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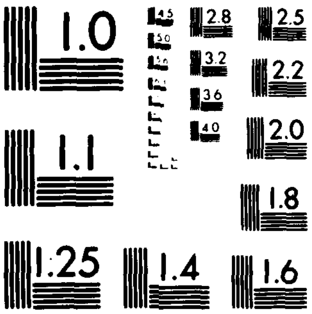

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Results of a Government and Industry Survey of the Heating Methods Used to Determine Missile Structural Temperatures

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The design and development of missile structures in an elevated temperature environment (Mach 2 to 6) has been demonstrated on many flight test and production programs. The approaches to structural design at elevated temperature were varied; each tailored to the unique, immediate technical challenges and schedule milestones facing the program manager. A conservative formulation was evolved to deal with elevated temperature effects and configuration complexities associated with the project at hand. A good structural design requires the expertise of many specialists and cuts across several technologies. A government and industry survey on structural design criteria and heat transfer analysis procedures to account for the effects of elevated temperatures was completed. This paper presents a summary of the results of the heating methods currently used.

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INTRODUCTION

Future missile systems designed to operate in the supersonic/hypersonic flight regime will encounter high structural temperatures due to the combination of aerodynamic heating on the external surface and combustion heating within the vehicle. Accurate prediction of the thermal environments and resultant structural temperatures is important for the selection of materials and the design of the vehicle structure. In the past three decades significant advances have been made in the development of heat transfer methods and experimental procedures for hypersonic vehicles. Some of these methods and procedures are being used to design current and future missile systems.

A government and industry survey (questionnaire plus selected field trips) was completed to provide a better understanding of how these methods and procedures are used in missile design criteria. The survey was organized according to the various involved disciplines. It was distributed to 37 government and industry organizations actively working in the design of missile systems. Twenty-seven completed or partially completed responses were returned. This paper presents a summary of the results for aerodynamic heating, convective heating and structural temperature analysis.

AERODYNAMIC HEATING

A better understanding of the aerodynamic heating methods used to predict missile structural temperatures is a key factor in developing sound design criteria. A typical missile flow field structure and related aerodynamic heating region is presented in Figure 1. Aerodynamic heating is the primary input that determines the missile skin temperatures, internal structural temperatures and temperature gradients. The subject has been studied both experimentally and analytically over several decades with most of the effort devoted to high supersonic and hypersonic flight regimes. With the advent of computers and high speed flight heat-transfer data, substantial improvements have been made in the technology. Current missile program plans require improvements in the methodology for missiles operating in the Mach 2 to 6 flight regime.

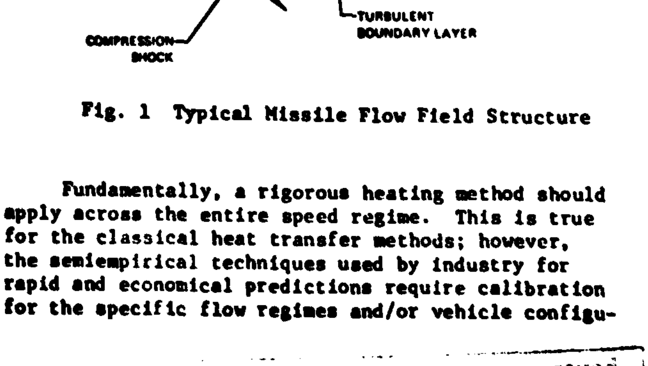

Fig. 1 Typical Missile Flow Field Structure

Fundamentally, a rigorous heating method should apply across the entire speed regime. This is true for the classical heat transfer methods; however, the semiempirical techniques used by industry for rapid and economical predictions require calibration for the specific flow regimes and/or vehicle configu-

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rations. The aerodynamic heating portion of the survey was designed to provide an updated understanding of the principal methods used by government and industry personnel. Results of the survey have been organized into selected flow regions to provide a clear picture of the methods employed. Table 1 contains the questions included in the survey together with brief summaries of the answers.

Windward Region

The windward region discussed herein is defined as the main body of the vehicle that has a positive flow deflection angle. The methods used to predict temperatures in these regions are very important. The temperatures are used to help select materials that will meet the design requirements with a minimum penalty on vehicle performance and cost. Perhaps the most severe structural temperature gradients (both in-board and peripheral), and therefore thermal stresses, are produced in this region. To calculate the heating the engineer must choose a flow field method that properly defines the inviscid flow. The choice is often difficult because of flow discontinuities created by the engine inlet. Elaborate computer codes have been developed to solve for the flow fields, but they are cumbersome and expensive. For engineering analyses the most useful solutions are based on simple body shapes such as flat plates (wedges), cones, hemispheres and cylinders. Several heating methods exist for these shapes and are used throughout the industry.

Participants were asked to identify (Table 1, Questions 1.1 and 1.2) which flat plate and cone heating method they use for laminar and turbulent flow. A majority of those surveyed use Eckerts reference enthalpy method (Reference 1) for both laminar and turbulent flow on a flat plate. The second and third choices for turbulent flow were Spalding-Chi (Reference 2) and Van Driest (Reference 3) respectively. For heating on a cone the respondents selected Eckerts reference enthalpy method on a flat plate with corrections for cross flow. The second and third choices were Lees and Reshotko (Reference 4) respectively.

Stagnation Region

The stagnation region discussed below is divided into two flow regimes: (1) stagnation point and (2) stagnation line. The stagnation point generally experiences the highest heating of any location on the missile. Fortunately, however, the high heating is limited to a small region near the stagnation point. Materials selected for use in this region must be capable of operating at or very near the peak recovery temperature which is determined by the missiles Mach-altitude trajectory. Perhaps more experimental heat transfer data have been obtained for the stagnation point and immediate region than any other flow regime. Excellent correlations exist between theory and experiment. The stagnation line includes the leading edge region of wings, fins, engine inlets and other lifting or control surface that protrude from the main body. Viscous flow over these surfaces can be laminar, transitional or turbulent depending on the freestream conditions. The similarity of flow between the stagnation line and the stagnation point, together with, the large amount of test data, have provided an excellent correlation between theory and data.

Participants in the questionnaire were asked to identify which stagnation heating method they used (Questions 1.3 and 1.4). For laminar flow at the stagnation point the method defined by Fay-Riddell (Reference 5) was the overwhelming choice. For laminar flow on the stagnation line the participants were evenly divided between Lees and Fay-Riddell. For turbulent flow, a majority use the method of Beckwith and Gallagher (Reference 7) followed closely by the method of Detra and Hidalgo (Reference 8). A small number of participants use flat plate methods such as $\rho_R u_R$, Van Driest or Colburn with corrections for cross flow.

Boundary Layer Transition

Boundary layer transition has been, perhaps, the most studied and least understood viscous flow phenomenon. For over 70 years the subject has been studied both analytically and experimentally. Vast amounts of data have been generated, evaluated and correlated. Correlations have been made with practically every known parameter. However, it appears that a solution is no closer than the early work by Tollmien (Reference 9) or Schlicting (Reference 10). It has been suggested (B.M. Ryan, Reference 11) that today's transition criteria are subject to change based on tomorrow's data--until a basic understanding of the phenomena is achieved.

The choice of a transition criterion is important for the successful design of the missile radomes. Thermal stress levels can exceed the structural capabilities of current domes and an incorrect choice of the transition criteria can lead to unacceptable design margins. Respondents were asked in the questionnaire to identify which transition criteria they use for heat transfer calculations (Question 1.5). A majority of those surveyed use the local Reynolds number method. The second most commonly used is the momentum thickness Reynolds number method. The two methods are basic approaches to estimating transition and usually produce a conservative design. The survey did not uncover any participants using a complex correlation parameter such as those developed during the Shuttle program. Also, in a number of the responses the participants stated that they assume all turbulent flow. In summary, it appears that most of the participants choose to follow a conservative approach to the thermal design of a radome.

Design Heating Methods

Design heating methods discussed below refer to the methods and procedures used to obtain aerodynamic heating for three levels of design (preliminary, detailed and final). The missile engineer has several options available to assist him in predicting aerodynamic heating: (1) computer programs, (2) wind tunnel data, (3) flight data, and (4) handbook charts or curves. Experience has shown that the use of a specific option in the preliminary design phase can significantly influence the final design. For example, preliminary design calculations are often used well into the design phase. Changes are allowed during the detailed design phase and are usually based on test data. If planned tests cannot be accomplished on time and the data reduced, the preliminary design calculations become final. It is therefore important to understand the level of detail the engineer uses to predict aerodynamic heating for preliminary, detailed and final design analysis.

Respondents to the questionnaire were asked to identify their preferred methods for predicting heating for preliminary, detailed and final design (Questions 1.6, 1.7 and 1.8). For preliminary design a majority use a computer to predict heating while a significant minority indicated that they use parametric curves or design charts. For detailed design, a majority indicated that they use a computer to predict heating and wind tunnel data to verify their theoretical model. Nearly all participants indicated that they use a computer model for the final design phase. In summary, the evolution of thermal analysis for a missile design is as follows: (1) a rough computer model using basic shapes to estimate the configuration for preliminary design, (2) a refined computer model which has been verified and/or modified with wind tunnel data, and (3) a final computer model for design verification and any off nominal trajectory calculations.

Secondary Heating

The questionnaire included two aerodynamic heating topics normally considered of secondary importance in missile design heating analysis. The topics which are discussed below are: (1) entropy layer effects and (2) surface roughness effects. Entropy layer effects on aerodynamic heating have been shown to be most important for the supersonic/hypersonic flight regime (see Figure 2). In the nose region a normal or near normal shock must be crossed and the loss of total pressure in the inviscid flow combined with variable surface pressures create a complex analytic problem. The prediction of heating in this region requires a complex computer solution that can be expensive. A simple flow model can be used if the surface pressure is known. The approach consists of calculating the heating based on properties obtained from a specified shock angle followed by an expansion to the local pressure. The questionnaire addressed this subject (Question 1.9) to determine in what phase of the design the participant considers entropy effects important. The majority indicated that they consider entropy effects during the detailed design phase. A large number indicated that they did not consider entropy effects until final or the verification phase. Also, a significant number did not include entropy effects at any point in their analysis.

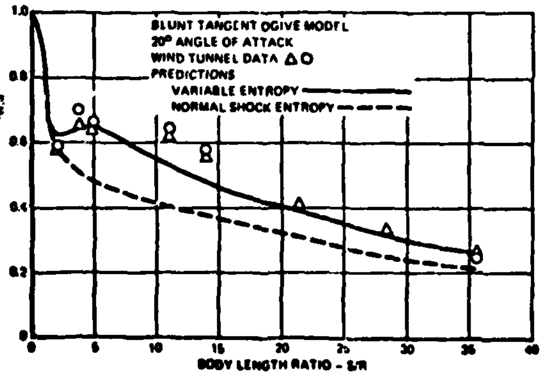

Fig. 2 Entropy Effects Increase Windward Heating Rates

Surface roughness effects become increasingly important as the missile flight speed is increased. Ablation from the radome surface increases the surface roughness thereby promoting boundary layer transition. The participants were asked to identify the design phase in which they give consideration to surface roughness (Questions 1.10). The majority consider roughness effects during the detailed design phase. A much smaller group considers roughness effects only during the final design. A significant group did not consider roughness effects important.

Methodology Work

Substantial improvements have been made in aerodynamic heating technology through the use of high speed flight data. The major emphasis has been in the hypersonic flight regime (re-entry vehicles). Missiles under current development in the Mach 2 to 6 flight regime (and potentially higher) could benefit significantly from improvements in heat transfer methodologies. The improvements are needed to reduce the uncertainty in predicting skin and structural temperatures to provide a payoff in design margins. To assess the current level of methodology work throughout the industry, the participants were asked to identify any work currently in progress or recently completed by their organizations (Question 1.11). A majority of participants indicated that their organizations were not currently working on and had not recently completed any heat transfer methodology development. A small number indicated that their methodology work consisted of updating existing in-house computer programs. Although a number of participants responded with brief abstracts of methodology work from their organizations, only a small number were identified as applicable to the Mach 2 to 6 missile flight regime.

Flow Fields

A typical missile flow field structure can be complex and the engineer must choose the proper method to define the shock layer and downstream flow properties. From these properties, the recovery temperature and the aerodynamic heat transfer coefficients are calculated. Although elaborate computer codes, such as the Method of Characteristics, have been developed to solve the flow field problem, they are cumbersome and expensive to apply. For engineering analysis, the most expedient flow field solutions are often based on simple body shapes such as flat plates, cones, hemispheres and cylinders. The engineer must choose which basic shape best approximates the flight vehicle configuration. The engineer must also choose which analysis tool (elaborate computer code, computer code with basic shapes or parametric curves) to use for preliminary, detailed or final design analysis. The participants were asked to identify in what phase of design (preliminary, detailed or final) they use a computer program to solve for the flow field structure (Question 1.13). A majority use a computer program during the detailed design phase. The second choice was a tie between the preliminary and final design phases. In summary, it appears that the participants consider a good description of the flow field structure essential for all phases of design analysis.

Special Areas

The special areas of aerodynamic heating that require an increasing amount of attention due to the higher Mach number regimes are: (1) leeward side (separated, reattached and vortex flow), (2) interference regions (fins, wings and duct inlets), and (3) protuberances and gaps.

Leeward Side. The flow on the leeward surface can be attached, separated or under the influence of strong vortices. Attached and separated flow heating rates are relatively low due to the low pressure expansion region. Heating predictions in these regions are extremely difficult due to the complex flow structure. Vortices can start in the boundary layer and extend into the inviscid flow region depending on vehicle geometry and stream parameters. Associated with vortex flow is a reattachment region which has significantly high heating rates. Both the onset of vortex flow and the increase in heating are very difficult to predict.

Participants in the questionnaire were asked to define the methods they use to predict heating in these regions (Question 1.14). A majority indicated that they prefer to use wind tunnel data. If no data are available for their particular configuration, they search the literature for applicable correlations. Several participants use multiplying factors which are applied to an equivalent flat plate heating value.

Interference Regions. Interference regions discussed below refer to heating on fins, wings and duct inlets and the region near their attachment to the missile body. Substantial experimental work has yielded several semiempirical techniques that can be used to estimate the heating (see Figure 3). The heating is principally due to higher local pressures induced by the shock boundary-layer interaction. These regions are very important to structural design engineer due to the increased temperatures.

Participants were asked to identify their preferred methods for predicting heating in these regions (Question 1.15). The majority prefer to use wind tunnel data supported by, or compared with, data correlations published in literature.

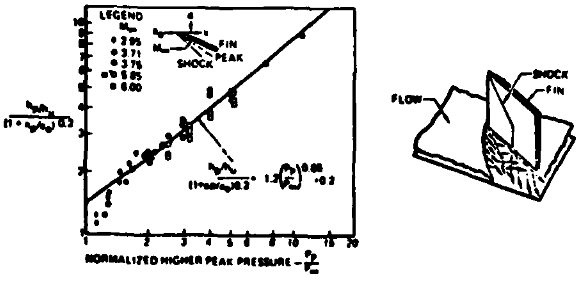

Fig. 3 Interference Heating Correlation

Protuberances and Gaps. Missile surfaces are usually smooth with minimum flow disturbances. However, as the flight Mach number increases, local heating becomes more severe and protuberances and gaps can become increasingly important. Protuberances (forward and aft facing) can be created when two materials with different thermal expansion coefficients are joined. A protuberance can increase the local heating and produce a higher temperature region on the structure. Also, to allow for thermal growth at these higher Mach numbers, gaps in joints must be incorporated. The gaps can increase the heating in the joint and affect the structural design.

Participants were asked to define their preferred methods for heating in protuberances and gaps (Question 1.16). A majority prefer to use wind tunnel data compared with data from the literature. The second most used method is to apply a safety factor to the undisturbed value in the region of the disturbance.

In summary, for the special areas of aerodynamic heating where complex flow over the missile cannot be evaluated analytically, the participants prefer to use wind tunnel data augmented by or compared with empirical correlations from literature.

INTERNAL FORCED AND FREE CONVECTION

Internal forced and free convection can have a large influence on missile structural and component temperatures. In many cases, heating from internal flow and combustion is the dominant heat source.

Inlet and Ducts

Inlet and duct flow can usually be characterized as an internal boundary layer developing under both adverse and favorable pressure gradients. While much research has been done in the general area and computer programs are available for performing these calculations, rarely is a detailed boundary layer analysis used in predicting design temperatures. Correlations such as Bartz (Reference 12) and pipe flow were found to be the most popular methods among the participants (Question 1.17). These methods are generally applied with some conservatism early in the design process with the predicted structural design temperatures being modified to correlate with experimental data as they become available.

Combustor and Nozzle

Prediction of structural temperatures in the combustor and nozzle regions may involve the consideration of forced convection, wall radiation, gas/particle radiation, and thermochemical reactions. Due to the complexity of the forced convection in these regions, recourse is usually made to turbulent pipe flow and correlations such as Bartz. A majority of participants in the survey use the Bartz correlation (Question 1.18). Analyses in these regions are usually conservative with the degree of conservatism decreasing when design verification testing is performed. Conservatism is generally applied in the heat flux calculation and/or in sizing the insulation/ablative material or cooling system.

Free Convection

Where free convection is considered important, the majority of participants use the classical textbook analysis for horizontal and vertical surfaces. A large number of those surveyed do not consider free convection important in most structural areas (Question 1.19).

STRUCTURAL TEMPERATURE ANALYSIS

Thermal Models

Methods and procedures used to calculate missile structural temperatures are additional factors in developing sound design criteria. It is important to understand the following: (1) how thermal models are formulated, (2) how node size and spacing are determined, (3) what method is used to analyze heat transfer across interfaces, and (4) how uncertainties in material properties are included in the analysis. For thermal modeling, the participants were asked to identify the design phases (preliminary, detailed or final) during which they use two and three dimensional models (Question 2.1). The preferred approach is to use two-dimensional models for preliminary and detailed design and three-dimensional models for detailed and final design calculations. Engineering judgement is used for selecting node size and node spacing (Question 2.2). For interface conductance (Question 2.3), the results indicate that most engineers prefer using test data. Generally, most engineers have a variety of computer programs available to perform conduction calculations. Most of these programs are based on the finite difference method. The finite element method is being used mostly in large analyses, particularly when a transfer of temperature data to a structural finite element program is necessary.

Major uncertainties in computing conduction within structural members are the material properties (conductivity, density and specific heat). The survey indicated (Question 2.4) that the majority of engineers use conservative values for material property data. A significant number evaluate the sensitivity to material properties to arrive at a safety factor. The way in which the material properties are factored depends on what condition is critical to the structural component (i.e., maximum temperature or maximum temperature gradient).

Radiation Heat Transfer

Radiation heat transfer between structural members becomes more important as the flight Mach number increases. The participants were asked to identify the methods they use to calculate internal radiation exchange factors (Question 2.5). Most participants use a computerized detailed view factor modeling analysis; such as the Thermal Radiation System Analyzer (TRASYS) computer program. A significant number use handbooks or standard textbooks to determine the view factors.

Heating Uncertainties

Procedures used to include heating uncertainties in structural temperature analysis were investigated. Participants were asked to describe their method or procedure for including heating uncertainties in the detailed design structural temperature analysis (Question 2.6). A majority indicated that heating uncertainties are included within their thermal models (use conservative assumptions) and the results are used as limit requirements. The second most used approach is to apply a constant factor to the calculated heating rate. The third choice selected is to use the most severe trajectory for detailed temperature analysis.

SUMMARY

Results of the questionnaire survey indicate that uncertainties are frequently not specifically accounted for in structural temperature analysis. Most engineers surveyed prefer using a computer during all phases of design (preliminary, detailed and final). Depending upon the complexity of the problem they use two and three dimensional models and use engineering judgement to determine node size and node distribution. The thermal models incorporate conservative values for material property data. Heating inputs to the models use conservative assumptions and are often based on a sensitivity analysis. Most analyst prefer using test data for all areas of thermal uncertainties.

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TABLE 1

SUMMARY OF SURVEY QUESTIONNAIRE

	QUESTION		RANKING OF ANSWERS		
			CONSENSUS	SECOND	THIRD
CONVECTIVE HEATING	1.1 IDENTIFY WHICH FLAT PLATE HEATING METHOD YOU USE?	LAMINAR TURBULENT	ECKERTS REFERENCE ENTHALPY ECKERTS REFERENCE ENTHALPY	* SPALDING-CHI	* VAN DRIEST
	1.2 IDENTIFY WHICH CONE HEATING METHOD YOU USE?	LAMINAR TURBULENT	FLAT PLATE/CROSS FLOW CORRECTIONS FLAT PLATE/CROSS FLOW CORRECTIONS	LEES LEES	RESHOTKO *
	1.3 IDENTIFY WHICH STAGNATION POINT HEATING METHOD YOU USE?		FAY-RIDDELL	*	*
	1.4 IDENTIFY WHICH STAGNATION REGION HEATING METHOD YOU USE?	LAMINAR TURBULENT	FAY-RIDDELL /LEES BECKWITH-GALLAGHER	 DETRA-HIDALGO	PE METHOD *
	1.5 WHICH BOUNDARY LAYER TRANSITION CRITERION DO YOU USE FOR AERODYNAMIC HEATING?		LOCAL REYNOLDS NUMBER	MOMENTUM THICKNESS REYNOLDS NUMBER	*
	1.6 WHAT ARE YOUR PREFERRED METHODS FOR PRELIMINARY DESIGN HEATING PREDICTIONS?		COMPUTER ANALYSIS	PARAMETRIC CURVES	*
	1.7 WHAT ARE YOUR PREFERRED METHODS FOR DETAILED DESIGN HEATING PREDICTIONS?		COMPUTER ANALYSIS *	WIND TUNNEL DATA	*
	1.8 WHAT ARE YOUR PREFERRED METHODS FOR FINAL DESIGN HEATING PREDICTIONS?		COMPUTER ANALYSIS	WIND TUNNEL DATA	*
	1.9 AT WHICH LEVEL OF THE DESIGN DO YOU CONSIDER ENTROPY LAYER EFFECTS?		DETAILED	FINAL OR VERIFICATION	PRELIMINARY/NOT CONSIDERED
	1.10 AT WHAT LEVEL OF DESIGN DO YOU CONSIDER SURFACE ROUGHNESS EFFECTS?		DETAILED	FINAL	NOT CONSIDERED
	1.11 WHAT AERO HEATING METHODOLOGY IS YOUR COMPANY WORKING ON?		NO COMPANY METHODS WORK	UP-DATING INHOUSE COMPUTER PROGRAMS	*
	1.12 AT WHAT LEVEL OF DESIGN DO YOU USE A COMPUTER PROGRAM TO SOLVE FOR THE MISSILE FLOWFIELD STRUCTURE?		DETAILED	FINAL	PRELIMINARY
	1.13 WHAT ARE YOUR PREFERRED METHODS FOR PREDICTING HEATING IN THE FOLLOWING REGIONS? (1) SEPARATED FLOW, (2) REATTACHMENT, (3) VORTEX		WIND TUNNEL TEST DATA	CORRELATIONS FROM LITERATURE	*
	1.14 WHAT ARE YOUR PREFERRED METHODS FOR PREDICTING INTERFERENCE HEATING IN REGIONS SUCH AS FINS, WINGS, AND DUCT INLETS?		WIND TUNNEL TEST DATA	CORRELATIONS FROM LITERATURE	*
	1.15 WHAT ARE YOUR PREFERRED METHODS FOR PREDICTING HEATING IN AREAS SUCH AS PROTUBERANCES AND GAPS?		WIND TUNNEL TEST DATA	SAFETY FACTOR APPLIED TO UNDISTURBED VALUE	*
	1.16 WHAT ARE YOUR PREFERRED METHODS FOR PREDICTING HEATING IN INLETS AND DUCTS?		TIE: ① BARTZ AND ② SUBSONIC FLOW ANALYSIS		TEST DATA
	1.17 HOW DO YOU CALCULATE INTERNAL HEATING FOR THE COMBUSTOR AND NOZZLE REGIONS?		BARTZ	BOUNDARY LAYER HEATING ANALYSIS	*
	1.18 WHAT METHOD DO YOU USE TO CALCULATE INTERNAL CONVECTION FOR STRUCTURAL TEMPERATURE ANALYSIS?		CLASSICAL TEXT BOOK APPROACH	DO NOT CONSIDER IMPORTANT	*
STRUCTURAL TEMPERATURE ANALYSIS	2.1 AT WHAT LEVEL OF DESIGN DO YOU USE TWO AND THREE DIMENSIONAL HEAT TRANSFER MODELS FOR STRUCTURAL TEMPERATURE ANALYSIS?	2D 3D	PRELIMINARY DETAILED	DETAILED FINAL	FINAL PRELIMINARY
	2.2 HOW DO YOU ACCOUNT FOR THERMAL MODEL SIZE (NUMBER OF NODES AND SPACING) WHEN PREDICTING DETAILED STRUCTURAL TEMPERATURES?		ENGINEERING EXPERIENCE	*	*
	2.3 HOW DO YOU ACCOUNT FOR INTERFACE CONDUCTANCE IN STRUCTURAL TEMPERATURE ANALYSIS?		TEST DATA	LITERATURE/HANDBOOK	*
	2.4 HOW DO YOU ACCOUNT FOR UNCERTAINTY IN MATERIAL PROPERTIES WHEN ASSESSING STRUCTURAL TEMPERATURES FOR DESIGN?		CONSERVATIVE VALUE/EVALUATE SENSITIVITY OF TEMPERATURES	APPLY A FACTOR TO NOMINAL VALUES	*
	2.5 WHAT METHOD DO YOU USE TO CALCULATE RADIATION EXCHANGE FACTORS FOR INTERNAL RADIATION?		DETAILED CALCULATION PROCEDURE **	HANDBOOK/TEXT BOOK APPROACH	
	2.6 FOR DETAILED DESIGN STRUCTURAL TEMPERATURE ANALYSIS HOW DO YOU ACCOUNT FOR HEATING UNCERTAINTIES?		INCLUDED WITHIN THERMAL CALCULATION AND RESULTS USED AS LIMIT REQUIREMENTS	APPLY CONSTANT FACTOR ON CALCULATED HEATING RATE	USE MOST SEVERE TRAJECTORY

* NOT ENOUGH RESPONSES TO SELECT SECOND AND THIRD RANKINGS

** TRASYS USED BY TWO RESPONDENTS

DATE

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