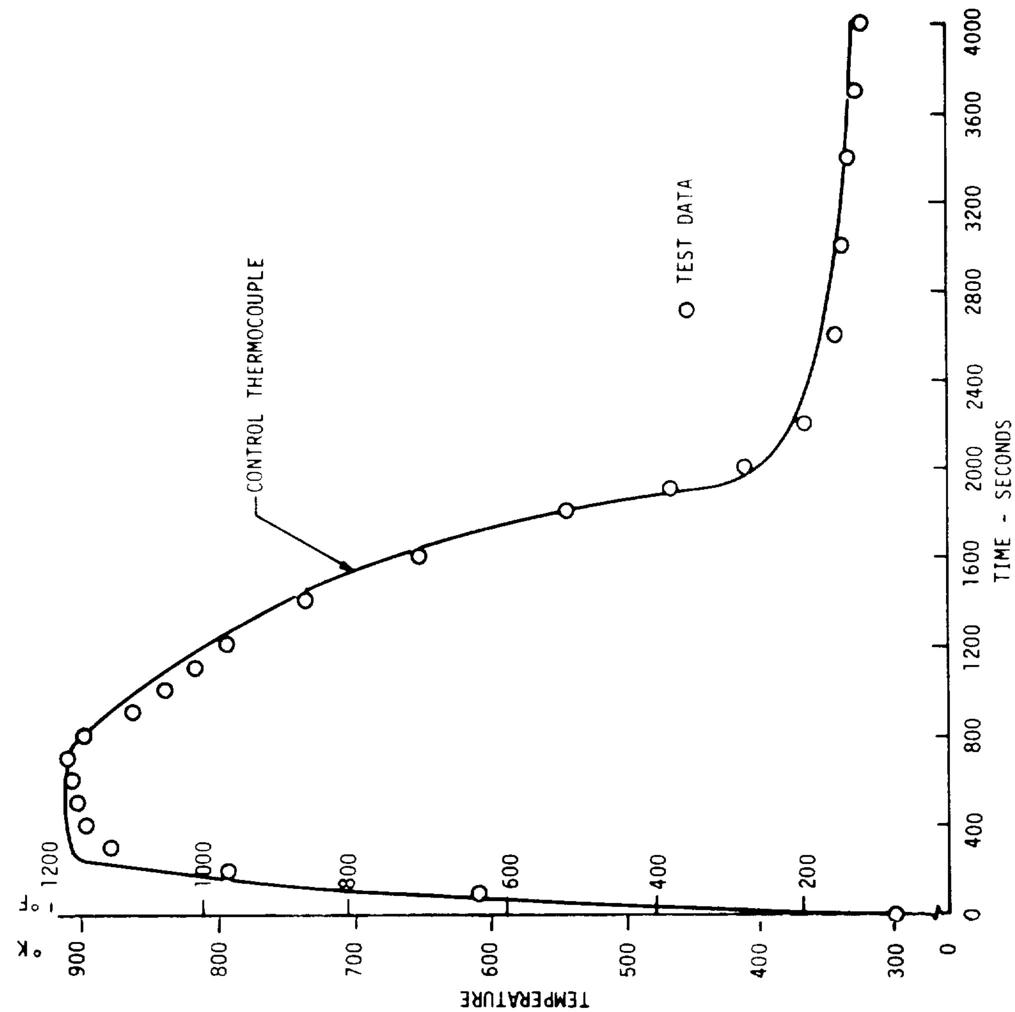


Figure 26a. COMPARISON OF PLANNED AND MEASURED CONTROL THERMOCOUPLE RESPONSE – 920°K (1200°F) TEST ENVIRONMENT

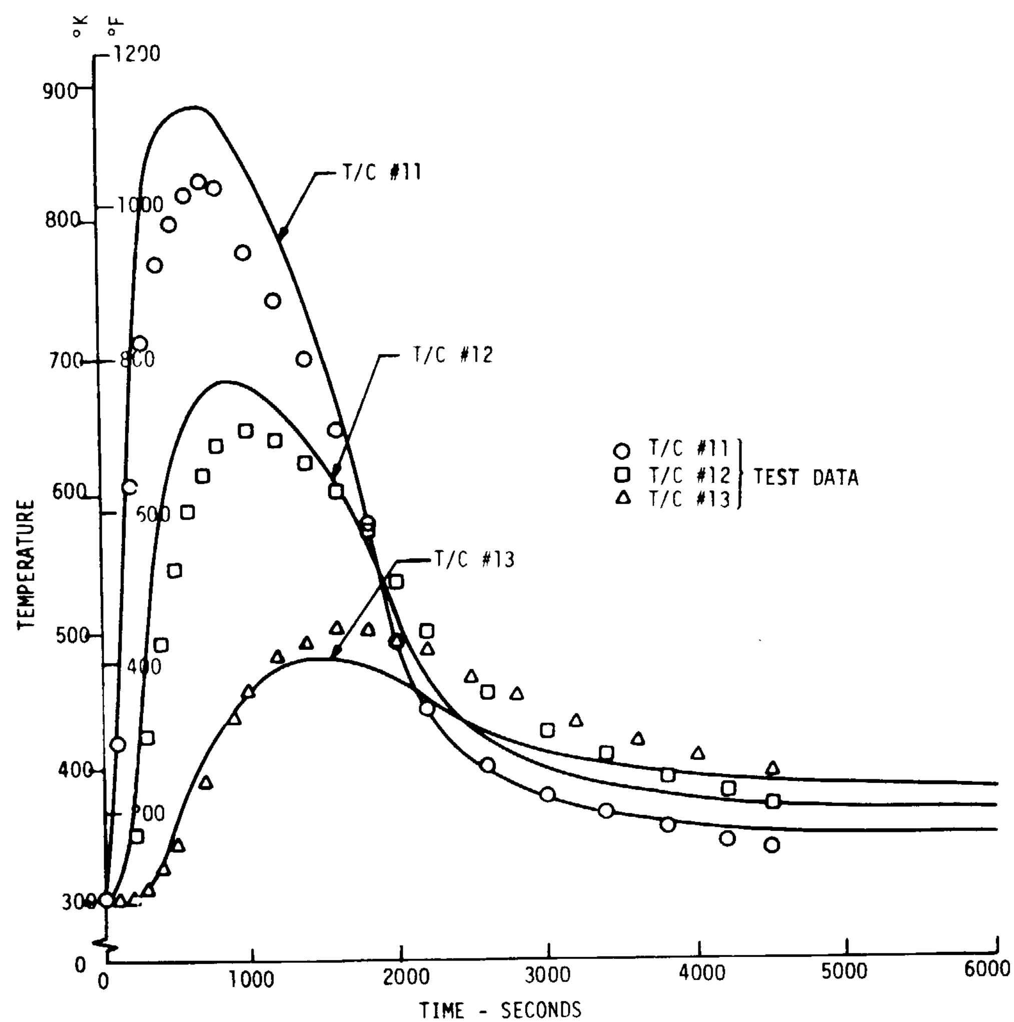


Figure 26b. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF STANDOFF THERMAL RESPONSE TO 920°K (1200°F) TEST ENVIRONMENT - G/E TEST ARTICLE

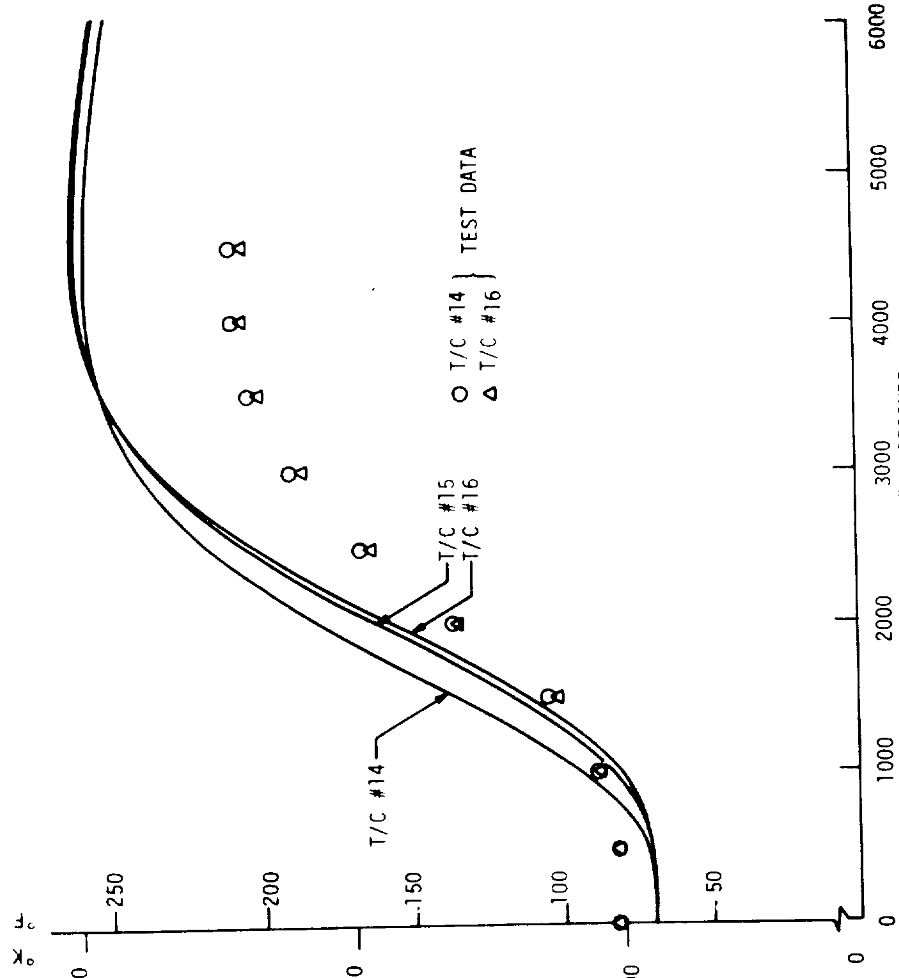


Figure 26c. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF G/E COMPOSITE PANEL THERMAL RESPONSE TO 920°K (1200°F) TEST ENVIRONMENT

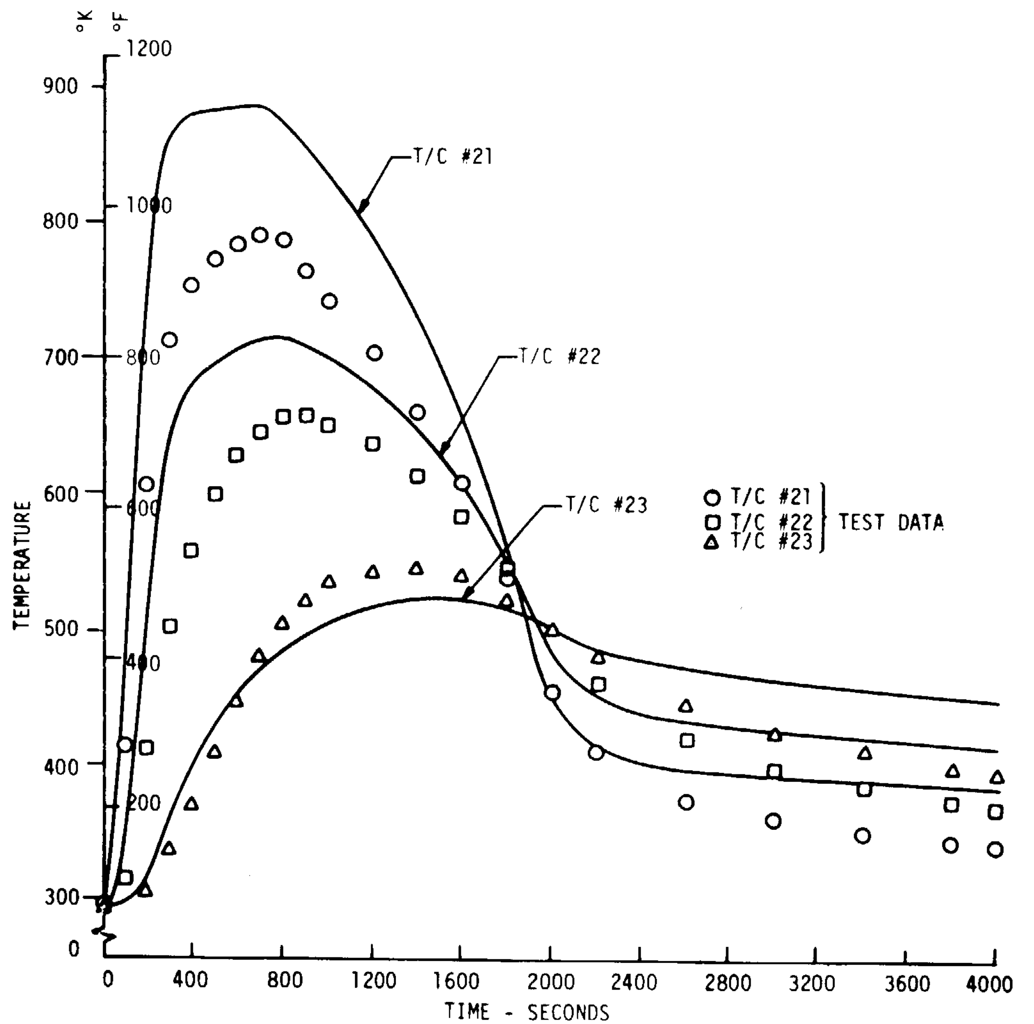


Figure 26d. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF STANDOFF THERMAL RESPONSE TO 920°K (1200°F) TEST ENVIRONMENT - B/Al TEST ARTICLE

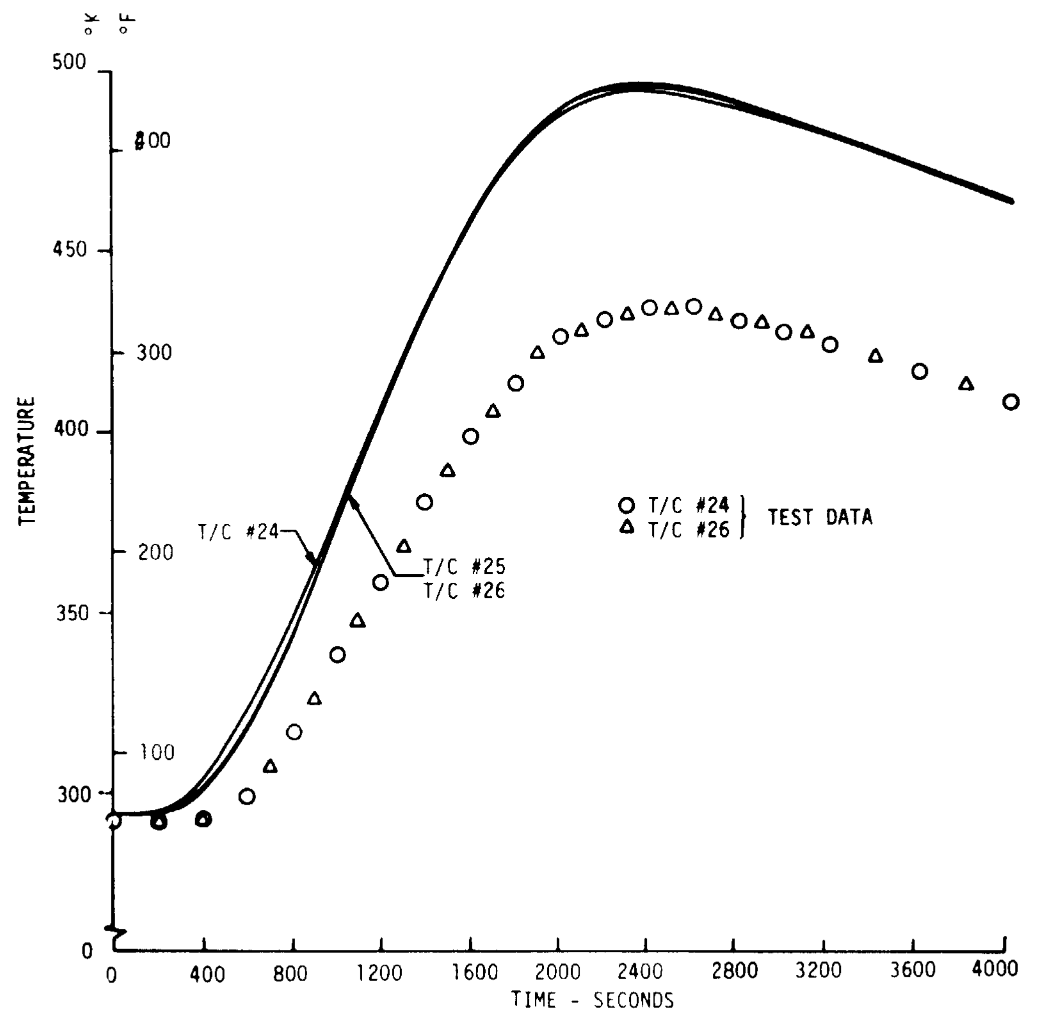


Figure 26e. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF B/Al COMPOSITE PANEL THERMAL RESPONSE TO 920°K (1200°F) TEST ENVIRONMENT

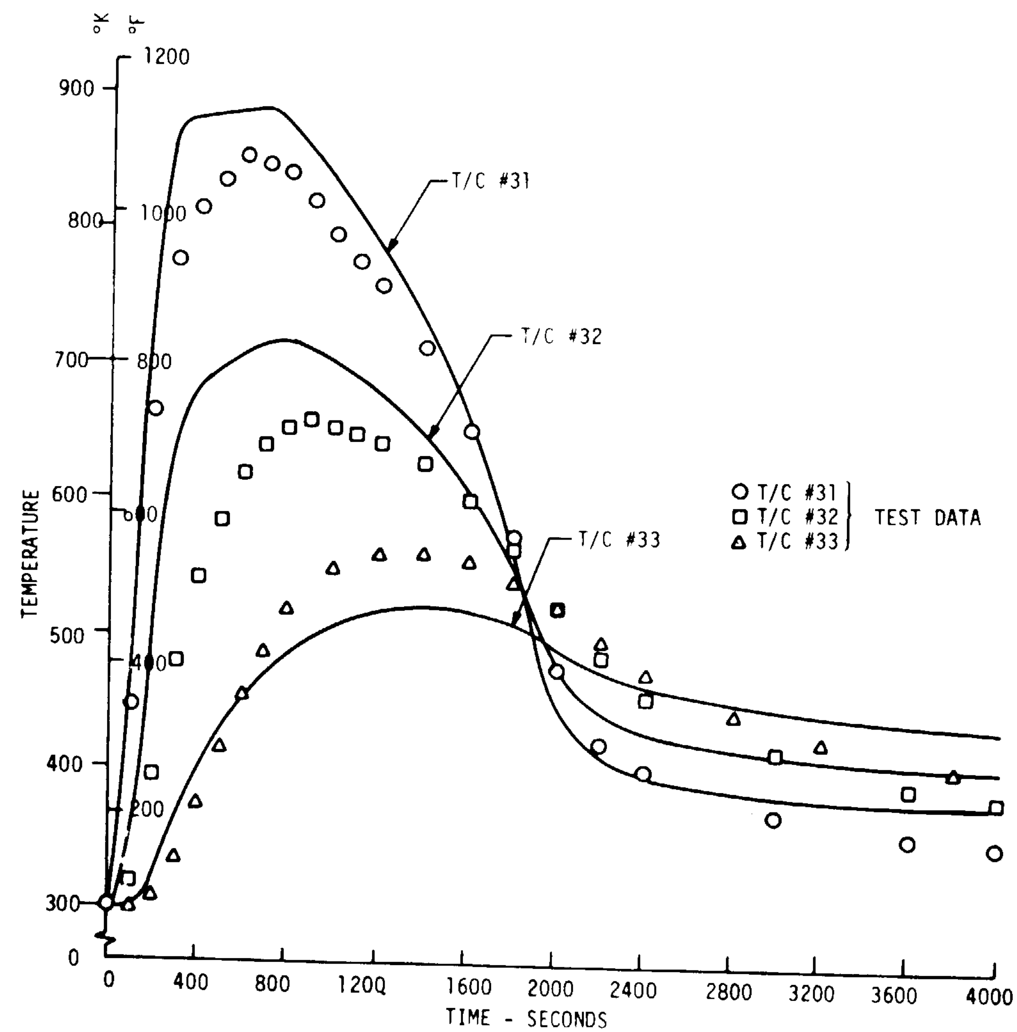


Figure 26f. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF STANDOFF THERMAL RESPONSE TO 920°K (1200°F) TEST ENVIRONMENT - B/PI TEST ARTICLE

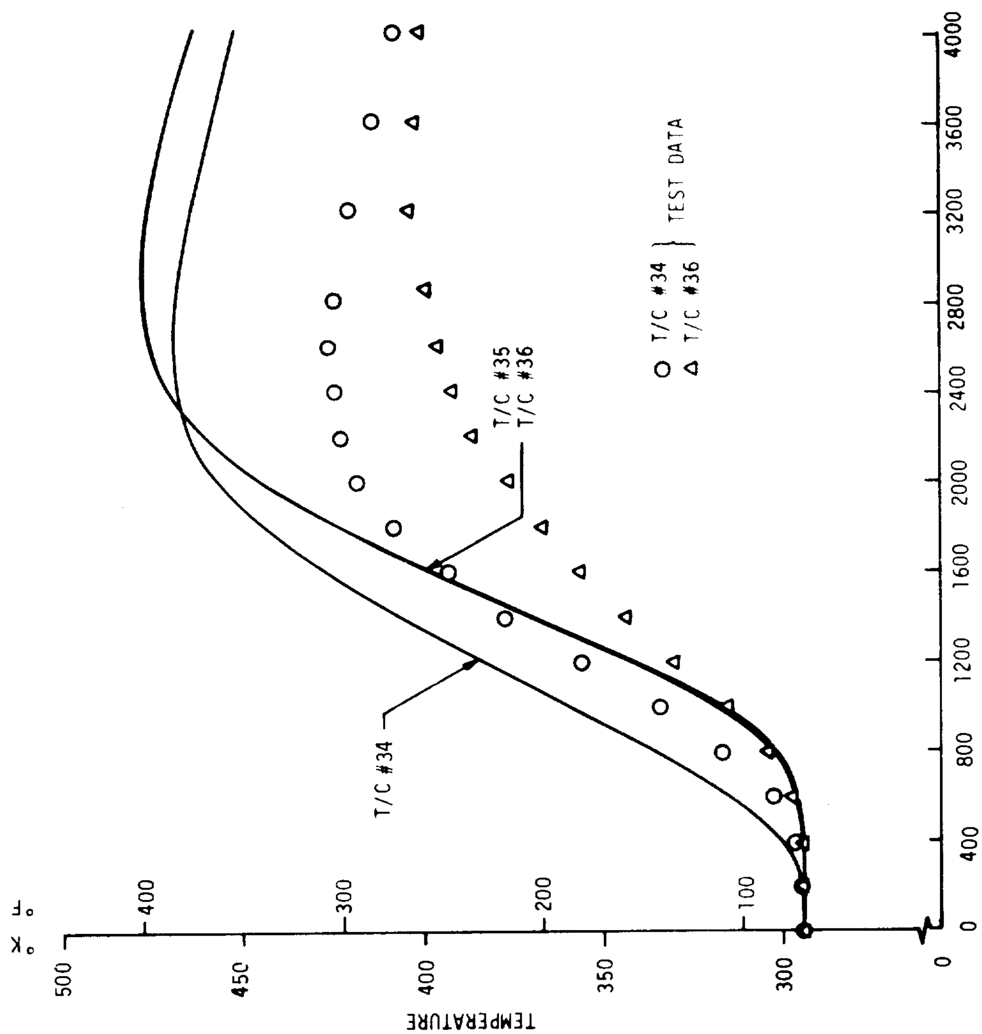


Figure 26g. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF B/PI COMPOSITE PANEL THERMAL RESPONSE TO 920°K (1200°F) TEST ENVIRONMENT

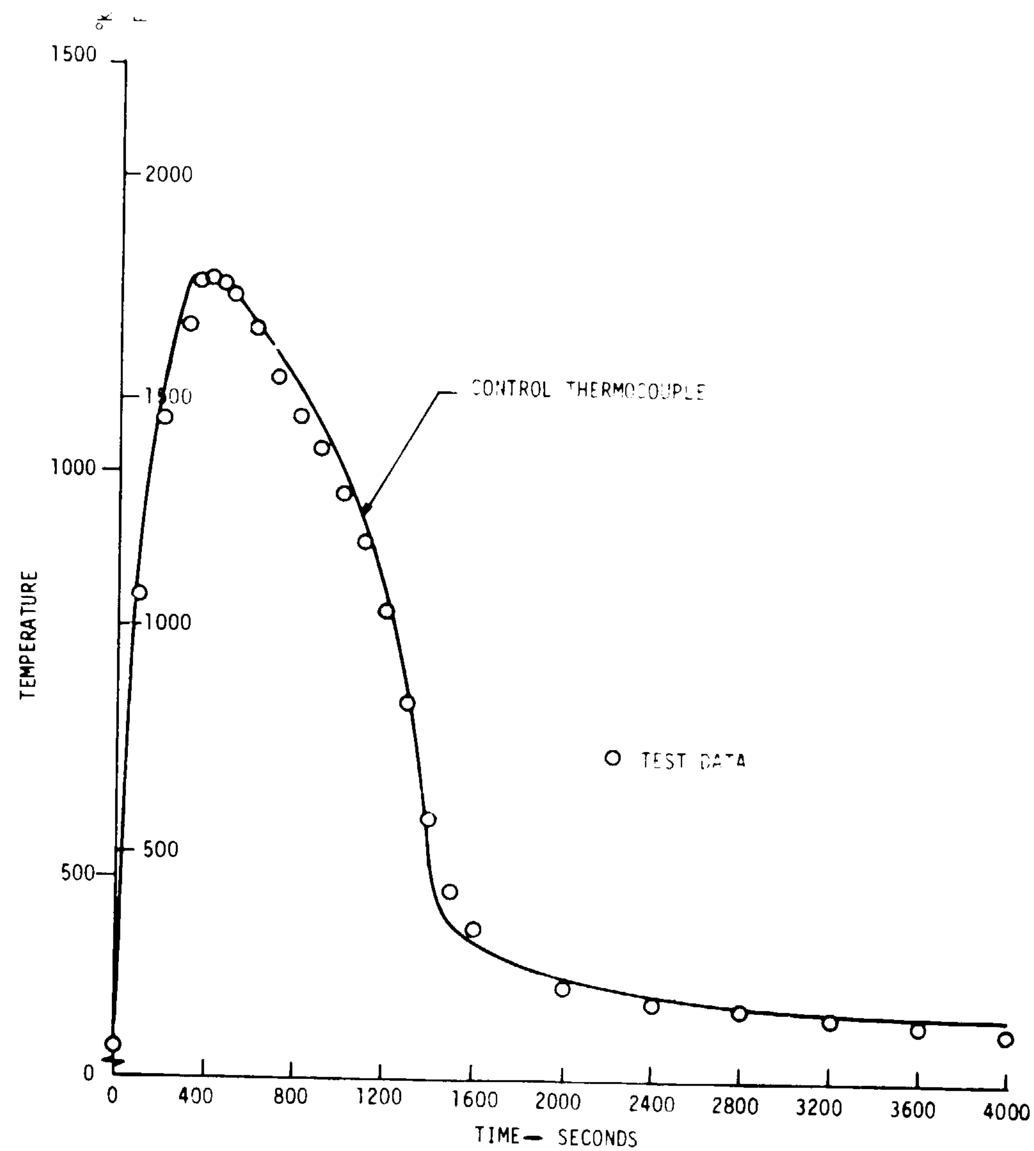


Figure 27a. COMPARISON OF PLANNED AND MEASURED CONTROL THERMOCOUPLE RESPONSE - 1255°K (1800°F) TEST ENVIRONMENT

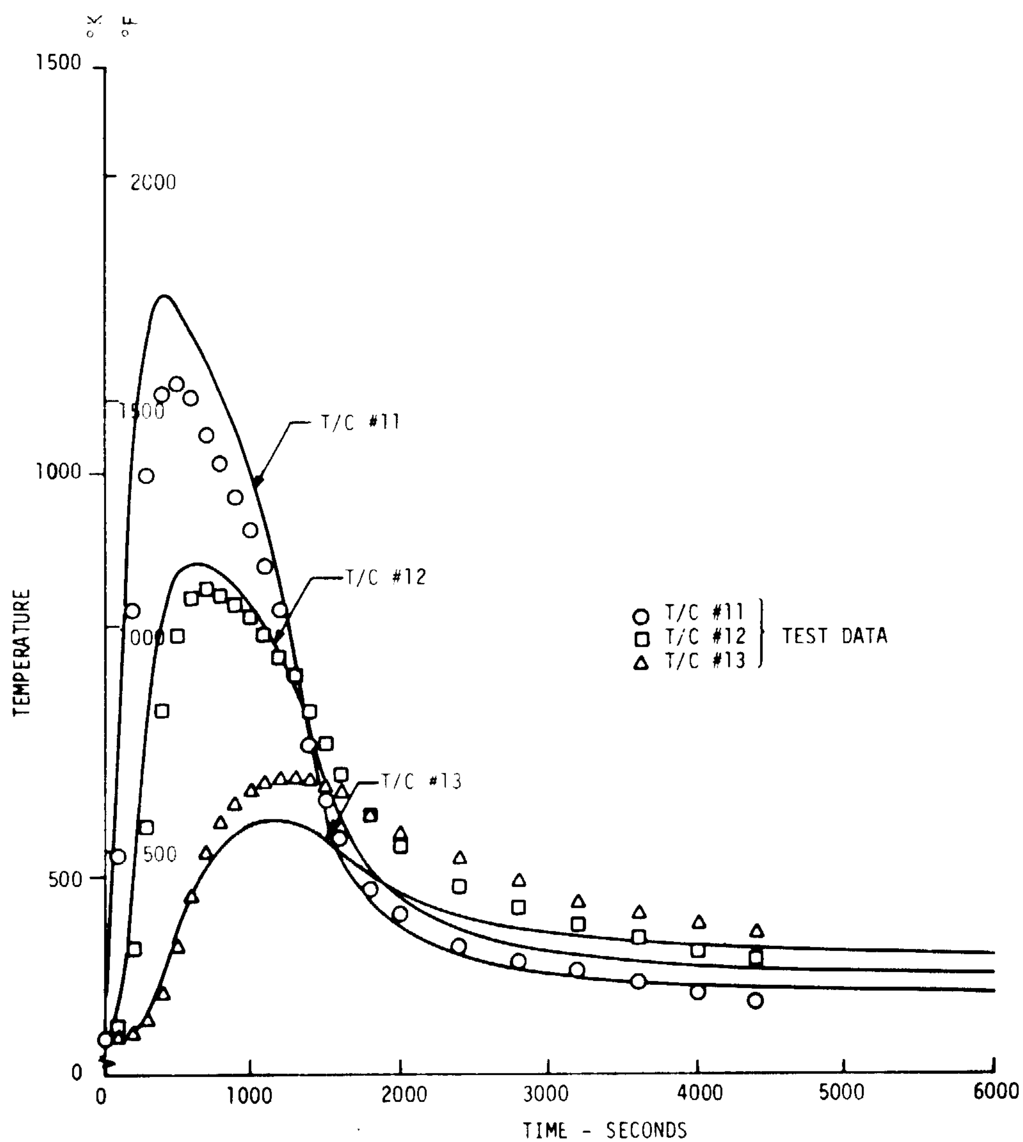


Figure 27b. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF STANDOFF THERMAL RESPONSE TO 1255°K (1800°F) TEST ENVIRONMENT - G/E TEST ARTICLE

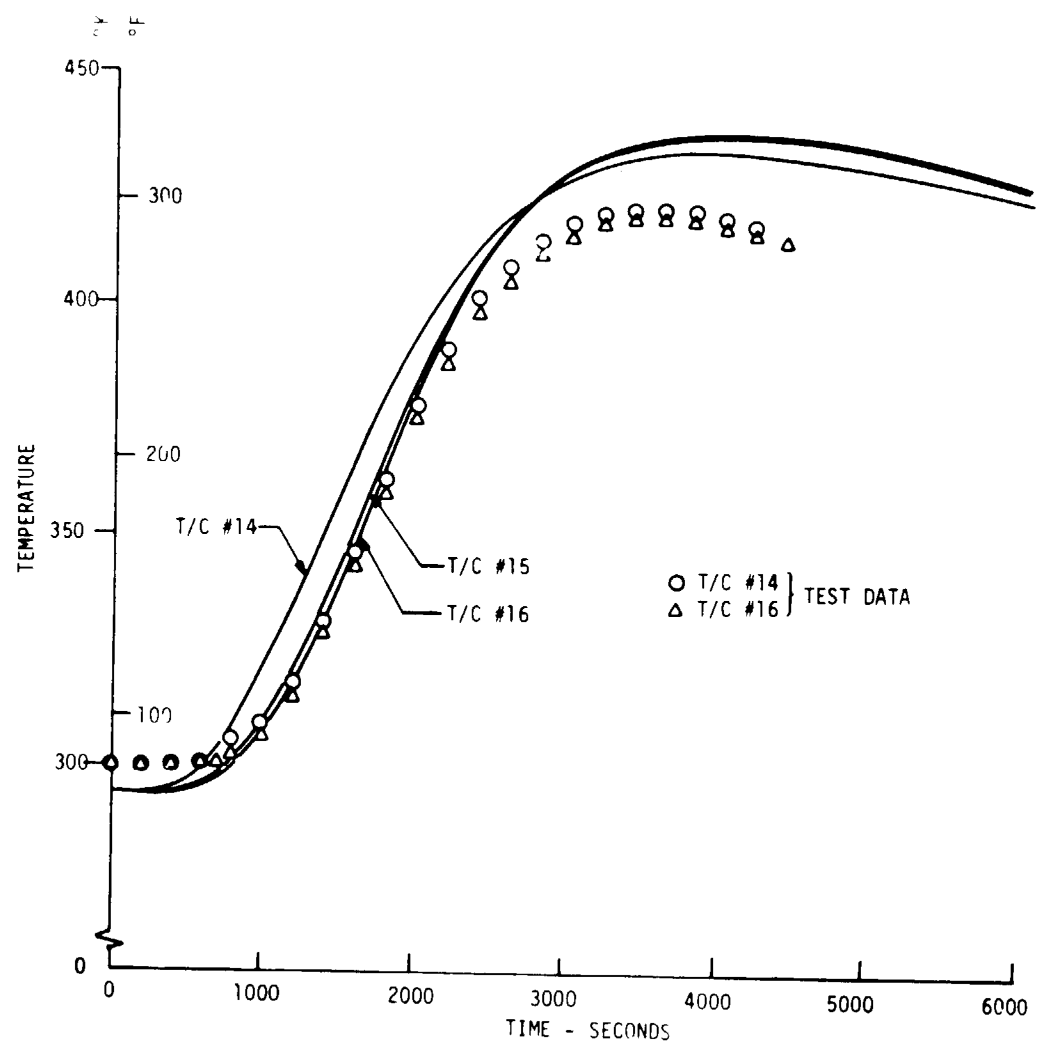


Figure 27c. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF G/E COMPOSITE PANEL THERMAL RESPONSE TO 1255°K (1800°F) TEST ENVIRONMENT

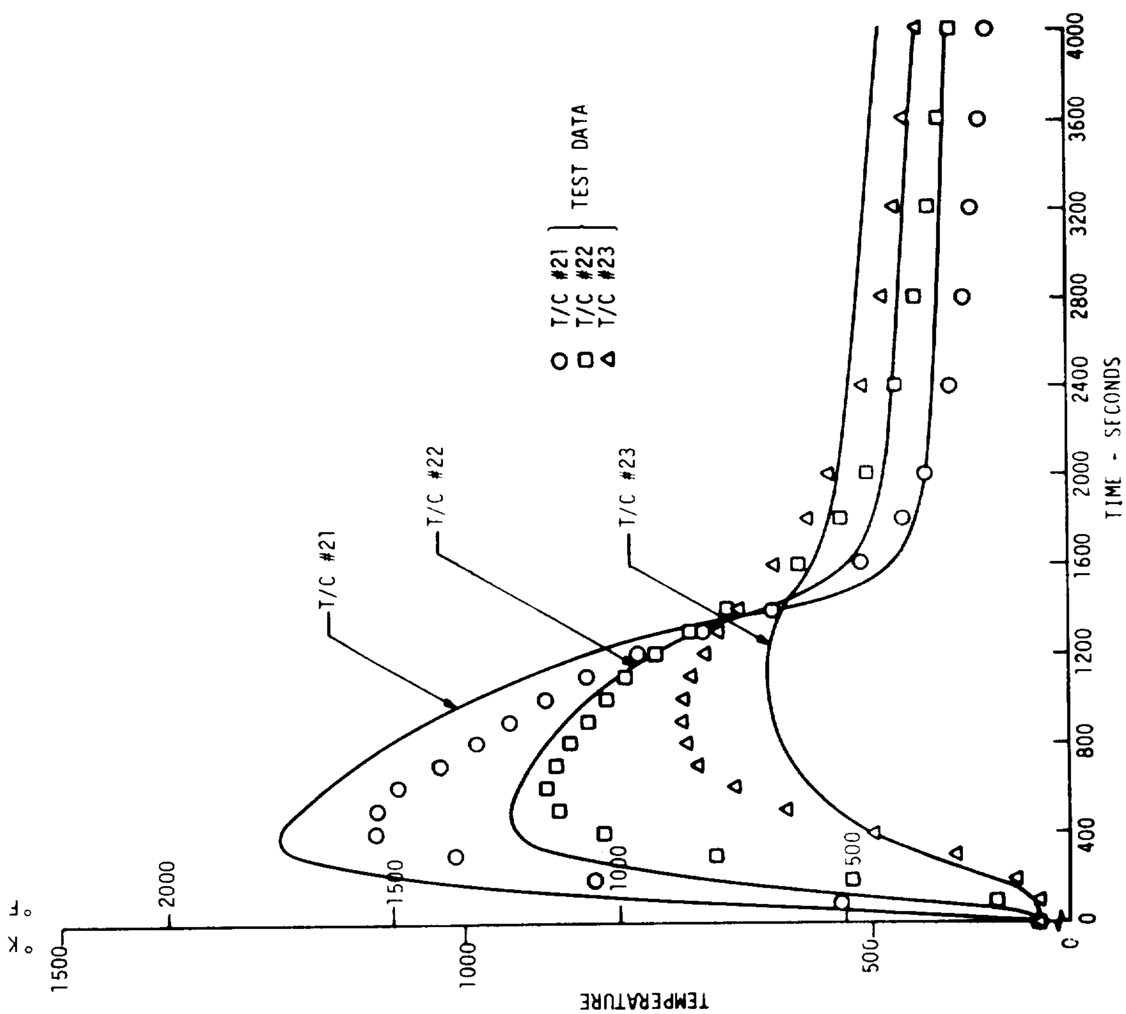


Figure 27d. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF STANDOFF THERMAL RESPONSE TO 1255°K (1800°F) TEST ENVIRONMENT - B/Al TEST ARTICLE

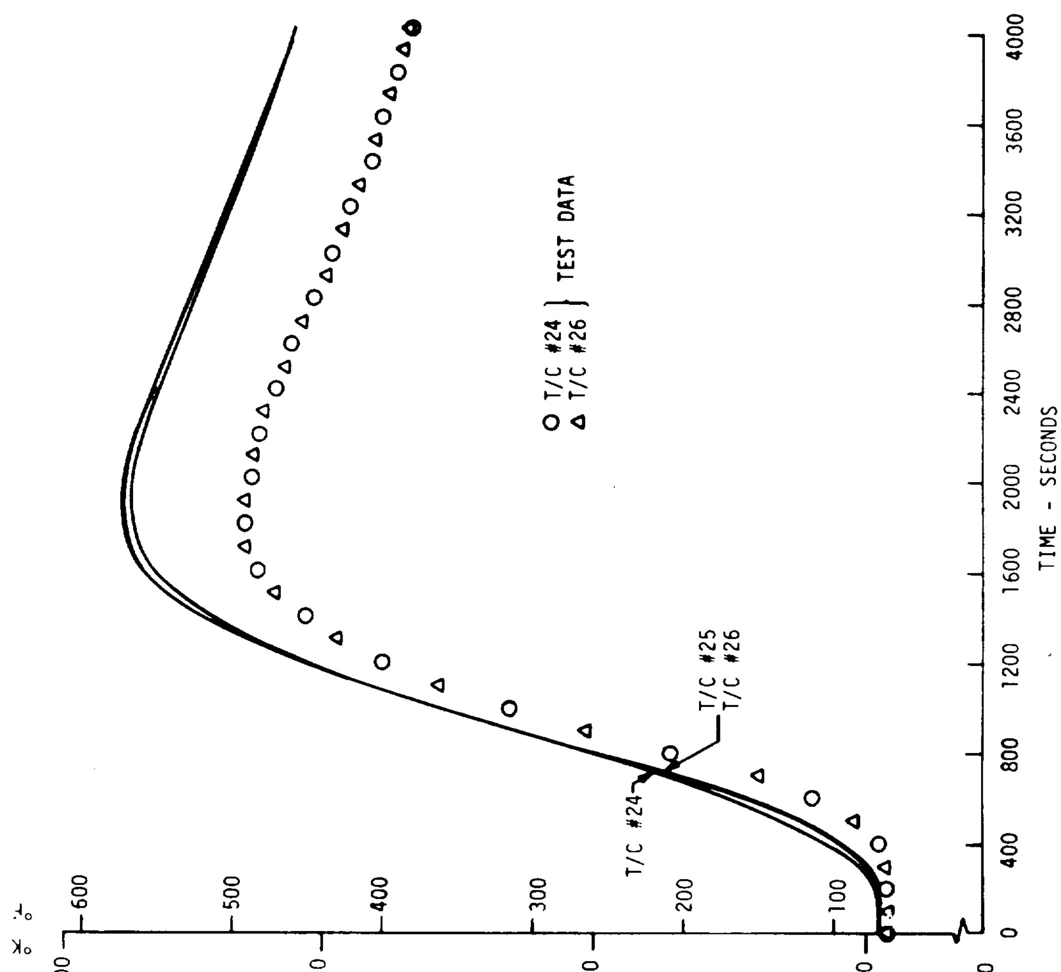


Figure 27e. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF B/Al COMPOSITE PANEL THERMAL RESPONSE TO 1255°K (1800°F) TEST ENVIRONMENT

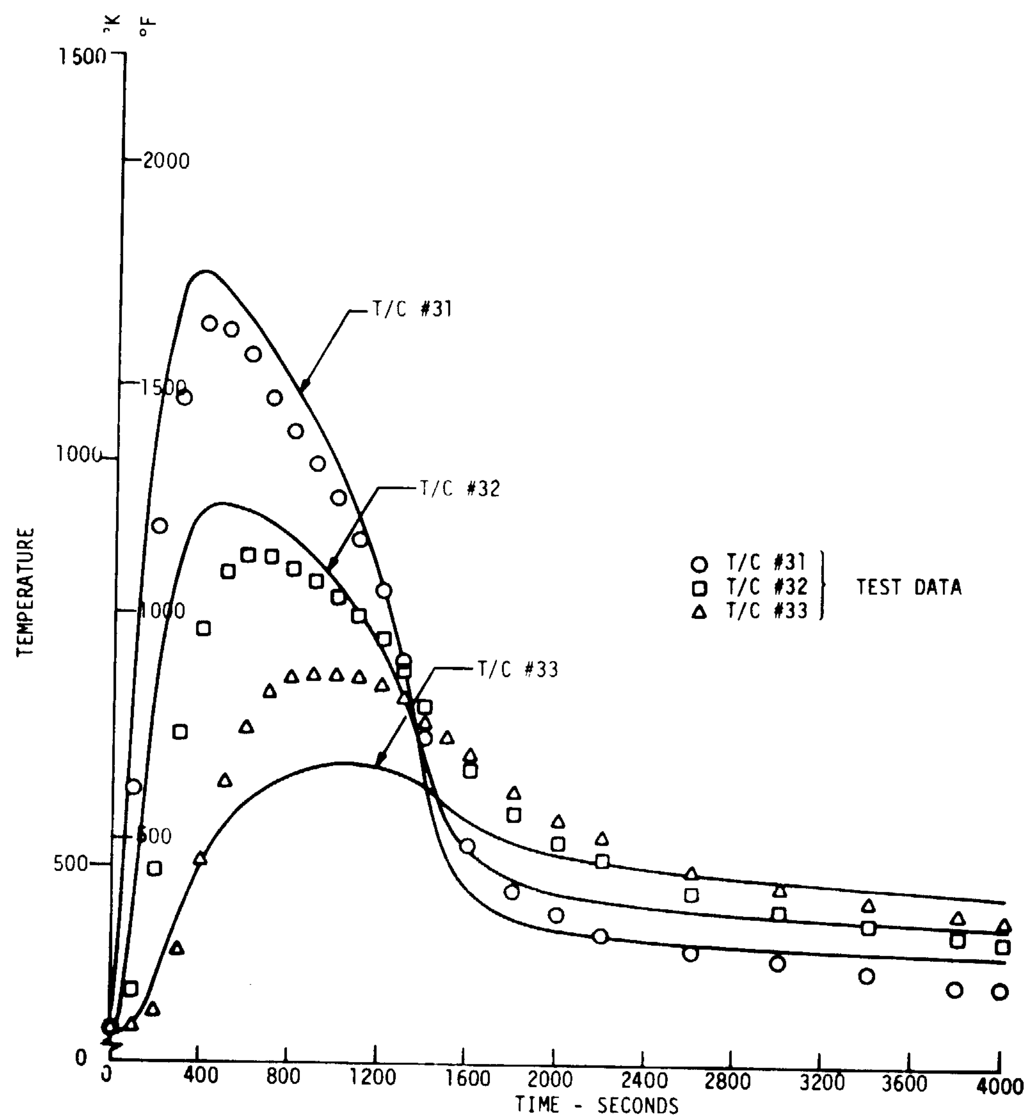


Figure 27f. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF STANDOFF THERMAL RESPONSE TO 1255°K (1800°F) TEST ENVIRONMENT - B/PI TEST ARTICLE

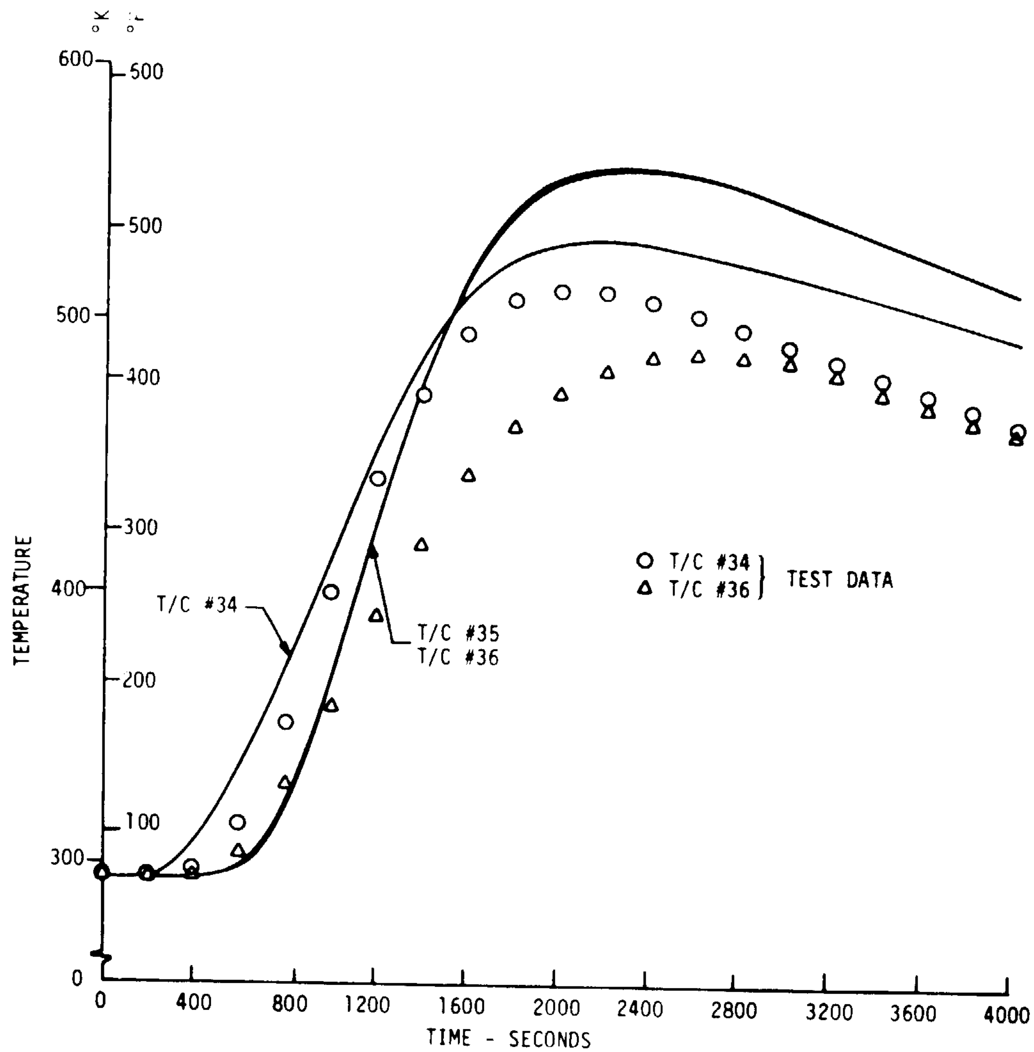


Figure 27g. COMPARISON BETWEEN PRETEST PREDICTION AND TEST MEASUREMENT OF B/PI COMPOSITE PANEL THERMAL RESPONSE TO 1255°K (1800°F) TEST ENVIRONMENT

TABLE I

THERMOPHYSICAL PROPERTIES DATA AVAILABILITY

FILAMENTARY REINFORCED ADVANCED COMPOSITES

PROPERTY	REFERENCE NO.					
	B/E	G/E	B/PI	G/PI	B/Al	OTHER RELATED
Test Data						
k	2, 3, 4, 5,	6, 7				8
C_p	3, 4, 5, 9	9				
α	2, 3, 4, 5	6, 9, 10, 11 12, 13	14	15	16, 17	
Analytical Models						
k	18					
α						19

TABLE II

THERMOPHYSICAL DESIGN VALUES OF ADVANCED COMPOSITES

PSEUDO-ISOTROPIC ARRAYS

MATERIAL SYSTEM	DENSITY kg/m^3 (lb/in^3)	MAXIMUM TEMPERATURE CAPABILITY °K (°F)	CONDUCTIVITY W/m-°K (Btu/Ft-hr-°F) 172°K(-150°F) TO RT	CONDUCTIVITY RT TO MAX. TEMP.	SPECIFIC HEAT kJ/kg-°K (Btu/lb-°F) 172°K(-150°F) TO RT	SPECIFIC HEAT RT TO MAX. TEMP	EXPANSION COEFFICIENT x 10^6 cm/cm/°K (in/in/°F) 172°K(-150°F) TO RT	EXPANSION COEFFICIENT RT TO MAX. TEMP.
B/E	1,995 (.072)	450 (350)	1.125 (.65)	1.225 (.708)	.965 (.23)	1.26 (.30)	4.68 (2.6)	6.3 (3.5)
G/E	1,550 (.056)	450 (350)	4.54 (2.62)	7.6 (4.39)	.63 (.15)	1.09 (.26)	0 (0)	0 (0)
B/PI	2,050 (.074)	590 (600)	1.125 (.65)	1.225 (.708)	.965 (.23)	1.26 (.30)	4.68 (2.6)	6.3 (3.5)
G/PI	1,605 (.058)	590 (600)	4.54 (2.62)	7.6 (4.39)	.63 (.15)	1.09 (.26)	0 (0)	0 (0)
B/Al	2,660 (.096)	617 (650)	44.8 (25.9)	44.8 (25.9)	.965 (.23)	.965 (.23)	4.5 (2.5)	6.3 (3.5)

TABLE III CONCEPT MATRIX

Environment / Composite	HAT-TYPE STAND-OFFS: Stand-Off Only	Isolators	Comp. Panel Heat Sink	Isolators/Heat Sink	Solid/Solid PCM	Solid/Liquid PCM	Isolators/PCM	Isolators/Heat Sink/PCM	Multi-Metal/Isolators	MM/Isolators/Heat Sink	MM/Solid/Solid PCM	MM/Solid/Liquid PCM	MM/Isolators/PCM	Active Cooling	Active Cooling/Isolators	SINE-WAVE STAND-OFFS: Stand-Off Only	Isolators	Comp. Panel Heat Sink	Isolators/Heat Sink	Solid/Solid PCM	Solid/Liquid PCM	Isolators/PCM	POST STAND-OFFS: Stand-Off Only	Isolators	Comp. Panel Heat Sink	Isolators/Heat Sink	Solid/Solid PCM	Solid/Liquid PCM	Isolators/PCM	Solid/Liquid PCM/Comp. Stand-Off
1645°K(2500°F) G/E		14a		14a	14a				14a	14a	14a	14b					15a	15a						16			16			17
1645°K(2500°F) B/E					14c					14b	14b		14b		14b		15a							16			16			17
1255°K(1800°F) G/E		14c	14c		14c		14c							14c		15a								16						17
1255°K(1800°F) B/E		14c	14d		14d		14d							14d			15a	15b		15b				16						17
1645°K(2500°F) G/PI		14d			14d																									
1645°K(2500°F) B/PI		14e																		15b										
1645°K(2500°F) B/AT		14e			14e																									
920°K(1200°F) B/PI		14e																												
920°K(1200°F) B/AT																15b														

TABLE IV WEIGHT COMPARISON OF TEMPERATURE SUPPRESSION CONCEPTS

MAXIMUM SURFACE TEMPERATURE °K (°F)	STANDOFF DESIGN	COMPOSITE STRUCTURE		TEMPERATURE SUPPRESSION		Δ UNIT WEIGHT* kg/m^2 (lb/ft^2)	REMARKS
		MATERIAL	MAX. TEMP. °K (°F)	CONCEPT	MATERIAL		
1645 (2500)	HAT SECTION	G/E	450 (350)	Isolators	Marinite-23	0.322 (0.066)	
					Syntactic PBI	0.42 (0.086)	
					Transite	1.8 (0.368)	
					Pyroceram	4.71 (0.965)	
				PCM	Solid/Solid (Polyethylene)	0.944 (0.193)	
					Solid/Liquid (Durene)	1.37 (0.28)	Requires Container
				Active Cooling	Coolant/H_2O Heat Exchanger	0.318 (0.065)	H_2O + Coolant Only
1645 (2500)	HAT SECTION	G/PI	590 (600)	Isolators	Marinite-23	0.194 (0.0396)	
					Syntactic PBI	0.252 (0.0515)	
					Transite	1.085 (0.222)	
					Pyroceram	2.82 (0.578)	
				PCM	Solid/Solid	0.572 (0.117)	
					Solid/Liquid	0.855 (0.175)	Requires Container
				Active Cooling	Coolant/H_2O Heat Exchanger	0.293 (0.06)	H_2O+Coolant Only

*Unit Weight Based on Composite Panel Area

TABLE IV WEIGHT COMPARISON OF TEMPERATURE SUPPRESSION CONCEPTS (CONTINUED)

MAXIMUM SURFACE TEMPERATURE °K (°F)	STANDOFF DESIGN	COMPOSITE STRUCTURE		TEMPERATURE SUPPRESSION		Δ UNIT WEIGHT* kg/m² (lb/ft²)	REMARKS
		MATERIAL	MAX. TEMP. °K (°F)	CONCEPT	MATERIAL		
1645 (2500)	HAT SECTION	B/Al	617 (650)	Isolators	Marinite-23 Syntactic PBI Transite Pyroceram	0.141 (0.0289) 0.184 (0.0376) 0.792 (0.162) 2.05 (0.42)	
				PCM	Solid/Solid Solid/Liquid	0.625 (0.128) 0.963 (0.197)	Requires Container
				Active Cooling	Coolant/H_2O Heat Exchanger	0.328 (0.067)	H_2O + Coolant Only
1255 (1800)	HAT SECTION	G/E	450 (350)	Isolators	Marinite-23 Syntactic PBI Transite Pyroceram	0.258 (0.0528) 0.336 (0.0688) 1.45 (0.297) 3.76 (0.77)	
				Heat Sink	Copper Beryllium	19.0 (3.89) 4.22 (0.865)	
				PCM	Solid/Solid Solid/Liquid	0.363 (0.0743) 0.524 (0.107)	Requires Container
				Active Cooling	Coolant/H_2O Heat Exchanger	0.1935(0.0396)	H_2O + Coolant Only

*Unit Weight Based on Composite Panel Area

TABLE IV WEIGHT COMPARISON OF TEMPERATURE SUPPRESSION CONCEPTS (CONTINUED)

MAXIMUM SURFACE TEMPERATURE °K (°F)	STANDOFF DESIGN	COMPOSITE STRUCTURE		TEMPERATURE SUPPRESSION		Δ UNIT WEIGHT* kg/m² (lb/ft²)	REMARKS
		MATERIAL	MAX. TEMP. °K (°F)	CONCEPT	MATERIAL		
1255 (1800)	HAT SECTION	G/PI	590 (600)	Isolators	Marinite-23 Syntactic PBI Transite Pyroceram	0.09 (0.0184) 0.117 (0.0239) 0.504 (0.103) 1.32 (0.270)	
				Heat Sink	Copper Beryllium	4.22 (0.865) 0.939 (0.192)	
				PCM	Solid/Solid Solid/Liquid	0.202 (0.0412) 0.306 (0.0627)	Requires Container
1255 (1800)	HAT SECTION	B/Al	617 (650)	Isolators	Marinite-23 Syntactic PBI Transite Pyroceram	0.0391 (0.008) 0.0509 (0.0104) 0.218 (0.0445) 0.572 (0.117)	
				Heat Sink	Copper Beryllium	2.52 (0.515) 0.562 (0.115)	
				PCM	Solid/Solid Solid/Liquid	0.202 (0.0412) 0.314 (0.0644)	Requires Container

*Unit Weight Based on Composite Panel Area

TABLE IV. WEIGHT COMPARISON OF TEMPERATURE SUPPRESSION CONCEPTS (CONTINUED)

MAXIMUM SURFACE TEMPERATURE °K (°F)	STANDOFF DESIGN	COMPOSITE STRUCTURE		TEMPERATURE SUPPRESSION		UNIT WEIGHT* kg/m² (lb/ft²)	REMARKS
		MATERIAL	MAX TEMP °K (°F)	CONCEPT	MATERIAL		
1645 (2500)	SINE WAVE	G/E	450 (350)	Isolators	Marinite-23	0.0398 (0.00815)	
					Syntactic PBI	0.0519 (0.0106)	
					Transite	0.224 (0.0457)	
					Pyroceram	0.581 (0.119)	
				Heat Sink	Copper	13.2 (2.71)	
					Beryllium	2.93 (0.60)	
				PCM	Solid/Solid	0.166 (0.034)	
					Solid/Liquid	0.238 (0.0486)	Requires Container

*Unit weight based on composite panel area.

TABLE V RELATIVE RATING OF TEMPERATURE SUPPRESSION CONCEPTS[1]

TEMPERATURE SUPPRESSION CONCEPT	RELATIVE WEIGHT	DESIGN SIMPLICITY	RELATIVE COST	TECHNOLOGY STATUS
Isolator	3	3	3	3
Heat Sink	1	3	2	3
Phase Change Material	2	2	2	2
Multi-metal Standoff/Isolator[2]	3	1	1	2
Active Cooling	1	1	1	2[3]

Rating System
1 - poor
2 - fair
3 - good

(1) Applicable to 1255°K (1800°F) and 1645°K (2500°F) maximum surface temperature environments
(2) Applicable only to max. surface temperature environments where Columbium standoff would be considered.
(3) Technology status rating lower for cooling the high temperature capability structures.

TABLE VI. TPS INSULATION/STANDOFF/ISOLATOR DESIGN DIMENSIONS
FROM DETAILED DESIGN ENTRY THERMAL ANALYSES

MAXIMUM SURFACE TEMPERATURE	STANDOFF		COMPOSITE STRUCTURE[1]		FIBROUS[2] INSULATION THICKNESS cm (in.)	ISOLATOR THICKNESS[3] cm (in.)
	DESIGN	HEIGHT cm (in.)	MATERIAL	MAX TEMP °K (°F)		
1255°K (1800°F)	Hat Section (Haynes 188)	6.85 (2.7)	G/E	450 (350)	5.59 (2.2)	5.71 (2.25)
		4.31 (1.7)	G/PI	590 (600)	3.05 (1.2)	3.81 (1.5)
		7.10 (2.8)	B/E	450 (350)	5.84 (2.3)	5.71 (2.25)
		4.57 (1.8)	B/PI	590 (600)	3.30 (1.3)	3.81 (1.5)
		4.06 (1.6)	B/AI	617 (650)	2.79 (1.1)	3.18 (1.25)
1645°K (2500°F)	Hat Section (Cb 752)	9.90 (3.9)	G/E	450 (350)	8.64 (3.4)	7.36 (2.9)*
		6.60 (2.6)	G/PI	590 (600)	5.34 (2.1)	5.59 (2.2)*
	Sine Wave (Cb 752)	9.90 (3.9)	G/E	450 (350)	8.64 (3.4)	1.905 (0.75)*
		6.60 (2.6)	G/PI	590 (600)	5.34 (2.1)	0.508 (0.2)*

(1) Refer to Figure 21 for dimensions.

(2) 96 kg/m^3 (6 lb/ft^3) Dynaflex insulation.

(3) PBI foam for 450°K (350°F) structure isolators.
Chem Ceram for for 590°K (600°F) and 617°K (650°F) structure isolators.

*Estimated from parametric and detailed thermal analysis.

TABLE VII COMPARISON OF THE PRETEST PREDICTIONS & THERMOCOUPLE MEASUREMENTS OF MAXIMUM TEST ARTICLE TEMPERATURES FOR 920°K (1200°F) MAXIMUM SURFACE TEMPERATURE CONDITION*

	GRAPHITE/EPOXY COMPOSITE			BORON/ALUMINUM COMPOSITE			BORON/POLYIMIDE COMPOSITE		
THERMOCOUPLE LOCATION	T/C NO.	PRETEST MAX. TEMP PREDICTION °K (°F)	MEASURED MAXIMUM TEMPERATURE °K (°F)	T/C NO.	PRETEST MAX. TEMP PREDICTION °K (°F)	MEASURED MAXIMUM TEMPERATURE °K (°F)	T/C NO.	PRETEST MAX. TEMP PREDICTION °K (°F)	MEASURED MAXIMUM TEMPERATURE °K (°F)
#1	11	884 (1130)	829 (1031)	21	885 (1135)	790 (962)	31	885 (1135)	853 (1078)
#2	12	683 (770)	646 (705)	22	715 (830)	659 (727)	32	715 (830)	658 (725)
#3	13	480 (405)	501 (444)	23	525 (485)	548 (526)	33	522 (480)	563 (554)
#4	14	400 (260)	371 (209)	24	494 (430)	435 (323)	34	469 (385)	426 (306)
#5	15	400 (260)	371 (209)	25	497 (435)	435 (323)	35	477 (400)	407 (271)
#6	16	400 (260)	370 (206)	26	497 (435)	435 (323)	36	477 (400)	405 (268)
#7	17	400 (260)**	371 (209)	27	497 (435)**	435 (323)	37	477 (400)**	403 (265)

*Refer to Figure 25 for thermocouple locations.
**Estimated (not included in 2-D thermal analyses).

TABLE VIII

COMPARISON OF PRETEST PREDICTIONS & THERMOCOUPLE MEASUREMENTS OF MAXIMUM TEST ARTICLE TEMPERATURES FOR 1255°K (1800°F) MAXIMUM SURFACE TEMPERATURE CONDITION*

THERMOCOUPLE LOCATION	GRAPHITE/EPOXY COMPOSITE			BORON/ALUMINUM COMPOSITE			BORON/POLYIMIDE COMPOSITE		
	T/C NO.	PRETEST MAX. TEMP PREDICTION °K (°F)	MEASURED MAXIMUM TEMPERATURE °K (°F)	T/C NO.	PRETEST MAX. TEMP PREDICTION °K (°F)	MEASURED MAXIMUM TEMPERATURE °K (°F)	T/C NO.	PRETEST MAX. TEMP PREDICTION °K (°F)	MEASURED MAXIMUM TEMPERATURE °K (°F)
#1	11	1222 (1740)	1112 (1543)	21	1229 (1750)	1119 (1554)	31	1229 (1750)	1168 (1641)
#2	12	890 (1140)	859 (1084)	22	945 (1240)	904 (1164)	32	945 (1240)	885 (1131)
#3	13	572 (570)	630 (672)	23	631 (675)	736 (863)	33	628 (670)	740 (871)
#4	14	434 (320)	420 (297)	24	570 (565)	527 (489)	34	530 (495)	510 (458)
#5	15	436 (325)	418 (294)	25	572 (570)	534 (500)***	35	556 (540)	494 (428)
#6	16	439 (330)	418 (294)	26	575 (575)	527 (489)	36	559 (545)	489 (420)
#7	17	439 (330)**	418 (294)	27	575 (575)**	527 (489)	37	559 (545)**	486 (415)

*Refer to Figure 25 for thermocouple locations.

**Estimated (not included in 2-D thermal analyses).

***Suspect data at time of maximum temperature.

TABLE IX

COMPARISON OF PRETEST & TEST STANDOFF & COMPOSITE MAXIMUM
ΔT's FOR 920°K (1200°F) MAXIMUM SURFACE TEMPERATURE CONDITION

COMPOSITE	MAXIMUM STANDOFF ΔT*		MAXIMUM COMPOSITE ΔT**	
	PRETEST °K (°F)	TEST °K (°F)	PRETEST °K (°F)	TEST °K (°F)
GRAPHITE/EPOXY	786 (955)	711 (820)	269 (24)	257 (3)
BORON/ALUMINUM	764 (915)	642 (695)	262 (12)	256 (0)
BORON/POLYIMIDE	764 (915)	704 (805)	299 (78)	296 (73)

COMPARISON OF PRETEST & TEST STANDOFF & COMPOSITE MAXIMUM
ΔT's FOR 1255°K (1800°F) MAXIMUM SURFACE TEMPERATURE CONDITION

COMPOSITE	MAXIMUM STANDOFF ΔT*		MAXIMUM COMPOSITE ΔT**	
	PRETEST °K (°F)	TEST °K (°F)	PRETEST °K (°F)	TEST °K (F)
GRAPHITE/EPOXY	1113 (1545)	997 (1335)	275 (35)	259 (6)
BORON/ALUMINUM	1038 (1405)	895 (1150)	266 (19)	256 (0)
BORON/POLYIMIDE	1038 (1405)	950 (1250)	307 (93)	309 (96)

*Standoff $\Delta T = T_{(T/C\ Loc.\ \#1)} - T_{(T/C\ Loc.\ \#3)}$

**Composite $\Delta T = T_{(T/C\ Loc.\ \#4)} - T_{(T/C\ Loc.\ \#6)}$

APPENDIXES

APPENDIX A

THERMOPHYSICAL PROPERTIES OF ADVANCED FILAMENTARY COMPOSITE CONSTITUENTS AND SYSTEMS

REF.	MATERIAL TYPE AND SYSTEM	FIBER CONTENT	ARRAY	CONDUCTIVITY [1]		THERMAL EXPANSION [1]		SPECIFIC HEAT	
				k	TEST TEMP.	α_T	TEST TEMP.	C_p	TEST TEMP.
2	BORON								
	4.0 Mil Dia. Fiber					2.7	Unkn.		
	5.6 Mil Dia. Fiber					2.7	Unkn.		
20	GRAPHITE								
	"Thornel" Graphite Fibers			(2) (3) 408-840 (L)	Unkn.			0.17	RT
				(2) (3)(4) 40-90 (T)	Unkn.			0.40	RT-2700
	EPOXY								
2	Narmco 2387					27-30 38-51	RT 350		
21	**"Epoxylite"** High Temperature Systems			8.7-11.6	Unkn.	22.2-27.8	Unkn.	0.28 0.33	RT 300

Fiber Content - % Vol.
Conductivity - BTU - In./Hr-ft^2-F
Expansion - 10^{-6} In./In.-F
Specific Heat - BTU/Lb-F
Temperature - ^oF

(1) Test Direction:
(L) - Longitudinal
(T) - Transverse
(P) - Perpendicular

(2) Pan Precursor

(3) Rayon Precursor

(4) Estimated by Union Carbide Corp. per D. Sheddon

THERMOPHYSICAL PROPERTIES OF ADVANCED FILAMENTARY COMPOSITE CONSTITUENTS AND SYSTEMS

REF.	MATERIAL TYPE AND SYSTEM	FIBER CONTENT	ARRAY	CONDUCTIVITY		THERMAL EXPANSION		SPECIFIC HEAT	
				k	TEST TEMP.	α_T	TEST TEMP.	C_p	TEST TEMP.
22	POLYIMIDE								
	PI Molding			1.0	Unkn.	24	Unkn.		
23	ALUMINUM								
	2014-T6, T652 Forgings			1060	Unkn.	12.4	68-200	0.21	Unkn.
	6061 Plate			1080-1150	Unkn.	13.8	Unkn.	0.21	Unkn.
24	GRAPHITE			720 (L) 720 (T)		-0.55 (L) 9.32 (T)		0.17	
	BORON			192 (L) 192 (T)		2.0 (L) 4.3 (T)			
	GRAPHITE/EPOXY			326 (L) 9.6 (T)		-0.4 (L) 18 (T)		0.21	
	BORON/EPOXY			13.2 (L) 7.2 (T)		2.5 (L) 7.9 (T)		0.28	

Fiber Content - % Vol.
Conductivity - BTU - In./Hr-ft^2-F
Expansion - 10^{-6} In./In.-F
Specific Heat - BTU/Lb-F
Temperature - ^oF

Test Direction:
(L) - Longitudinal
(T) - Transverse
(P) - Perpendicular

THERMOPHYSICAL PROPERTIES OF ADVANCED FILAMENTARY COMPOSITE CONSTITUENTS AND SYSTEMS

REF.	MATERIAL TYPE AND SYSTEM	FIBER CONTENT	ARRAY	CONDUCTIVITY		THERMAL EXPANSION		SPECIFIC HEAT	
				k	TEST TEMP.	α_T	TEST TEMP.	C_p	TEST TEMP.
4	BORON/EPOXY Narmco Rigidite 5505	≃ 50	(0)	14.3 13.8 (L) 13.5	73 0 -100	2.6 (L) 2.0	0 - RT -100 - RT	0.28	100
				7.0 6.0 (T) 5.3	80 0 -100	11.1 (T) 9.9	0 - RT -100 - RT		
				5.5 5.3 (P) 5.0	75 0 -100	9.6 (P) 9.3	0 - RT -100 - RT		
7 (6)	BORON/EPOXY Declared typical of Narmco 5505 and 3M SP-272		Unknown	13.3 (L)	Unknown	2.3 (L) 47. (T)	Unknown Unknown		

Fiber Content - % Vol.
Conductivity - BTU - In./Hr-ft^2-F
Expansion - 10^{-6} In./In.-F
Specific Heat - BTU/Lb-F
Temperature - $^\circ$F

Test Direction:
(L) - Longitudinal
(T) - Transverse
(P) - Perpendicular

(5 Based on literature search, not in-house described data

THERMOPHYSICAL PROPERTIES OF ADVANCED FILAMENTARY COMPOSITE CONSTITUENTS AND SYSTEMS

REF.	MATERIAL TYPE AND SYSTEM	FIBER CONTENT	ARRAY	CONDUCTIVITY k	CONDUCTIVITY TEST TEMP.	THERMAL EXPANSION α_T	THERMAL EXPANSION TEST TEMP.	SPECIFIC HEAT C_p	SPECIFIC HEAT TEST TEMP.
				2.45	-65	1.83	-100		
				2.48	0	2.43 (L)	+100		
			(0)	2.62 (P)	RT	2.83	350		
				2.76	200	8.24	-100		
				3.03	400	11.05 (T)	100		
						19.78	350		
				2.16	-50	2.04	-100		
	BORON/EPOXY			2.50	0	2.68 (L)	100		
5	Narmco Rigidite 5505	50	(0/±45)	2.41 (P)	RT	3.37	350		
				2.90	200	4.97 (T)	-100		
				2.90	400.	6.30	100		
				2.26	-60	2.54	-100		
				2.38	0	3.36 (L)	100		
			(0/±60)	2.47 (P)	RT	3.50	350		
				2.70	200	2.72	-100		
				2.90	400	3.45 (T)	100		
						4.04	350		

Fiber Content - % Vol.
Conductivity - BTU - In./Hr-ft^2-F
Expansion - 10^{-6} In./In.-F
Specific Heat - BTU/Lb-F
Temperature - ^{o}F

Test Direction:
(L) - Longitudinal
(T) - Transverse
(P) - Perpendicular

THERMOPHYSICAL PROPERTIES OF ADVANCED FILAMENTARY COMPOSITE CONSTITUENTS AND SYSTEMS

REF.	MATERIAL TYPE AND SYSTEM	FIBER CONTENT	ARRAY	CONDUCTIVITY k	CONDUCTIVITY TEST TEMP.	THERMAL EXPANSION α_T	THERMAL EXPANSION TEST TEMP.	SPECIFIC HEAT C_p	SPECIFIC HEAT TEST TEMP.
9	BORON/EPOXY 3M SP-272	Unknown	(0)			1.0	-100		
						2.0 (L)	100		
						3.0	350		
						7.0	-100		
						9.5 (T)	100		
						7.5	350		
			(±45)			2.1	-100		
						2.8 (L)	100		
						3.2	350	0.28	50
						2.1	-100		
						2.9(45°)(1)	100		
						3.3	350		
			(0/±45)			1.25	-100		
						1.65 (L)	100		
						2.65	350		
						3.90	-100		
						5.30 (T)	100		
						2.70	350		

Fiber Content - % Vol.
Conductivity - BTU - In./Hr-ft^2-F
Expansion - 10^{-6} In./In.-F
Specific Heat - BTU/Lb-F
Temperature - °F

(1) Test Direction:
(L) - Longitudinal
(T) - Transverse
(P) - Perpendicular

THERMOPHYSICAL PROPERTIES OF ADVANCED FILAMENTARY COMPOSITE CONSTITUENTS AND SYSTEMS

REF.	MATERIAL TYPE AND SYSTEM	FIBER CONTENT	ARRAY	CONDUCTIVITY		THERMAL EXPANSION		SPECIFIC HEAT	
				k	TEST TEMP.	α_T	TEST TEMP.	C_p	TEST TEMP.
6	Narmco 5206, Type II (Modmor II/1004)	65-69	(0)	75.8	72.6	-0.75 (L)	RT → 350		
				67.3	12.4	-0.87 (L)	-300 → RT		
				56.0 (L)	-76.6	17.0 (T)	RT → 350		
				38.7	-178.5	11.0 (T)	-300 → RT		
						30.0 (P)	RT → 350		
						12.0 (P)	-300 → RT		
	GRAPHITE/EPOXY		(0)			-0.11(L)	RT → 350		
						-0.24(L)	-300 → RT		
						30.0 (T)	RT → 350		
						12.0 (T)	-300 → RT		
	Fiberite 1305B (HTS/X05)		(± 30)			-4.70(L)	RT → 350		
						-1.50(L)	-300 → RT		
						16.0 (T)	RT → 350		
						5.4 (T)	-300 → RT		
			(±45)			0.22(L)	RT → 350		
						0.61 (L)	-300 → RT		

Fiber Content - % Vol.
Conductivity - BTU - In./Hr-ft^2-F
Expansion - 10^{-6} In./In.-F
Specific Heat - BTU/Lb-F
Temperature - ^oF

Test Direction:
(L) - Longitudinal
(T) - Transverse
(P) - Perpendicular

THERMOPHYSICAL PROPERTIES OF ADVANCED FILAMENTARY COMPOSITE CONSTITUENTS AND SYSTEMS

REF.	MATERIAL TYPE AND SYSTEM	FIBER CONTENT	ARRAY	CONDUCTIVITY k	CONDUCTIVITY TEST TEMP.	THERMAL EXPANSION α_T	THERMAL EXPANSION TEST TEMP.	SPECIFIC HEAT C_p	SPECIFIC HEAT TEST TEMP.
7	High Modulus G/E	Unknown	Unknown	120	Unknown	-0.8 (L)	Unknown		
						47.0 (T)	Unknown		
	High Strength G/E	Unknown	Unknown	120	Unknown	-0.8 (L)	Unknown		
						47.0 (T)	Unknown		
9	GRAPHITE/EPOXY GY 70/X904	50.8-54.8	(0)			- 0.47 (L)	RT 350		
						- 0.65	-300 RT		
						22.16 (T)	RT 350		
						13.6	-300 RT		
			(± 45)			- 0.41(45°)(1)	RT 350		
						- 0.45	-300 RT		
	GRAPHITE/EPOXY HTS/X904	Unknown	(0)			- 0.25	-300 to 500	0.11	-200
						15.5		0.145	-100
			±45			1.8		0.20	RT
						0.6		0.235	150
			0/± 45			1.8		0.27	250
						5.1		0.31	350

Fiber Content - % Vol.
Conductivity - BTU - In./Hr-ft^2-F
Expansion - 10^{-6} In./In.-F
Specific Heat - BTU/Lb-F
Temperature - ^oF

(1) Test Direction:
(L) - Longitudinal
(T) - Transverse
(P) - Perpendicular

THERMOPHYSICAL PROPERTIES OF ADVANCED FILAMENTARY COMPOSITE CONSTITUENTS AND SYSTEMS

REF.	MATERIAL TYPE AND SYSTEM	FIBER CONTENT	ARRAY	CONDUCTIVITY k	CONDUCTIVITY TEST TEMP.	THERMAL EXPANSION α_T	THERMAL EXPANSION TEST TEMP.	SPECIFIC HEAT C_p	SPECIFIC HEAT TEST TEMP.
10	GRAPHITE/EPOXY GY 70/508	Unknown	$(0/90)_T$			- 0.38 (L) - 0.12	-300 RT -250 RT		
	GRAPHITE/EPOXY HMG-50/E715	Unknown	$(0/90)_T$			- 0.44 - 0.44 0.00 0.00	-320 RT -320 RT -200 RT RT 225		
			$(0/\pm60)_T$			- 0.35 0.00 (L) 0.00	-320 RT -200 RT RT 225		
	Modmor I/E715		$(0/90)_T$			- 0.32 (L)	-320 to RT		
	Thornel 50/ERLA 4617		$(0/90)_T$			- 0.32 (L)			

Fiber Content - % Vol.
Conductivity - BTU - In./Hr-ft^2-F
Expansion - 10^{-6} In./In.-F
Specific Heat - BTU/Lb-F
Temperature - ^oF

Test Direction:
(L) - Longitudinal
(T) - Transverse
(P) - Perpendicular

THERMOPHYSICAL PROPERTIES OF ADVANCED FILAMENTARY COMPOSITE CONSTITUENTS AND SYSTEMS

REF.	MATERIAL TYPE AND SYSTEM	FIBER CONTENT	ARRAY	CONDUCTIVITY k	CONDUCTIVITY TEST TEMP.	THERMAL EXPANSION α_T	THERMAL EXPANSION TEST TEMP.	SPECIFIC HEAT C_p	SPECIFIC HEAT TEST TEMP.
11	GRAPHITE EPOXY Thornel 75S/ERLB 4617	67.2	(0/±60)			- 0.45 (L) - 0.58	-280 → RT RT → 212		
						- 0.36 (T) - 0.72	-280 → RT RT → 212		
		65.31	(0/90/±45)$_s$			- 0.39 (T) - 0.58	-280 → RT RT → 212		
	GRAPHITE/EPOXY Modmor II/E293	Unknown	(0/±60)$_s$			1.30 (L) 1.97	-280 → RT RT → 212		
12	GRAPHITE/EPOXY Thornel 75S/ERLB 4617	66.32	(0/±60)			- 0.45 (L) (6) - 0.41	-280 → RT RT → 212		
13	GRAPHITE/EPOXY Thornel 50/E-798	≥55-60	(0)			- 0.3 (L)	RT → 350		
						10.0 (T)	RT → 325		
8	G/POLYESTER Modmor I/Polyester	50	(0)	116.	Unknown	- 0.46 (L) 16.0 (T)	Unknown		

Fiber Content - % Vol.
Conductivity - BTU - In./Hr-ft^2-F
Expansion - 10^{-6} In./In.-F
Specific Heat - BTU/Lb-F
Temperature - ^oF

Test Direction:
(L) - Longitudinal
(T) - Transverse
(P) - Perpendicular

(6) Measured with Opton Equipment

THERMOPHYSICAL PROPERTIES OF ADVANCED FILAMENTARY COMPOSITE CONSTITUENTS AND SYSTEMS

REF.	MATERIAL TYPE AND SYSTEM	FIBER CONTENT	ARRAY	CONDUCTIVITY k	CONDUCTIVITY TEST TEMP.	THERMAL EXPANSION α_T	THERMAL EXPANSION TEST TEMP.	SPECIFIC HEAT C_p	SPECIFIC HEAT TEST TEMP.
14	BORON/POLYIMIDE B/Pyrolin 4707	Unknown	$(+5/-12.5/+25/-40/+45)_s$			3.5 (L)	RT → 800		
						3.65 (T)	RT → 800		
15	GRAPHITE/ POLYIMIDE Modmor II/Gemon L	62.6	(0)			-0.38 (L)	-300 → RT		
						0.8 (L)	RT → 500		
						15.0 (T)	-300 → RT		
						25.0 (T)	RT → 500		
		60.1	$(0_3/+45/90_3/\pm45/0_3)_s$			0.2 (L)	-300 → RT		
						0.2 (L)	RT → 500		
						0.86 (T)			
						0.2 (T)			

Fiber Content - % Vol.
Conductivity - BTU - In./Hr-ft^2-F
Expansion - 10^{-6} In./In.-F
Specific Heat - BTU/Lb-F
Temperature - ^oF

Test Direction:
(L) - Longitudinal
(T) - Transverse
(P) - Perpendicular

THERMOPHYSICAL PROPERTIES OF ADVANCED FILAMENTARY COMPOSITE CONSTITUENTS AND SYSTEMS

REF.	MATERIAL TYPE AND SYSTEM	FIBER CONTENT	ARRAY	CONDUCTIVITY		THERMAL EXPANSION		SPECIFIC HEAT	
				k	TEST TEMP.	α_T	TEST TEMP.	C_p	TEST TEMP.
16	BORON/ALUMINUM B/2219	25	(0)			3.82	RT to 700		
		37	(0)			3.45 (L)			
		50	(0)			3.20			
						10.6 (T)			
			(0/90)			3.98 (L)			
			(±60)			2.58 (T)			
17	BORON/ALUMINUM 4.0 Mil Dia. B/Al	50	(0)			2.71 (L) 8.45 (T)	-300 → RT		
	BORON/ALUMINUM 5.6 Mil Dia. B/Al	50	(0)			2.20 (L) 3.36 (L)	-320 → RT RT - 700		
						8.99 (T) 11.84 (T)	-320 → RT RT - 700		
	BORON/ALUMINUM Borsic/Al	50	(0)			3.28 (L) 11.12 (T)	-320 → RT		

Fiber Content - % Vol.
Conductivity - BTU - In./Hr-ft^2-F
Expansion - 10^{-6} In./In.-F
Specific Heat - BTU/Lb-F
Temperature - ^oF

Test Direction:
(L) - Longitudinal
(T) - Transverse
(P) - Perpendicular

APPENDIX B. THERMAL PROPERTIES OF TPS STANDOFF AND TEMPERATURE SUPPRESSION MATERIALS

TPS MATERIAL	TEMP. (F)	k (B/FT-HR-F)	C_p (B/LB-F)	ρ (LB/FT^3)	$k/\rho C_p$ (FT^2/HR)
Titanium 6Al-4V	70	4.14	.130	276	.1152
	200	4.32	.136		.1152
	400	5.03	.148		.123
	600	6.0	.159		.137
	800	7.0	.170		.149
	1000	7.95	.180		.160
Inconel 718	70	6.41	.104	513	.120
	200	7.14			.134
	400	8.16			.153
	600	9.18			.172
	800	10.31			.193
	1000	11.4			.214
	1200	12.25			.230
	1400	13.45	.104		.252
Rene'41	100	6.4	.06		.207
	200	6.8	.065	515	.203
	400	7.65	.08		.186
	600	8.8	.092		.186
	800	9.9	.105		.184
	1000	11.0	.12		.178
	1200	12.15	.135		.175
	1400	13.3	.145		.178
	1600	14.55	.16		.177
Haynes 188	100	5.5	.097	575	.0985
	200	6.25	.10		.109
	400	7.5	.106		.123
	600	8.75	.112		.137
	800	10.0	.117		.149
	1000	11.25	.122		.161
	1200	12.5	.127		.172
	1400	13.75	.132		.182
	1600	15.0	.137		.191
	1800	16.65	.141		.206
TD Nichrome	100	5.8	.101	535	.108
	200	6.3	.1035		.114
	400	7.45	.109		.127
	600	8.6	.115		.14
	800	9.7	.121		.15
	1000	10.9	.127		.161
	1200	12.1	.133		.171
	1400	13.35	.139		.18
	1600	14.6	.144		.189
	1800	15.85	.15		.198
	2000	17.1	.156		.205

TPS MATERIAL	TEMP. (F)	k (B/FT-HR-F)	C_p (B/LB-F)	ρ (LB/FT^3)	$k/\rho C_p$ (FT^2/HR)
Columbium 752	100	25.9	.061	563	.753
	200	26.2	.062		.751
	400	27.	.065		.738
	600	27.6	.0675		.727
	800	28.4	.07		.722
	1000	29.2	.073		.710
	1200	29.9	.076		.70
	1400	30.6	.0785		.692
	1600	31.4	.081		.688
	1800	32.1	.084		.679
	2000	32.9	.087		.674
	2200	33.6	.0895		.666
	2400	34.4	.092		.664
	2500	34.7	.0935		.659
Tantalum T-111	100	24.5	.024	1041	.98
	400	26.8	.025		1.028
	800	29.5	.0265		1.07
	1200	32.5	.0285		1.093
	1600	35.3	.031		1.093
	2000	38.2	.034		1.08
	2400	41.	.036		1.093
	2800	44.	.0395		1.07
	3000	45.5	.041		1.065
		$k_{\perp}/k_{XVERSE}$			
Carbon-Carbon (O_2 Inhibited)	70	8.1/5.8	.17	88	.388
	1470	8.1/11.6	.32		.41
	3000	13.3/13.3	.37		.41

Material	Temp (F)	k (B/Ft-Hr-F)	Cp (B/Lb-F)	ρ (Lb/Ft^3)	k/ρCp (Ft^2/Hr)	L* (B/Lb)
Type 304 or 321	0	7.5	.120	500	.125	
Stainless Steel	400	9.8	.129		.152	
	800	12.2	.137		.178	
	1200	14.5	.146		.199	
	1600	16.9	.155		.218	
	2000	19.3	.164		.236	
Syntactic PBI Foam		.065	.3	31	.007	
Chem Ceram Foam (ρ = 18 pcf)	70	.0375	.35	18	.00595	
	750	.05			.00794	
	1110	.075			.0119	
Chem Ceram Foam (ρ= 25 pcf)	70	.056	.35	25	.0064	
	750	.075			.00857	
	1110	.113			.0129	
Molded Polyimide		.3	.35	117.5	.0073	
Molded Chem Ceram		.583	.35	125	.0133	
Marinite-23	200	.0484	.25	23	.00842	
	400	.05	.28		.00778	
	600	.0517	.31		.00725	
	800	.0541	.34		.00692	
Transite		.375	.3	100	.0125	
Pyroceram		1.4	.26	155	.035	
Solid/Solid PCM (Polyethylene)		Not Used	.5	60		80
Solid/Liquid PCM (Durene)		Not Used	.3	56		67
Dowtherm G (Coolant)		Not Used	.45	60		

APPENDIX C

TEST PLAN FOR THERMAL DESIGN VERIFICATION OF HIGH TEMPERATURE TPS ATTACHMENTS TO COMPOSITE MATERIALS

TEST PLAN SCOPE

The scope of this test plan includes detailed pre-test thermal analyses, fabrication and procurement of test hardware, assembly of test specimens, test specimen instrumentation, radiant heating environment tests, and comparison of test data with analytical thermal data.

TEST OBJECTIVE

The object of this test program is to obtain temperature measurements for verification of thermal analysis methods and thermal property data utilized in the preliminary design evaluation of high temperature TPS attachments to composite structures per Task 4 of NAS 8-27041, "Thermal Design of Composite Material High Temperature Attachments."

DETAILED PRE-TEST THERMAL ANALYSES (Subtask 4.1)

The thermal tests will consist of three composite materials (Graphite/Epoxy, Boron/Polyimide, and Boron/Aluminum) exposed simultaneously to two different radiant heating environments. Detailed 2-D thermal analyses have been performed to define the two environments (1200F and 1800F maximum surface temperatures) such that maximum temperatures of the three composite materials will not exceed design temperature limits (350F for Graphite/Epoxy, 600F for Boron/Polyimide, and 650F for Boron/Aluminum). The exposure time for the 1200F surface temperature condition is limited to that which will produce temperature increases of the composite substructure to approximately two-thirds of the design temperature limit; the exposure time for the 1800F surface temperature environment is defined analytically to produce composite structure maximum temperatures to within 90-95% of design limits. With the definition of these environments, detailed thermal analyses will be performed to establish temperature histories throughout each test specimen, including the instrumented locations on each specimen. The two environments are illustrated graphically in Figures 1(a) and 1(b).

TEST ARTICLE DESIGN AND TEST REQUIREMENTS DEFINITION (Subtask 4.2)

The general test arrangement design is presented in Figure 2. The heating area of the radiant lamp fixture is approximately 19 by 22 inches. For prevention of edge heat sink effects, the three test specimens are located such that no edge of any test article is closer than 2.5 inches to the heating area boundary and 3 inches to any other test article. Fibrous insulation (6 pcf Dynaflex) above the composite structure simulates the insulation of a design TPS system and is also provided in the test arrangement to support the test articles and insulate the composite structure panels from edge conditions and heat sink effects of the test bed. A layer of Irish Refrasil Cloth over the entire heated surface provides a constant emittance surface. Fiber orientations for each 4 x 7 inch composite panel have been selected to produce temperature gradients on the lengthwise centerline of the standoff/composite panel specimens and are schematically illustrated in Figure 2 in the upper left-hand corner of each composite panel outline.

The radiant environments discussed previously will be controlled by a feedback system driven by a pre-programmed surface temperature measured by a control thermocouple located in the center of the test area (away from the influence of the test specimens). A detailed description of the components required for each test article is provided by Table I.

TEST HARDWARE FABRICATION AND PROCUREMENT (Subtask 4.3)

The components required for the tests (Table I) will be obtained from in-house stock, fabricated, or purchased. The stainless steel standoffs, which simulate the thickness to height ratio of the Haynes 188 standoffs (utilized in the detailed thermal analysis) are to be fabricated per Figures 3(a)-1 and Figure 3(a)-2. The PBI and Chem Ceram Foam Isolators (Figures 3(b)-1, 3(b)-2, 3(b)-3) as well as the molded PI and Chem Ceram bushings (Figure 3(c)) are to be purchased. The Graphite/Epoxy, Boron/Polyimide, and Boron/Aluminum composite panels will be fabricated per Table I dimensions and orientations. The Dynaflex insulation and fasteners will be provided for the tests from in-house stock.

ASSEMBLY OF TEST ARTICLES (Subtask 4.4)

The assembly of the test components will be performed per Figures 2 and 4. Figure 2 shows the location of test specimens relative to the test bed and radiant lamp fixture, and Figure 4 illustrates the standoff/isolator/composite assembly. The basic test article assembly includes the stainless steel hat-type standoff attached to the composite panel by a machine screw (3/16" diameter) through a thermal isolator block (PBI or Chem Ceram Foam). Molded bushings (PI or Chem Ceram) fit through the leg of the standoff and the composite panel, and are fitted flush to the top and bottom of the isolator block during assembly. The bushings provide for thermal isolation of the screw from the standoff leg, and for thermal isolation of the composite material from the screw.

TEST SPECIMEN INSTRUMENTATION (Subtask 4.5)

Instrumentation of the test articles will be accomplished per Figures 2 and 4 Thermocouples will be located in the center of the standoff cap (#1), half way down the standoff height (#2), at the edge of the standoff leg (#3), on the composite panel lengthwise centerline directly below #3 (#4), along the lengthwise centerline, .75 inches from #4 (#5), along the lengthwise centerline at the edge of the panel (#6), and in the direction perpendicular to the lengthwise center-line, 1.50 inches from #4 (#7). Refer to Figures 2 and 4 for a pictorial representation of thermocouple locations. Each of the three test articles will be instrumented in the same manner.

A control thermocouple will be provided on the surface of the Refrasil Cloth in the center of the test area, as discussed previously, and will function as a feedback controller of radiant flux to the pre-programmed surface temperature, which is to be measured by the control thermocouple.

THERMAL TESTS (Subtask 4.6)

The thermal testing will be conducted in the 19 by 22 inch test fixture, utilizing the environments, test specimens, test specimen arrangement, and measurement scheme discussed. Test recording time will be determined from pre-test thermal analysis (Subtask 4.1)

TEST DATA AND TEST DATA REDUCTION (Subtask 4.7)

The test data generated shall consist of the following:

1. Dimensional measurements of test specimen assemblies and thermocouple locations.

2. Dimensional measurements of test assembly including spacing of test specimens, insulation thicknesses (both pre-test and post-test measurements), and relationship of radiant lamp bank to simulated TPS surface.

3. Temperature history recordings for test specimen thermocouples and control thermocouple.

Reduction of the test data shall be presented in a format suitable for use in analytical procedures. All test data will be reported in engineering units suitable for use in analytical procedures.

POST-TEST ANALYSES (Subtask 4.8)

Subsequent to receipt of the recorded test data, comparisons of the temperature histories predicted analytically at the thermocouple locations (pre-test analyses) will be made with the test data. The test data will be evaluated in this perspective, and any data anomalies (either analytical or test) will be assessed.

FIGURE 1(a). 1200F TEST ENVIRONMENT

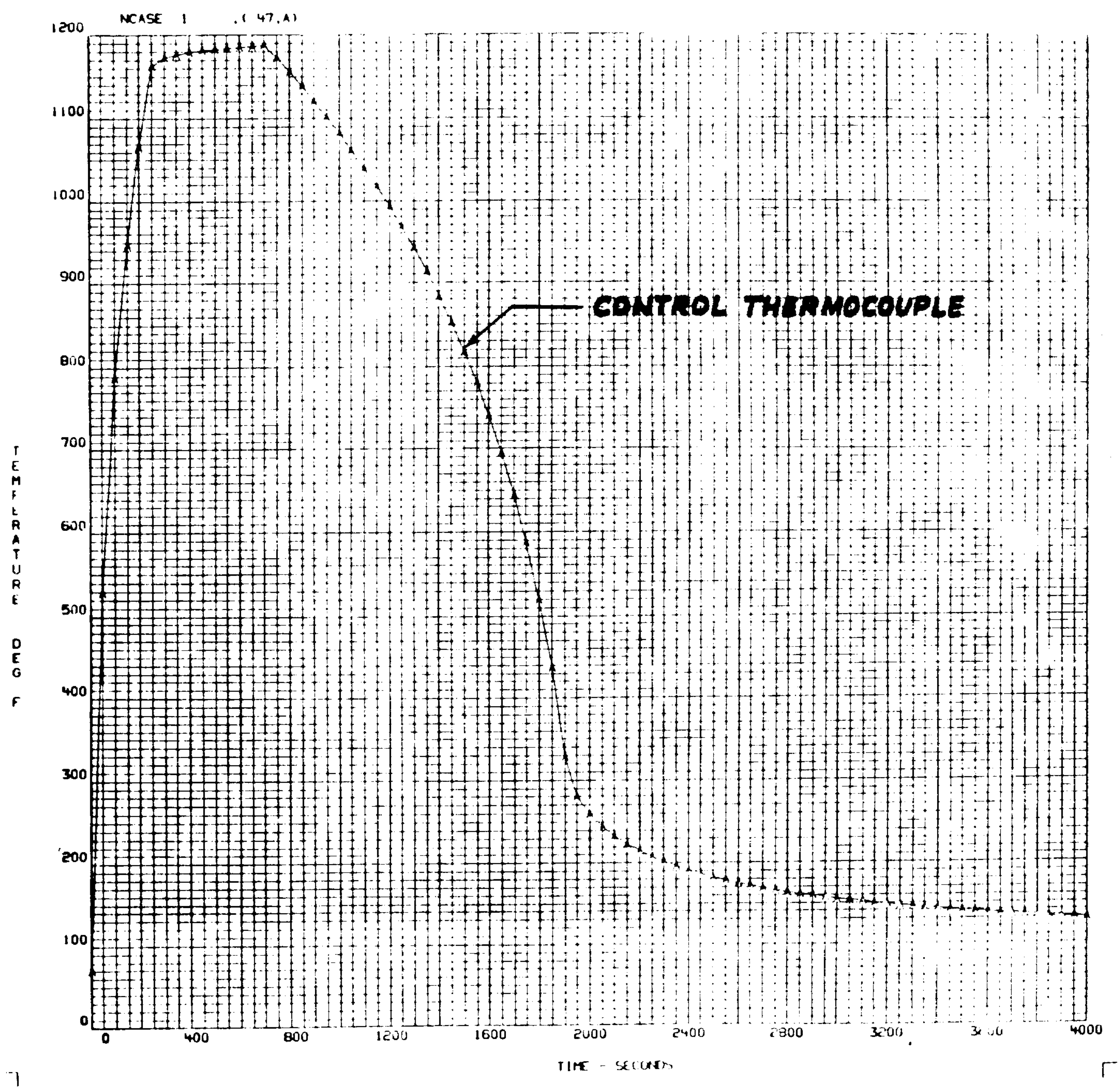
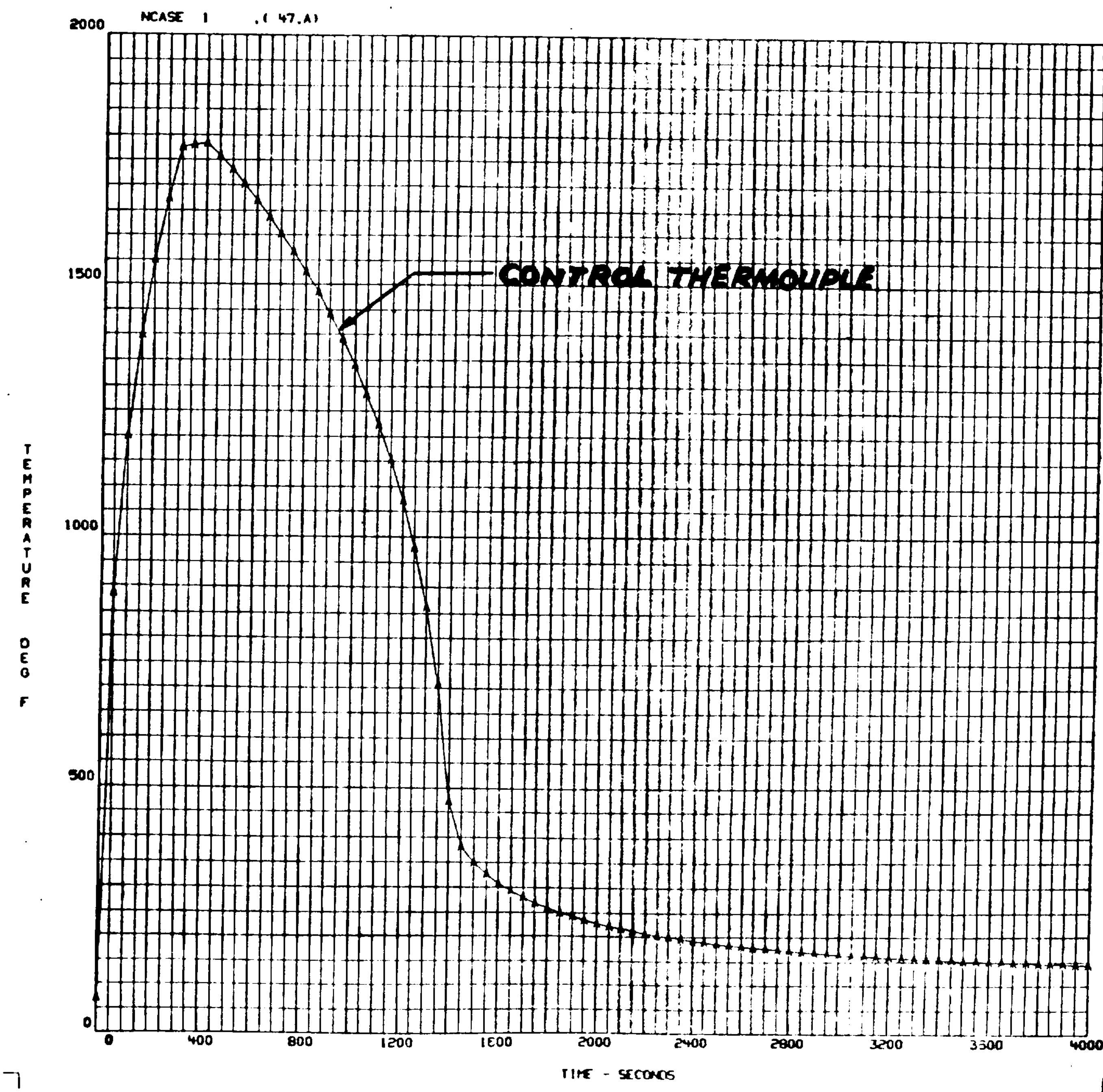


FIGURE 1 (b). 1800F TEST ENVIRONMENT



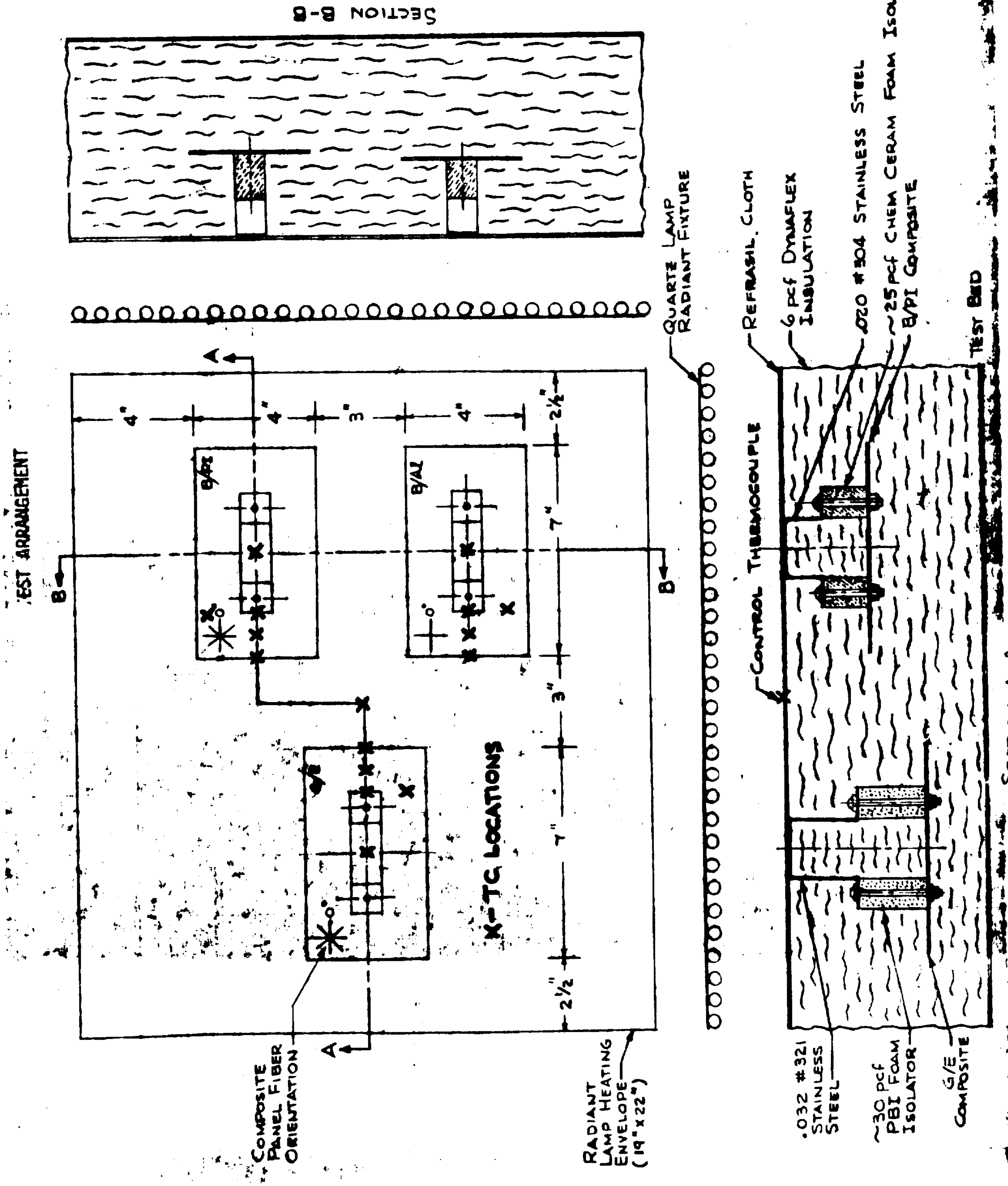
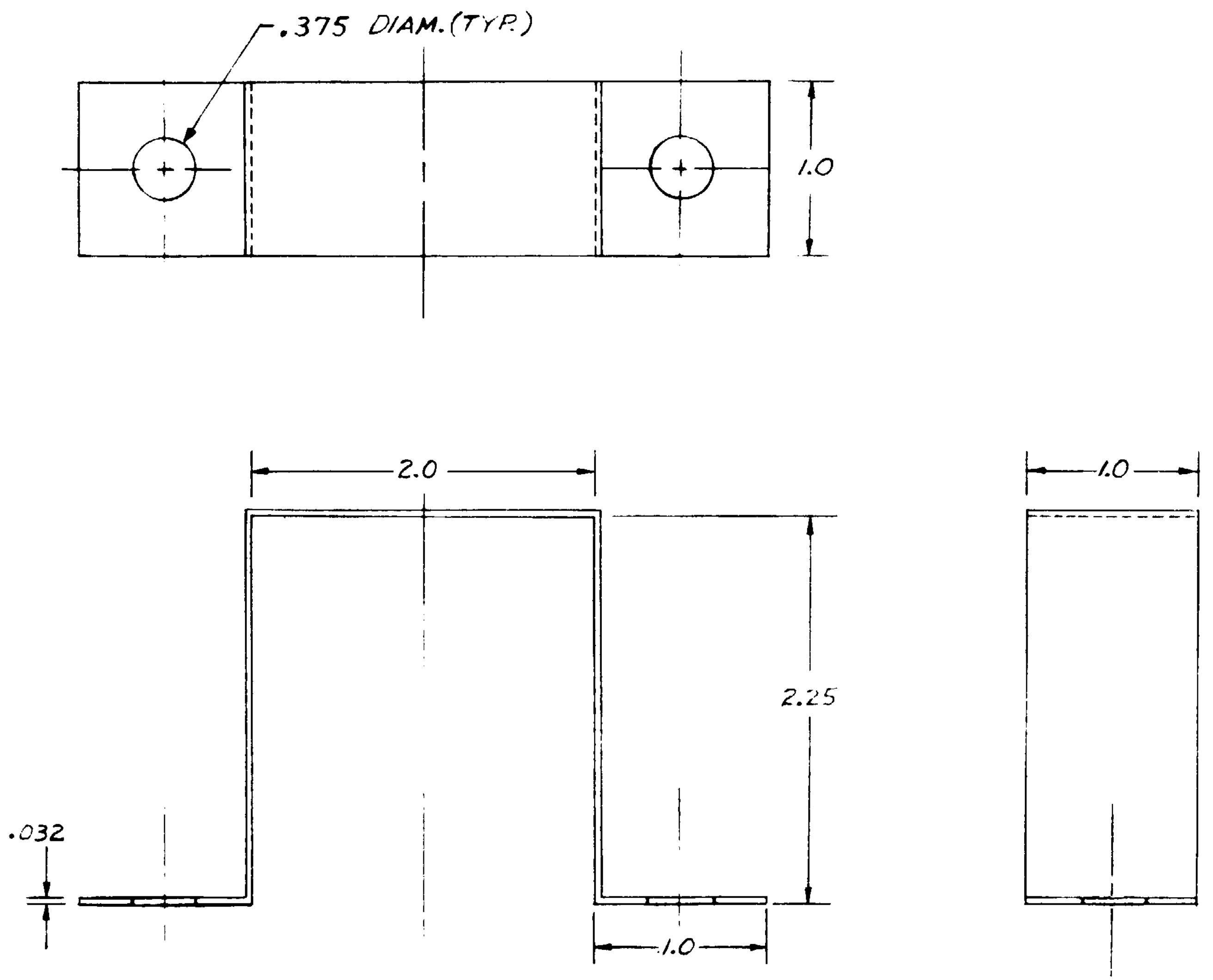

Section B-B
Test Arrangement
B
B
A
A
4"
4"
3"
4"
2½"
7"
3"
7"
2½"
B/AL
B/AL
X-TC Locations
Composite Panel Fiber Orientation
Radiant Lamp Heating Envelope (19" x 22")
Quartz Lamp Radiant Fixture
Refrasil Cloth
6 pcf Dynaflex Insulation
.020 #304 Stainless Steel
~25 pcf Chem Ceram Foam Isolator
B/PI Composite
Test Bed
Control Thermocouple
.032 #321 Stainless Steel
~30 pcf PBI Foam Isolator
G/E Composite
Section A-A

FIGURE 3(a)-1. STAINLESS STEEL STAND-OFF FOR G/E TEST SPECIMEN



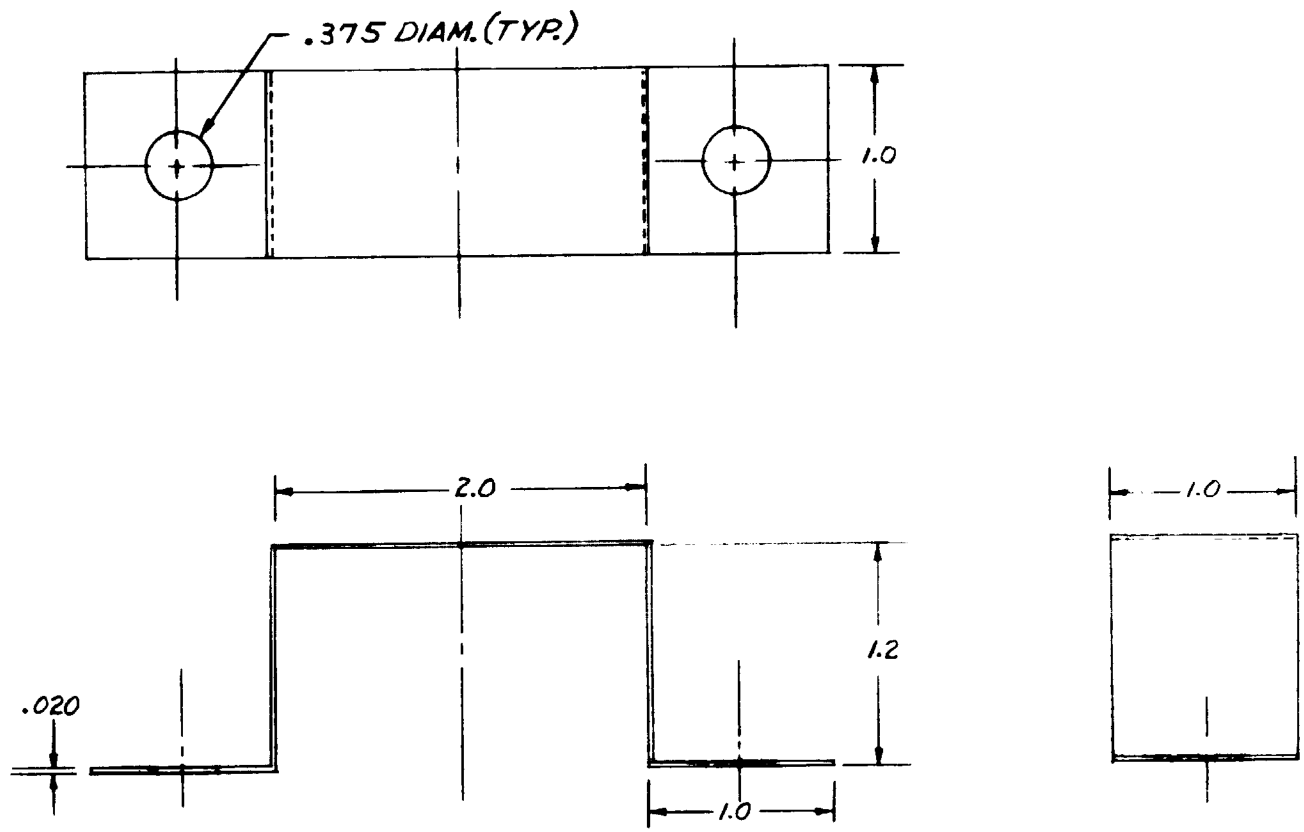
.032 #321 STAINLESS STEEL (1 REQ'D)

SCALE : 1/1

REVISED 12-10-71

GWM 12-3-71

FIGURE 3(a)-2. STAINLESS STEEL STAND-OFFS FOR B/PI AND B/AL TEST SPECIMENS



.020 #304 STAINLESS STEEL (2 REQ'D)

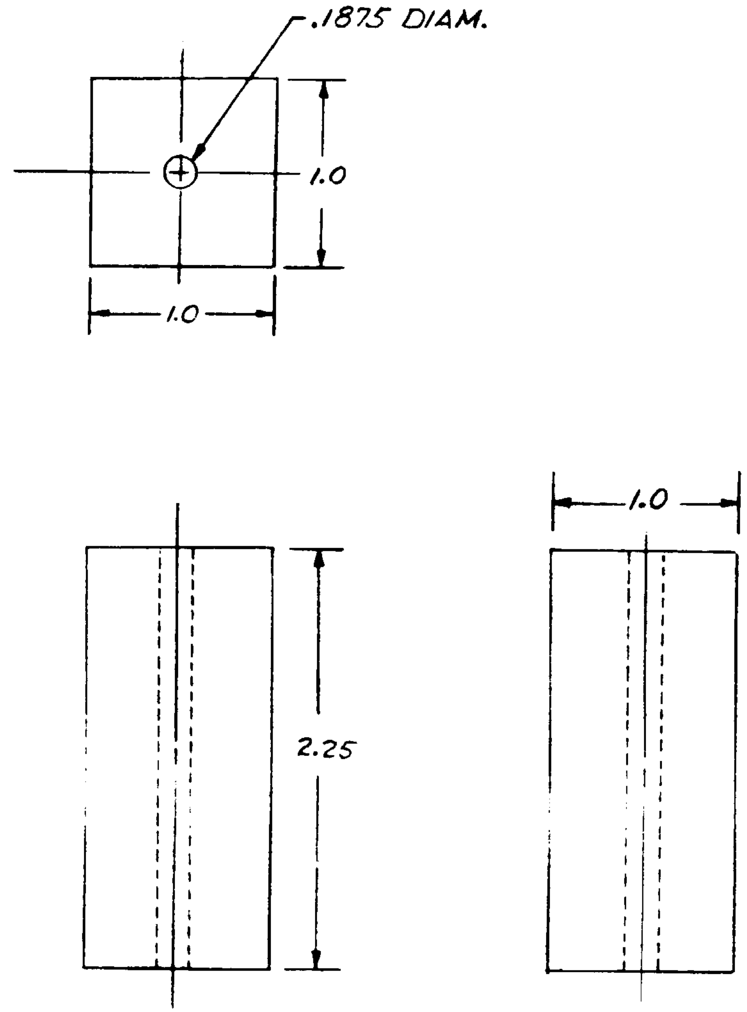
SCALE : 1/1

REVISED 12-10-71

GWM 12-3-71

2

FIGURE 3(b)-1. THERMAL ISOLATORS FOR G/E TEST SPECIMEN



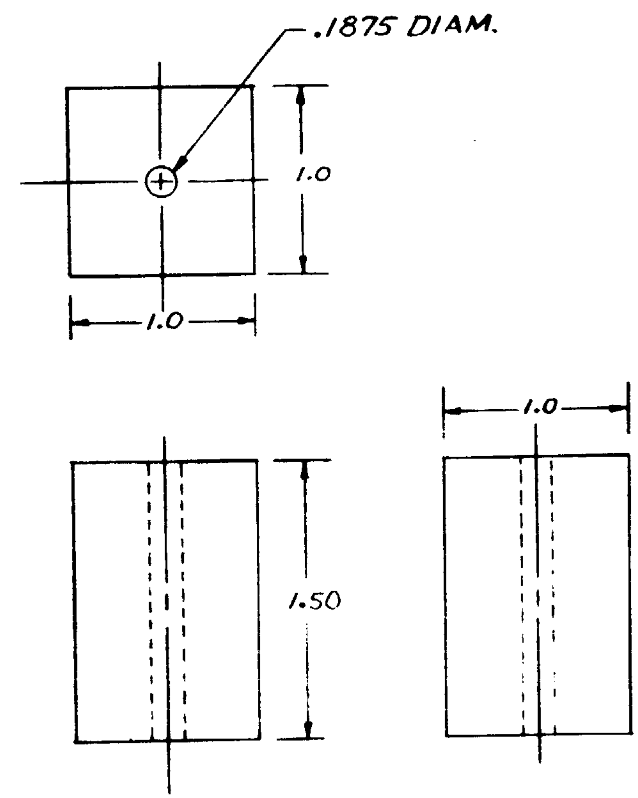
SYNTACTIC PBI FOAM (~31 PCF) BLOCK
(3 REQ'D)

SCALE: 1/1

GWM 12-3-71

3

FIGURE 3(b)-2. THERMAL ISOLATORS FOR B/PI TEST SPECIMEN



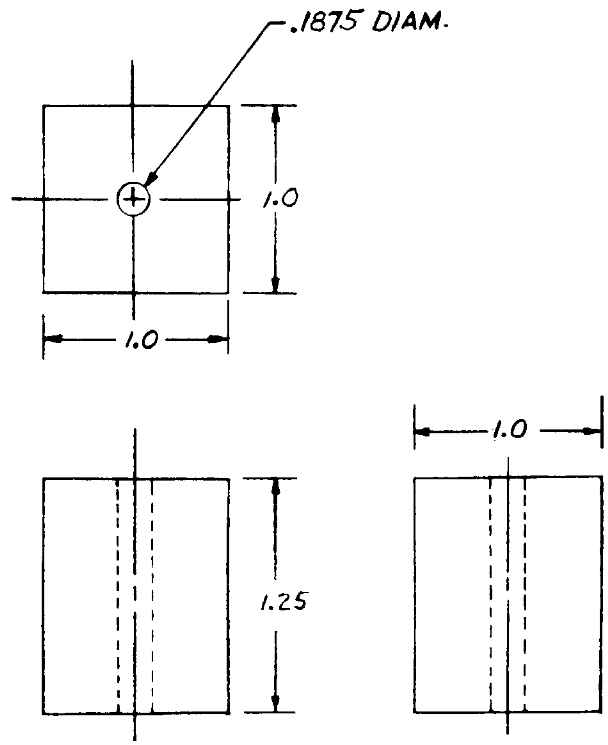
CHEM CERAM FOAM (~25 PCF) BLOCK
(4 REQ'D)

SCALE: 1/1

GWM 12-3-71

4

FIGURE 3(b)-3. THERMAL ISOLATORS FOR B/AL TEST SPECIMEN



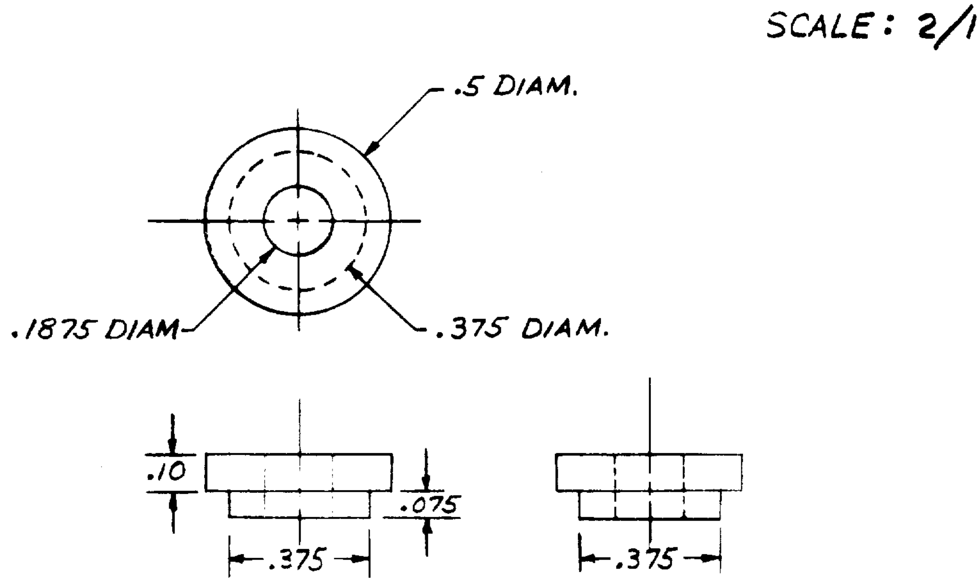
CHEM CERAM FOAM (~25 PCF) BLOCK
(4 REQ'D)

SCALE: 1/1

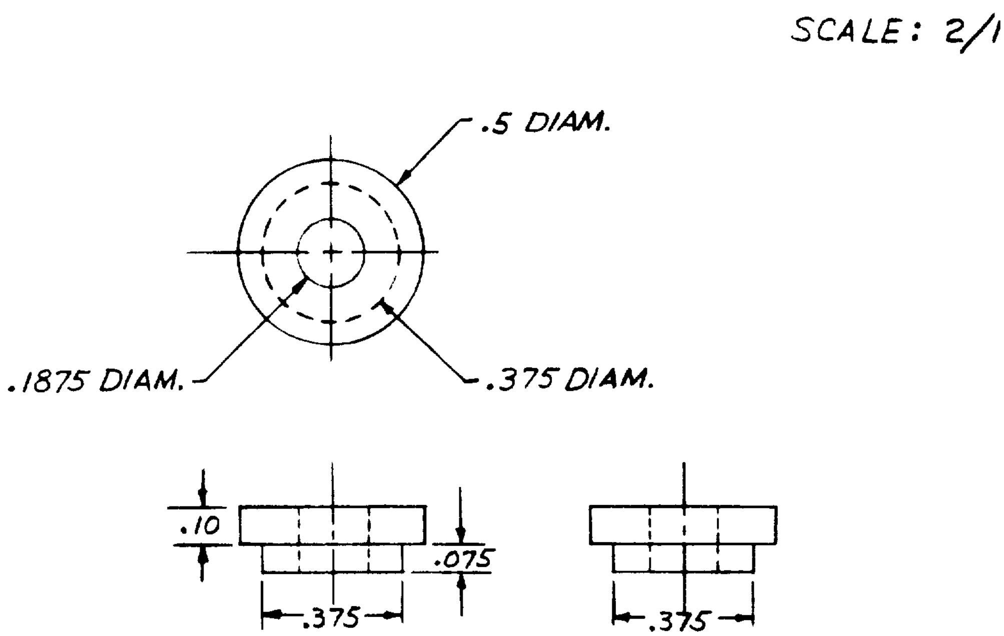
GWM 12-3-71

5

FIGURE 3(c). BUSHINGS FOR G/E, B/PI, AND B/AL TEST SPECIMENS



MOLDED POLYIMIDE (~120 PCF) BUSHING
(6 REQ'D)



MOLDED CHEM CERAM (~125 PCF) BUSHING
(12 REQ'D)

GWM 12-3-71

FIGURE 4. STAND-OFF/COMPOSITE SYSTEM ASSEMBLY AND THERMOCOUPLE LOCATIONS FOR TEST

NOTES: (1.) DYNAFLEX INSULATION NOT SHOWN

(2.) ISOLATION BUSHINGS FIT TO TEST CONFIGURATION

(3.) REFER TO FIGURE 2 FOR TEST CONFIGURATION AND COMPOSITE PANEL FIBER ORIENTATION RELATIVE TO TEST CONFIGURATION.

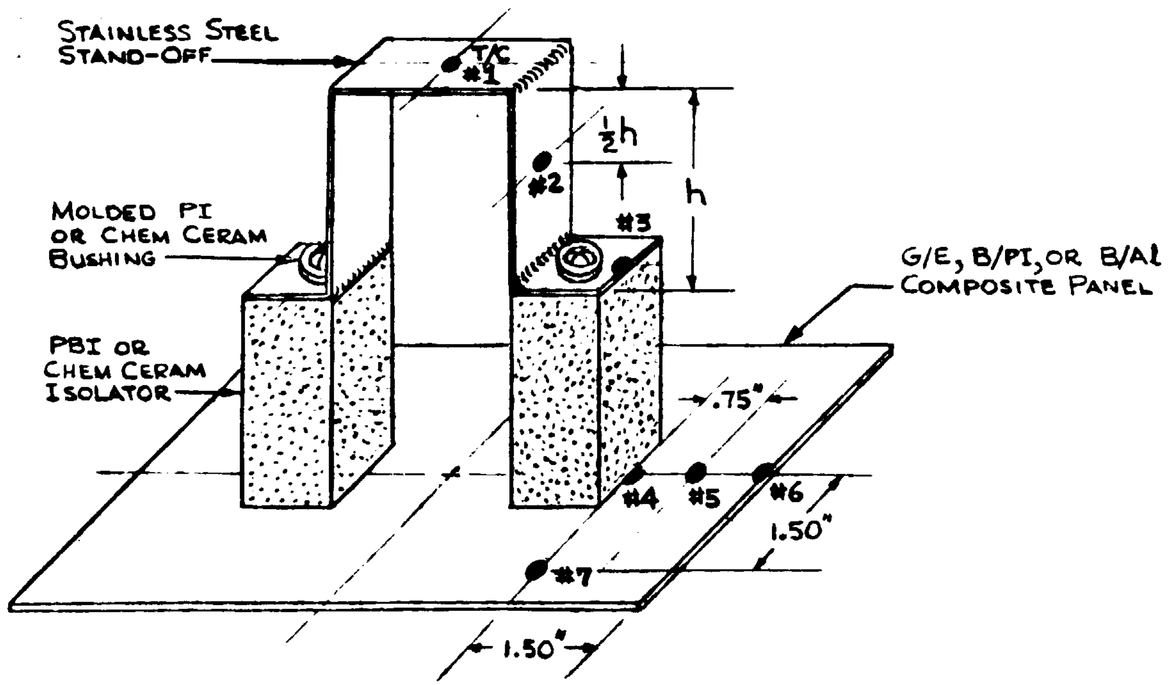


TABLE I. TEST SPECIMEN COMPONENT DESCRIPTION

	B/Al	B/PI	G/E
COMPOSITE MATERIAL STRUCTURE			
Configuration	Sheet	Sheet	Sheet
Sheet thickness (approx)	0.042"	0.04"	0.06"
Lay-up (no. of plys)	8	8	8
Fiber orientation	90°	2[0°/±45°/90°]	2[0°/±45°/90°]
Fiber content (% vol)	~ 45%	~ 50%	~ 55%
Fiber	.004D B	.004D B	.0075D HMS G
Filler	Al	P13N	3002
Sheet size	~ 4" x 7"	~ 4" x 7"	~ 4" x 7"
ISOLATOR BUSHING*	Molded Ceramic (~125 pcf)	Molded Ceramic (~125 pcf)	PI Molded (~120 pcf)
Diameter O.D.	4@ .5/.375	4@ .5/.375	4@ .5/.375
Diameter I.D.	3/16"	3/16"	3/16"
Thickness	.175"	.175"	.175"

TABLE I. TEST SPECIMEN COMPONENT DESCRIPTION (CONTINUED)

	B/M1	B/PI	S/E
ISOLATOR BLOCK	Chem Ceram (~25 pcf)	Chem Ceram (~25 pcf)	PBI foam (~30 pcf)
Width/length	1"/1.25"	1"/1.5"	1"/2.25"
Depth	1"	1"	1"
Bolt Hole Diam.	3/16"	3/16"	3/16"
STANDOFF			
Material	#304 Stainless Steel	#304 Stainless Steel	#321 Stainless Steel
Thickness	.020"	.020"	.032"
Height	1.20"	1.20"	2.25"
Depth	1"	1"	1"
FIBROUS INSULATION	6 pcf Dynaflex	6 pcf Dynaflex	6 pcf Dynaflex
Thickness above composite	2.45"	2.70"	4.50"
Thickness below composite	4.0"	3.80"	2.0"
Surface Overlay Specimen	Refrasil Cloth	Refrasil Cloth	Refrasil Cloth
Number of Thermocouples	7 Total	7 Total	7 Total

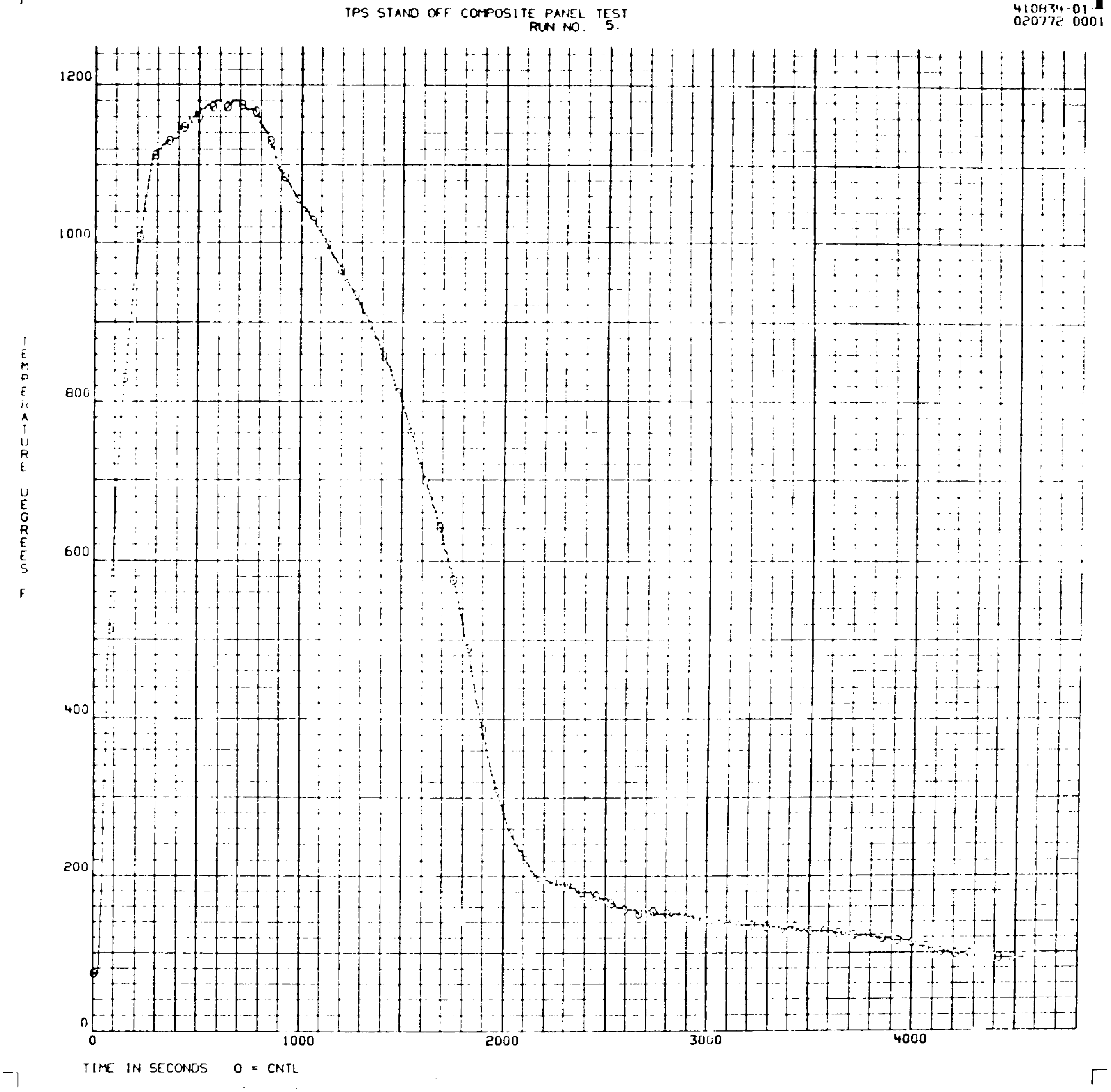
* Dimensions shown are for procurement purposes.
Bushings will be fit to test configuration during assembly.

TABLE I. TEST SPECIMEN COMPONENT DESCRIPTION (CONTINUED)

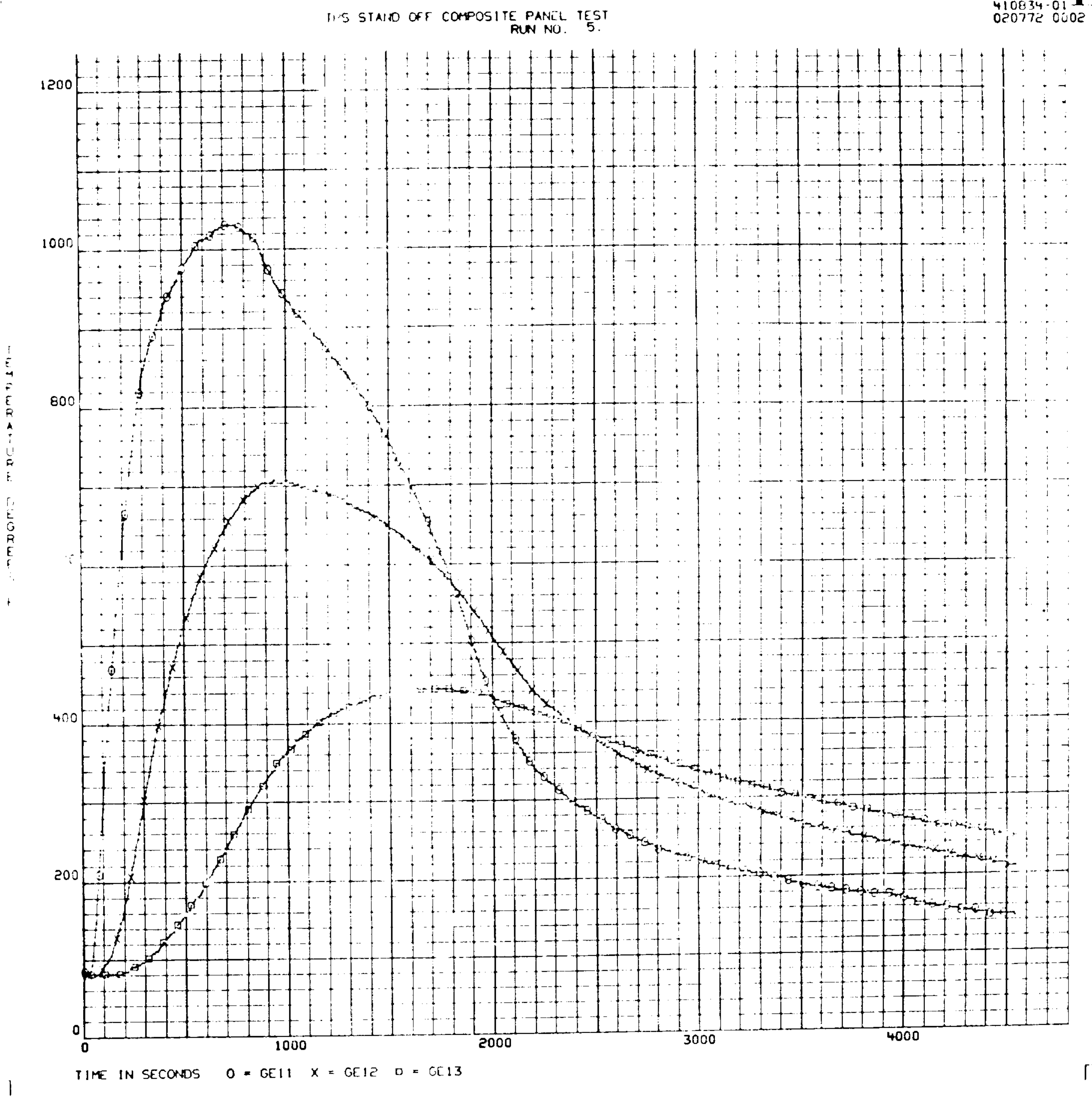
	B/Al	B/PI	G/E
FASTENERS			
Machine Screws	NAS1133C-24 (3 req'd)	NAS1133C-28 (3 req'd)	NAS1133C-40 (3 req'd)
Nuts		ME 114-0002-0004 (10 req'd)	
Washers		LD 153-0002-2203 (12 req'd)	

APPENDIX D

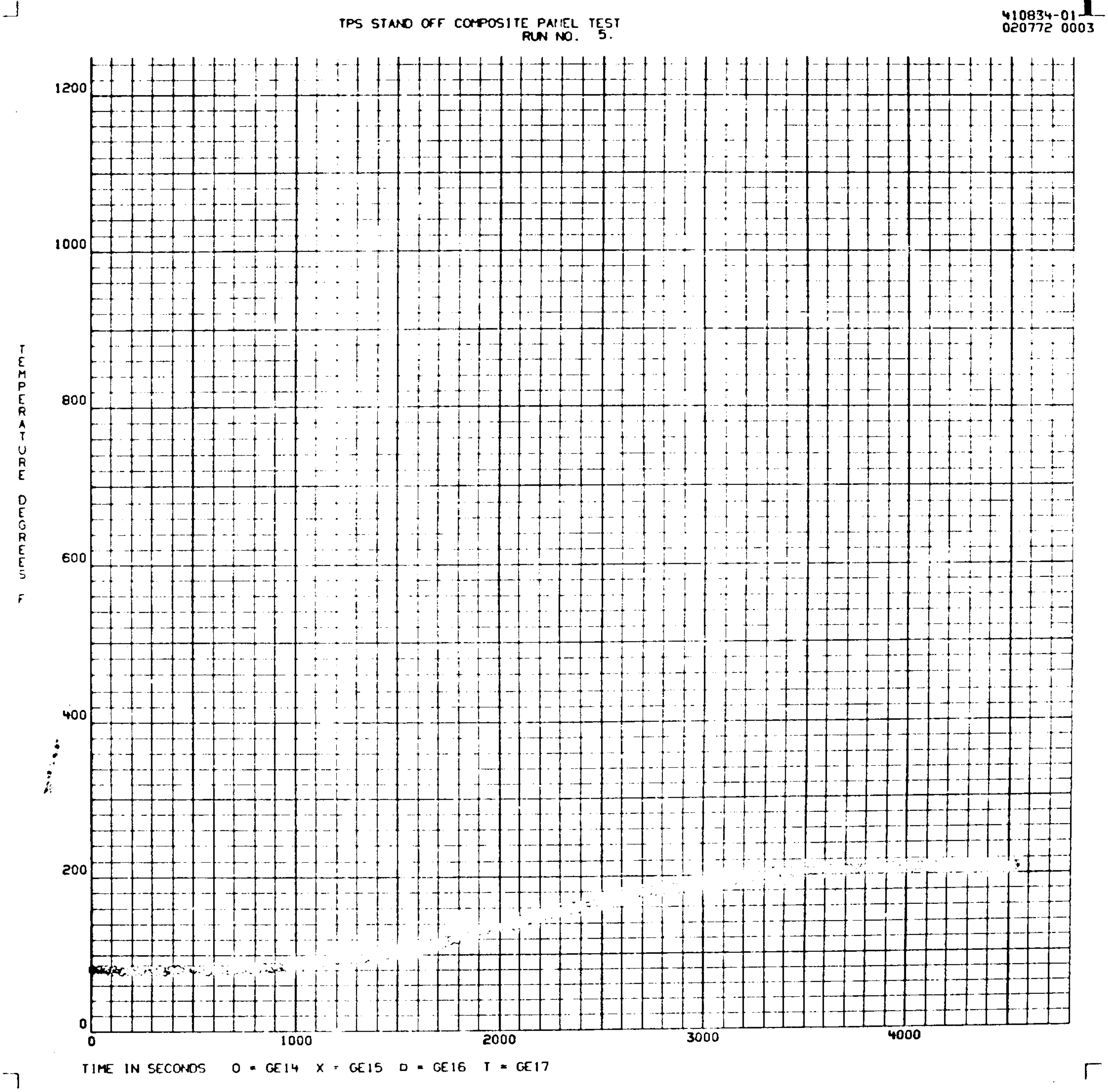
CONTROL TEMPERATURE - 1200F ENVIRONMENT



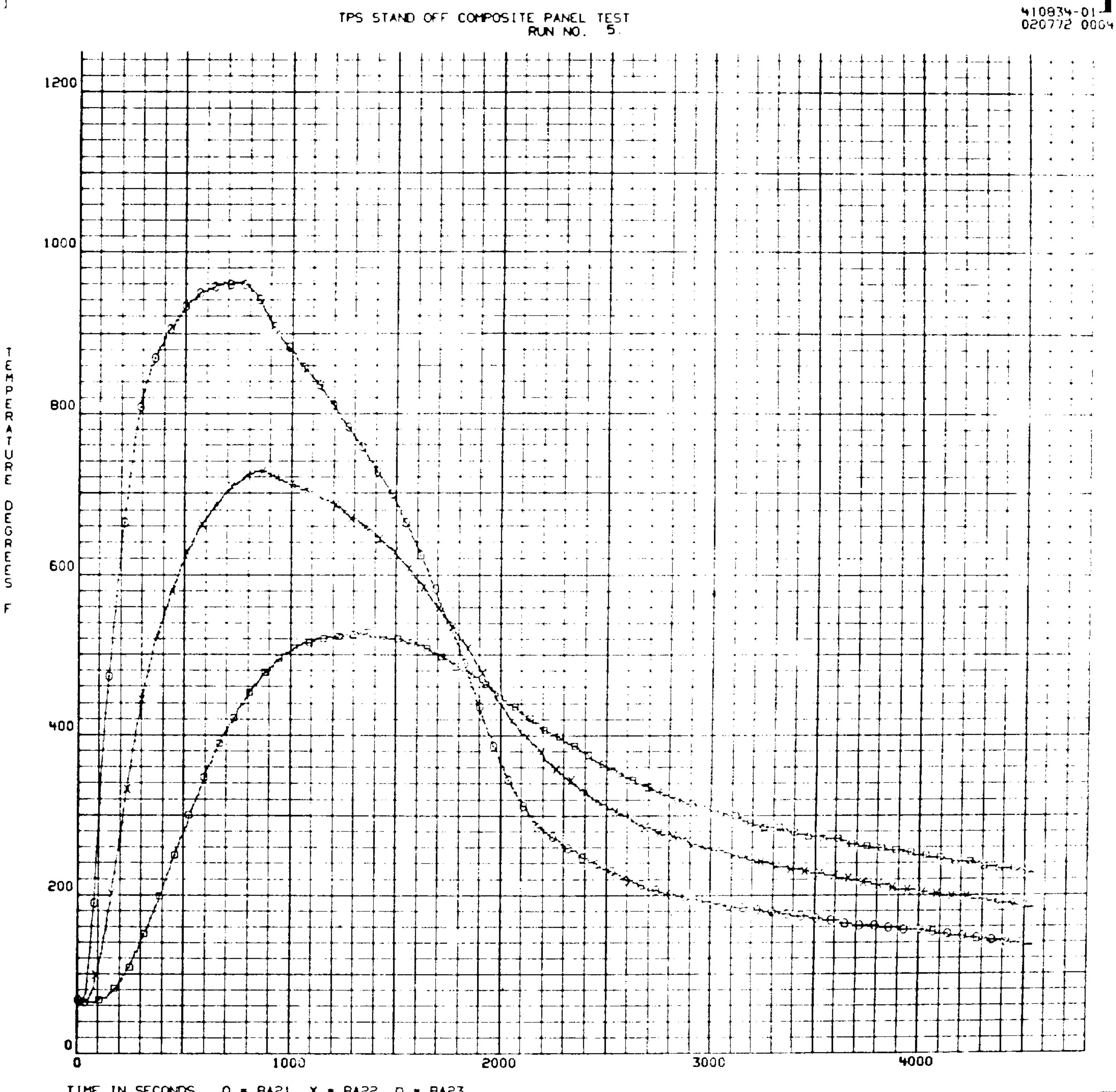
STANDOFF TEMPERATURES - 1200F ENVIRONMENT, GRAPHITE/EPOXY



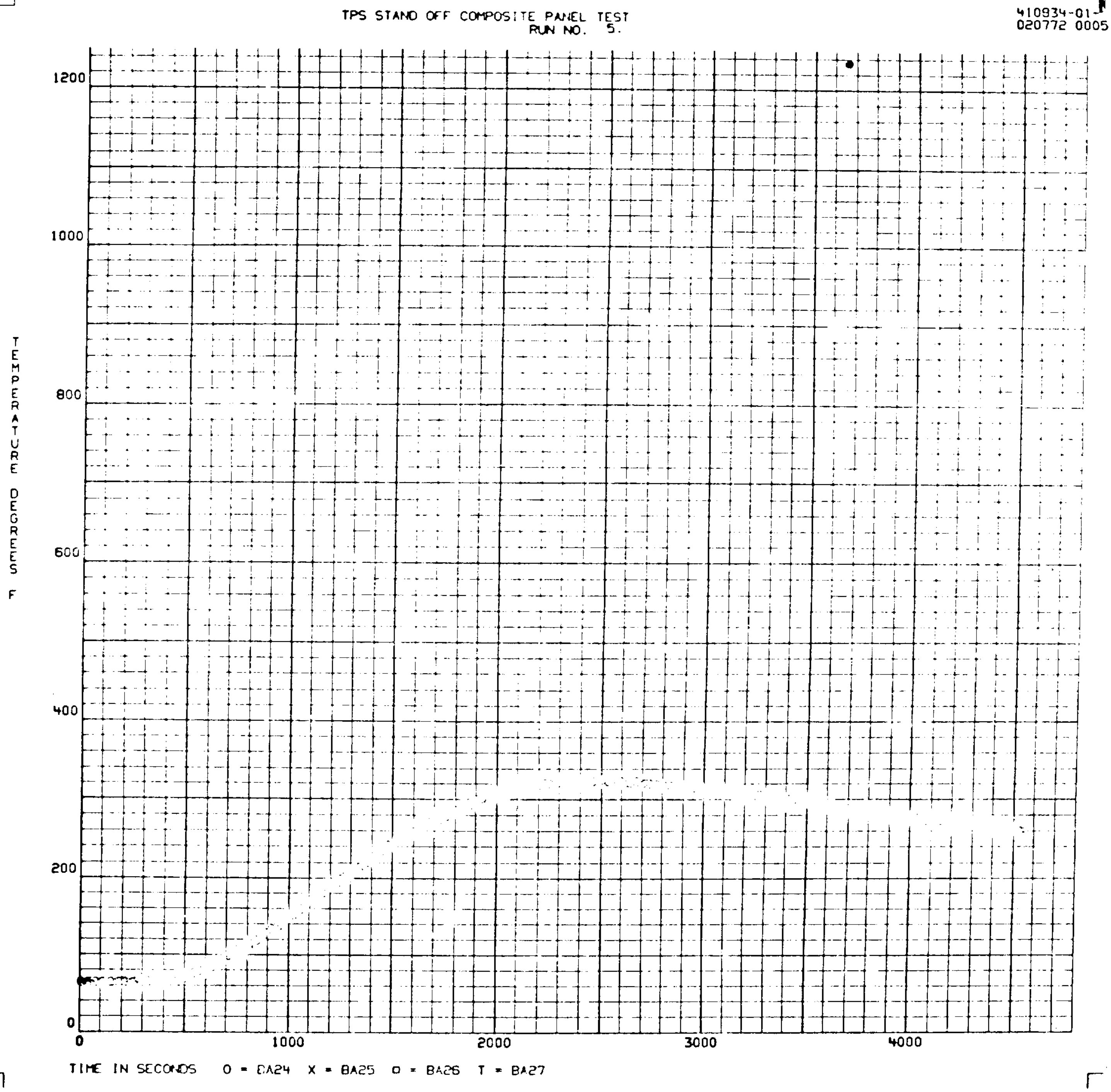
COMPOSITE TEMPERATURES - 1200F ENVIRONMENT, GRAPHITE/EPOXY



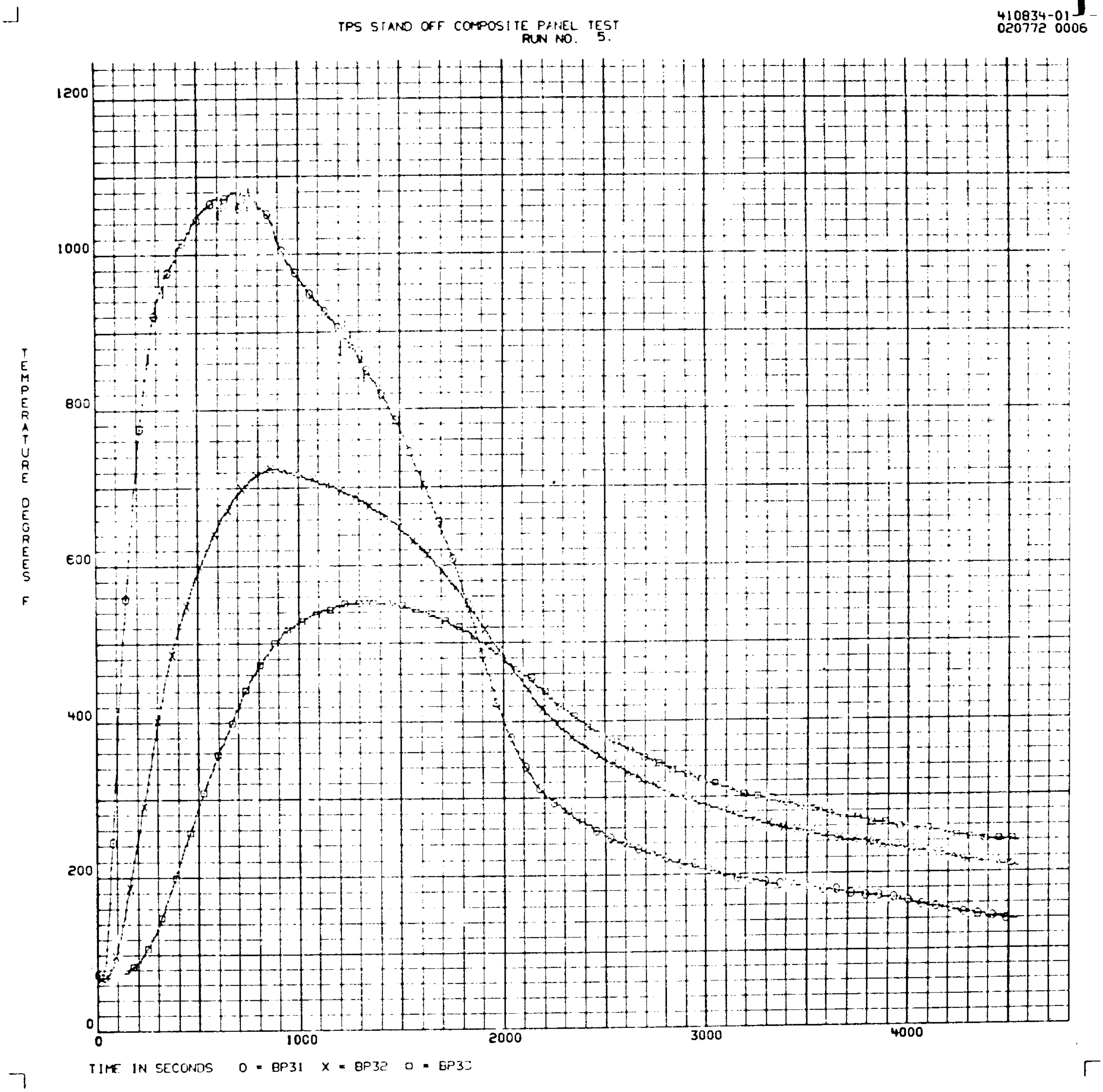
STANDOFF TEMPERATURES - 1200F ENVIRONMENT, BORON/ALUMINUM



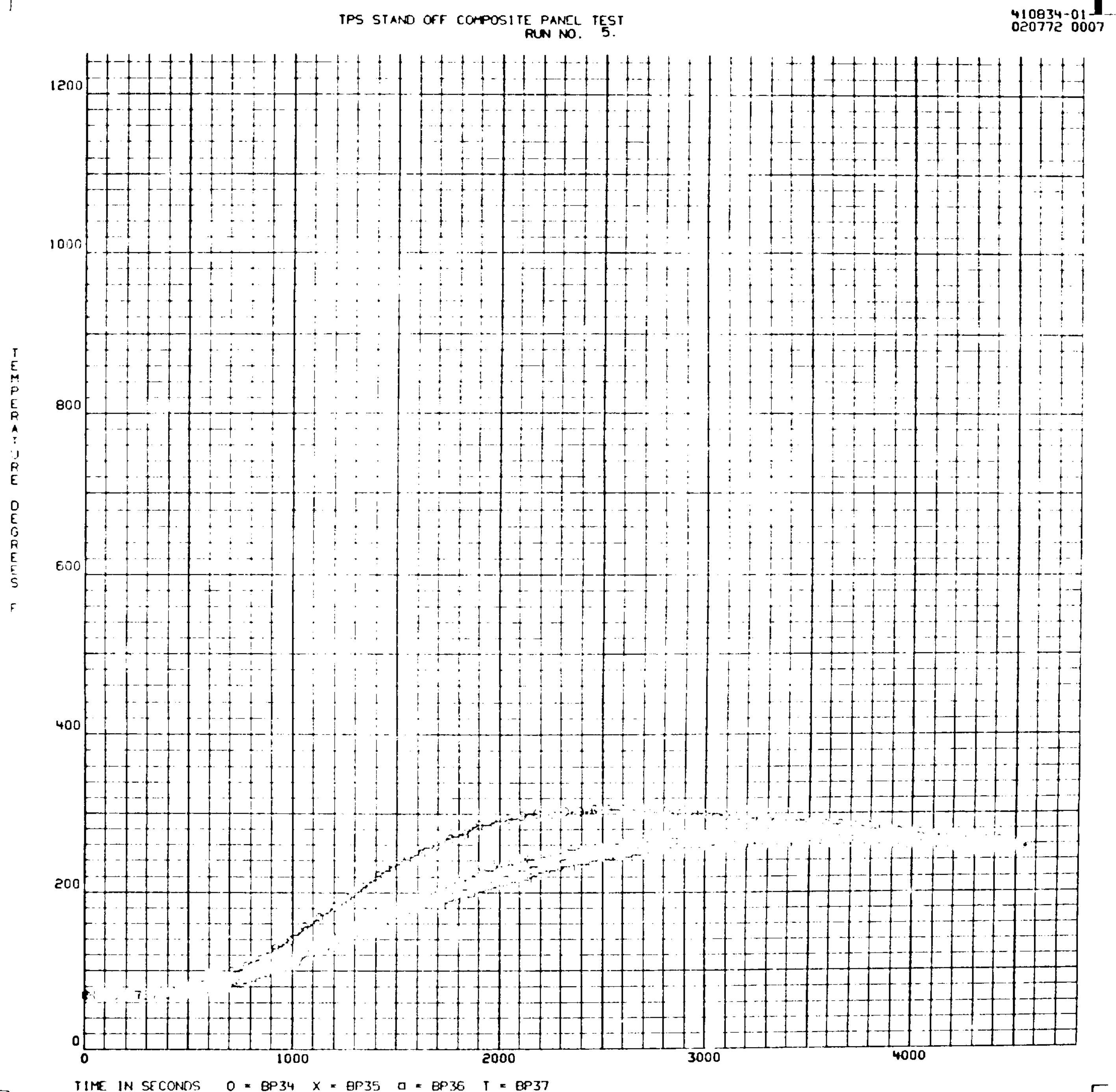
COMPOSITE TEMPERATURES - 1200F ENVIRONMENT, BORON/ALUMINUM



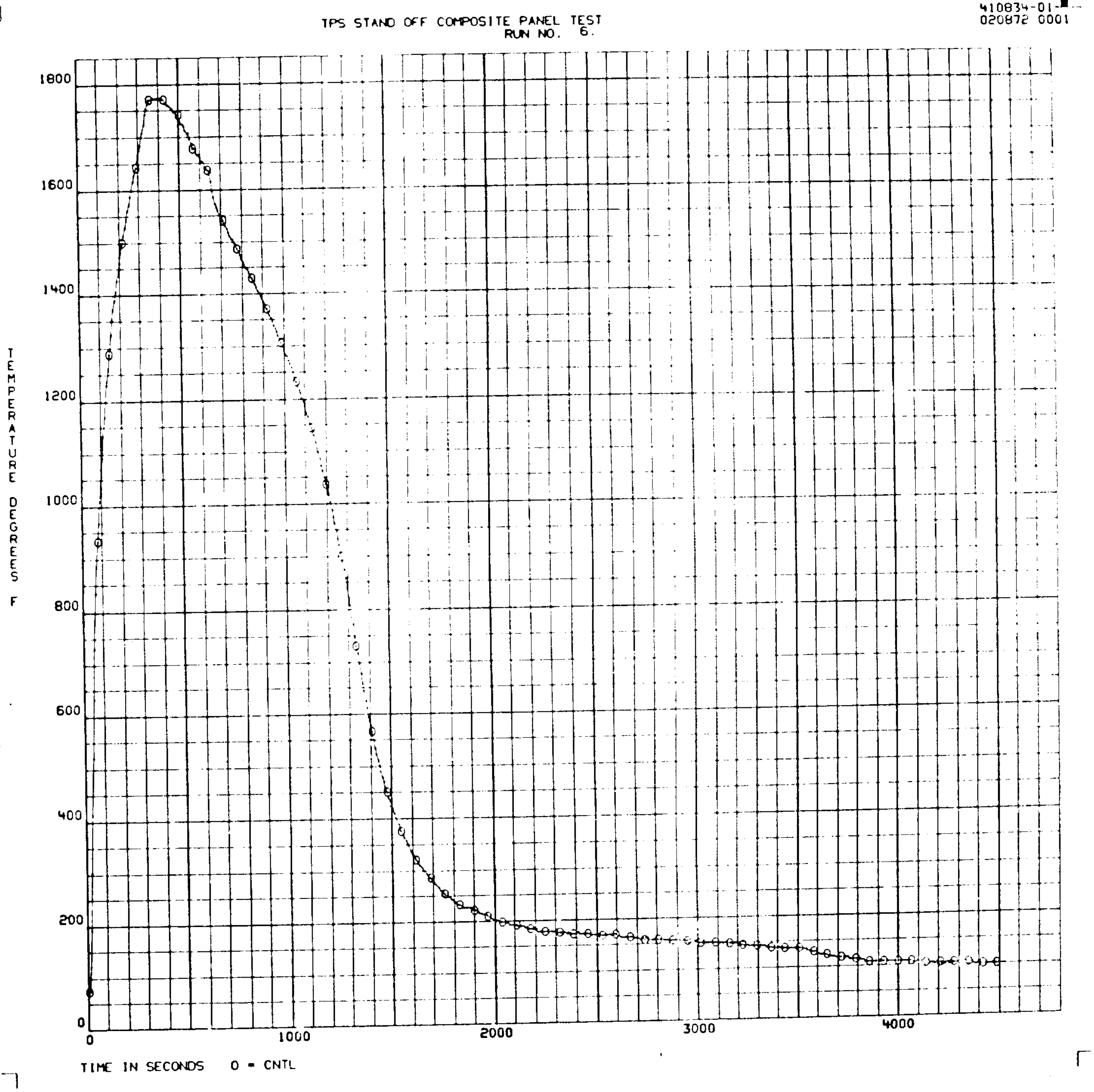
STANDOFF TEMPERATURES- 1200F ENVIRONMENT, BORON/POLYIMIDE



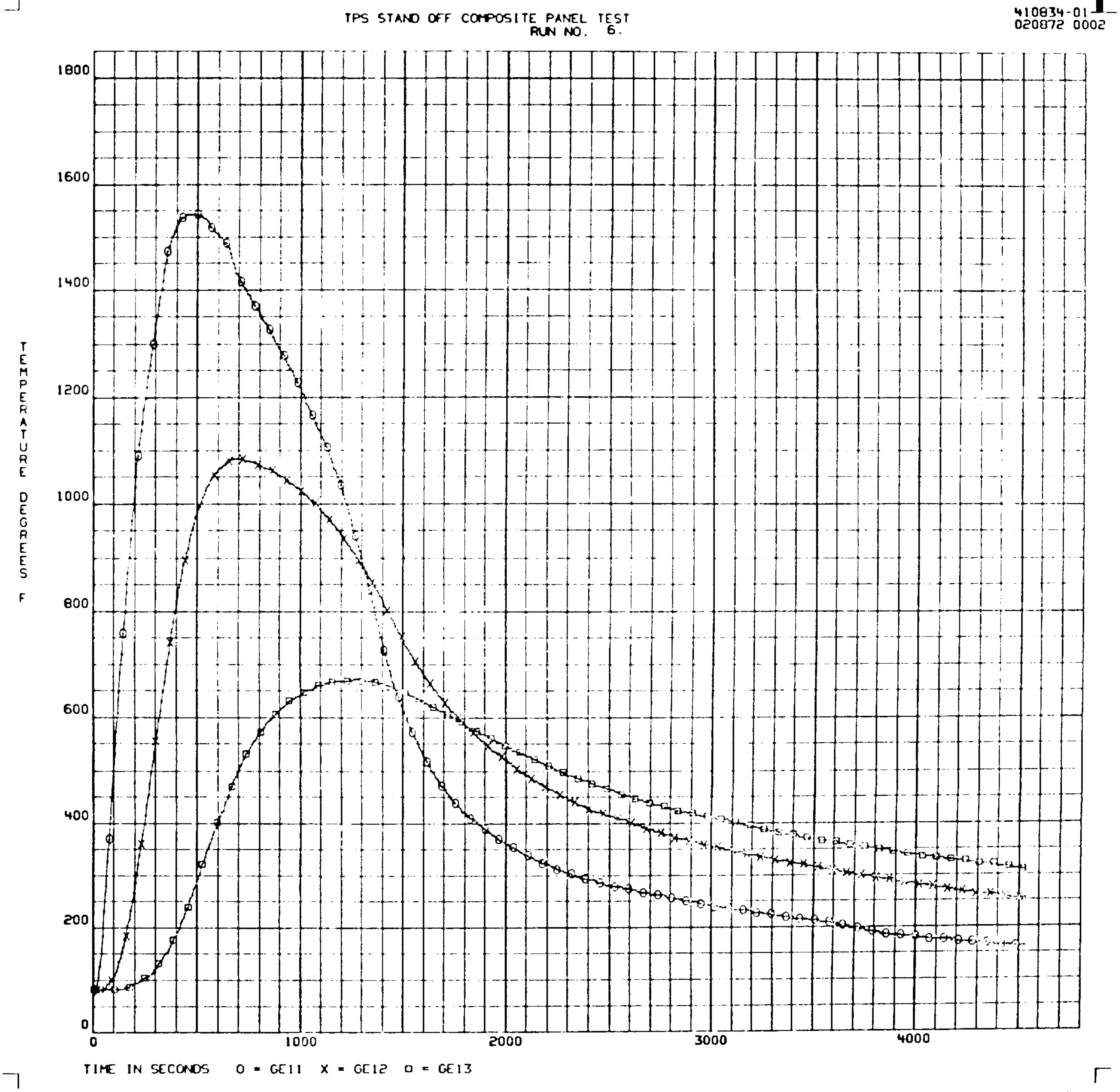
COMPOSITE TEMPERATURES - 1200F ENVIRONMENT, BORON/POLYIMIDE



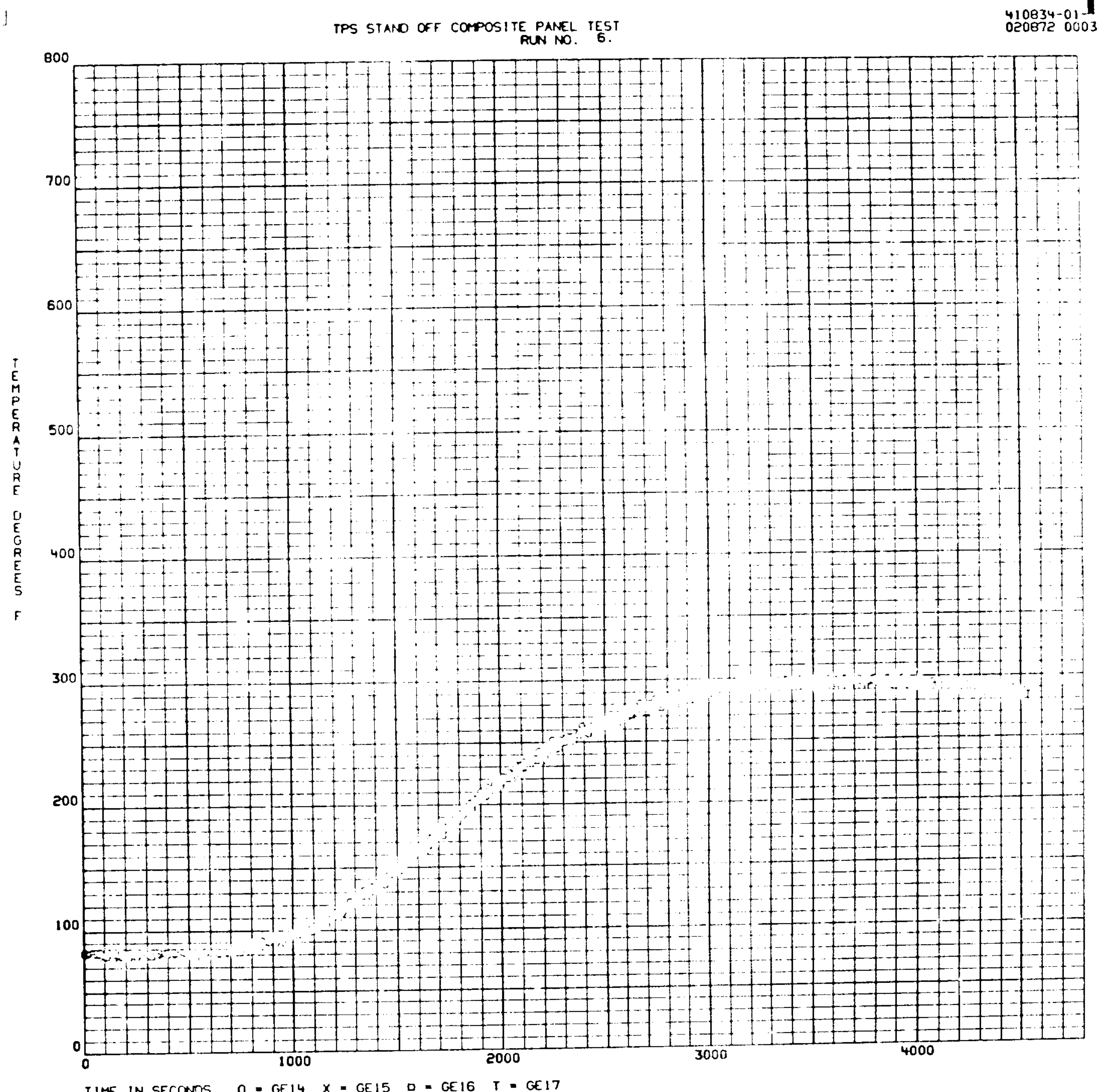
CONTROL TEMPERATURE - 1800F ENVIRONMENT



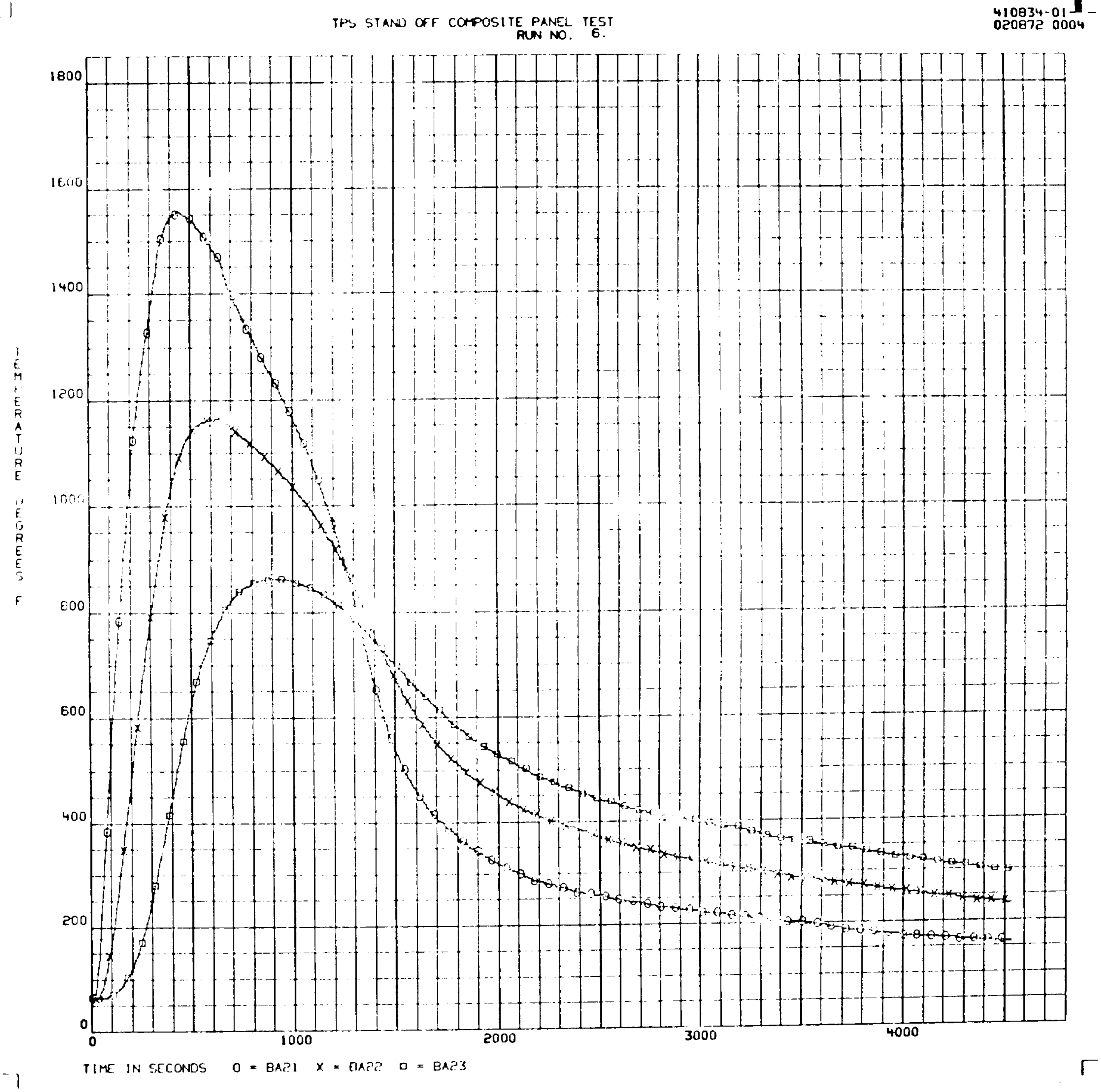
STANDOFF TEMPERATURES - 1800F ENVIRONMENT, GRAPHITE/EPOXY



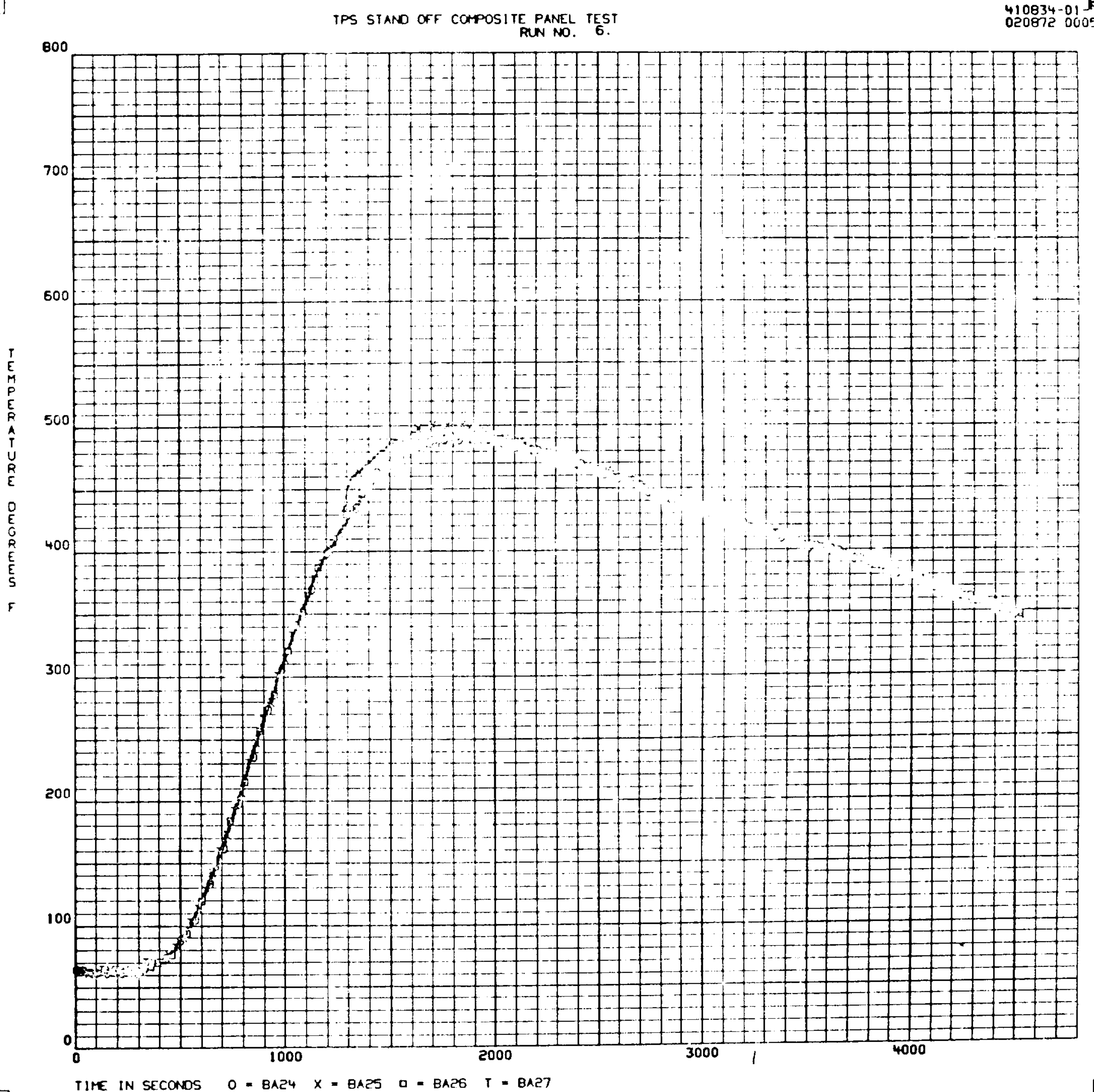
COMPOSITE TEMPERATURES - 1800F ENVIRONMENT, GRAPHITE/EPOXY



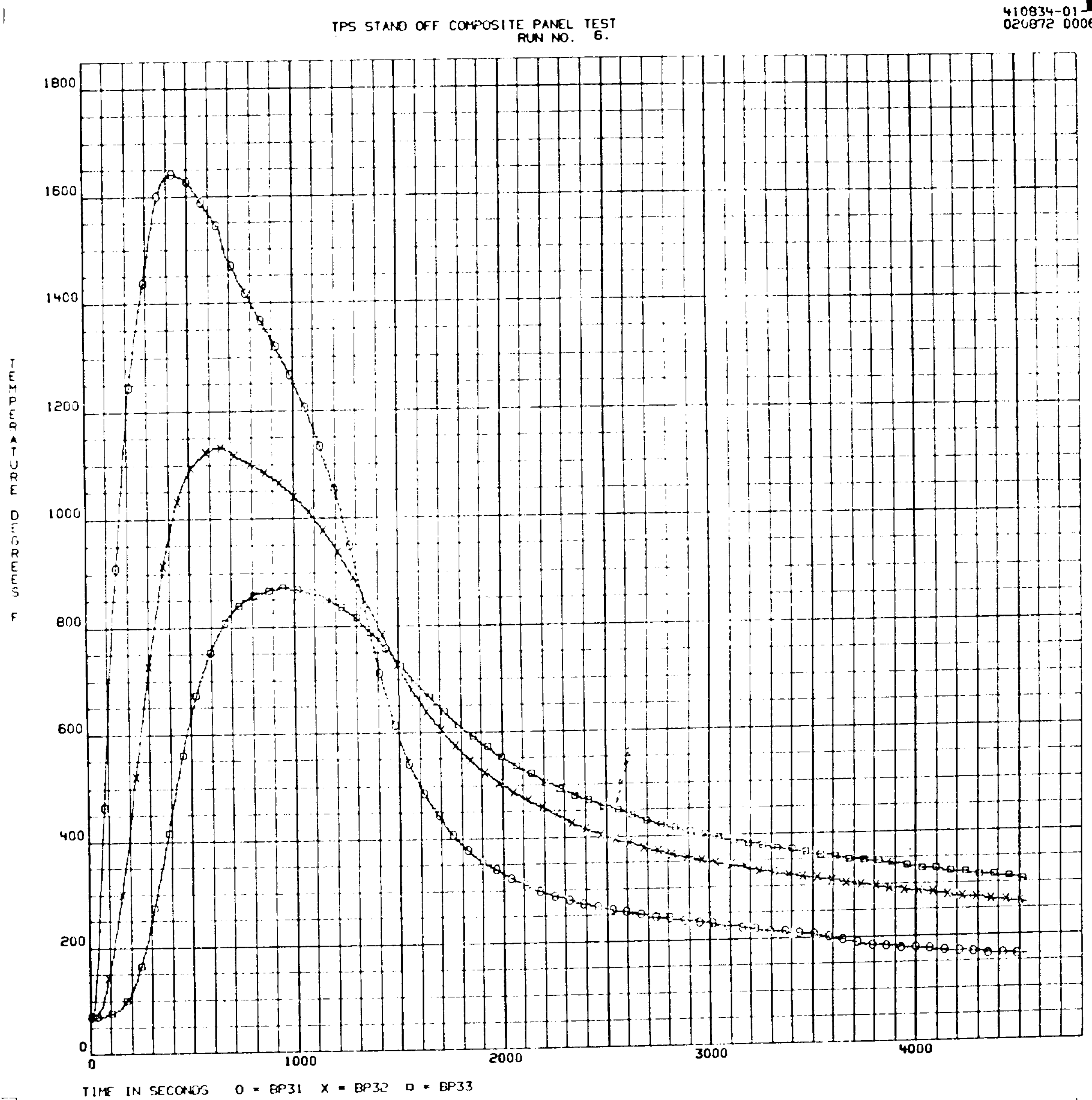
STANDOFF TEMPERATURES - 1800F ENVIRONMENT, BORON/ALUMINUM



COMPOSITE TEMPERATURES- 1800F ENVIRONMENT, BORON/ALUMINUM



STANDOFF TEMPERATURES - 1800F ENVIRONMENT, BORON/POLYIMIDE



Space Division
North American Rockwell

COMPOSITE TEMPERATURES- 1800F ENVIRONMENT, BORON/POLYIMIDE