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ORBITER ENTRY AEROTHERMODYNAMICS

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ABSTRACT

The challenge in the definition of the entry aerothermodynamic environment arising from the challenge of a reliable and reusable Orbiter is reviewed in light of the existing technology. A balanced use of prior, current, and advanced levels of technological sophistication was employed to achieve reasonable design requirements, design heating, and preflight confidence, respectively. Select problems pertinent to the Orbiter development are discussed briefly with reference to more comprehensive treatments. These problems include boundary-layer transition, leeward-side heating, shock/shock interaction scaling, tile gap heating, and nonequilibrium effects such as surface catalysis. Sample measurements obtained from test flights of the Orbiter are presented with comparison to preflight expectations. In summary, a reliance on both numerical and wind-tunnel simulations has afforded an efficient means for defining the entry environment and an adequate level of preflight confidence. The high-quality flight data provide an opportunity to refine the operational capability of the Orbiter and serve as a benchmark both for the development of aerothermodynamic technology and for use in meeting future entry heating challenges.

INTRODUCTION

The goals of the Space Transportation System (STS) have been to provide routine, cost-effective, and reliable means for carrying man and cargo to Earth orbit and return. Evaluations of achieving these goals led to the challenges of designing and developing a reusable Orbiter vehicle which could both perform atmospheric braking and achieve a land landing. These conflicting configuration requirements for the Orbiter were reconciled by altering the flight configuration with a high angle of attack for entry and then a low angle of attack for approach and landing. The high angle-of-attack entry configuration, the associated entry flight regime, and the relatively large size of the Orbiter provided some relief for the development of a weight-effective and reusable entry thermal protection system (TPS).

Guidelines for the Shuttle program (emanating from constraints on funding rate and minimum development costs) included limiting technology development, except as required, to meet the program goals. The development of reusable engines and a reusable TPS, however, required the development of conceptually new systems and an associated level of technology necessary to provide a level of confidence that these systems could perform adequately to meet the program goals. The challenge for the definition of the Orbiter entry heating was to develop reliable predictions on the basis of existing facilities and state-of-the-art capabilities, supplemented (as required) by advances in technology and understanding necessary to provide preflight confidence of success. This challenge was significant in light of the geometric complexity of the Orbiter configuration, the penalties of unnecessary weight in the system, the reuse requirement, and the basic severity of the entry environment. The Orbiter could not afford the weight associated with a conservative approach toward defining the entry TPS requirements. This approach would have mitigated the challenge and maintained the precedent set by previous entry vehicle designs.

A quantitative understanding of the entry heating phenomena for the windward surface of simple configurations was well established in the 1950's. Analysis and experiment had characterized convective heat transfer in a highly dissociated gas including the basic effects of finite-rate chemical and thermodynamic reactions. The flight mechanics leading to an optimum entry from the standpoint of entry heating for simple configurations was also well established in this era. This technology was used in the design and development of the orbital entry Mercury and Gemini vehicles and extended for the design and development of the more severe lunar return of the Apollo command module. These capsules all employed nonreusable ablators, but most important, they were designed with a level of conservatism which could not be tolerated on the Orbiter. This conservatism stemmed from the compounding of conservatism in the TPS requirements, the TPS performance, and the entry heating. An additional level of sophistication required by the Orbiter was the imposition of heating-rate and boundary-layer transition constraints on the entry flight trajectories to accommodate the reusable TPS capabilities and the insulation requirements, respectively.

TRIAD DILEMMA AND APPROACH

The Orbiter system and performance requirements dictated a more accurate, more precise, and more intricate definition of entry heating than for any previous system. On the other hand, the three-dimensional geometric complexity and the large scale of the Orbiter (compared to wind-tunnel models) posed a greater challenge to the definition of the entry flowfield and subsequent heating than had any previous system. To complete the triad, resources were extremely limited, particularly with regard to technology development. This triad dilemma was dealt with by a triad approach based heavily on experience with previous entry heating problems (ref. 1). The lowest level was a simplified heating model (developed at representative locations on the vehicle) for early system design and for entry trajectory design (ref. 2). The second level of the approach, the design methodology, employed the current state-of-the-art aerothermodynamic technology in ground testing, data correlation, and analysis of both ground test and flight (ref. 3). This effort provided "nominal" entry heating for all locations on the vehicle as TPS design requirements (ref. 4). This heating was considered "nominal" since no uncertainties or conservative factors were applied to the correlation of wind-tunnel data or analysis of the design environment for the design trajectory. To provide adequate preflight confidence in the use of "nominal" heating for design and to address technology deficiencies, the third level of the approach involved select advanced state-of-the-art efforts (ref. 5), parametric studies, and preflight uncertainty evaluations of the entry heating and TPS performance (ref. 6).

SIMPLIFIED HEATING MODEL

The simplified heating model used on the Orbiter was comparable to the design methodology used on the previous blunt manned entry capsules. At representative locations on the Orbiter, a first-order scaling of wind-tunnel data to flight conditions was performed for laminar and turbulent convective heating as well as for boundary-layer transition. Local heat transfer at a given angle of attack was correlated with the heat transfer to the stagnation point of a sphere (assuming equilibrium air). Boundary-layer transition and turbulent heating were correlated as a function of the Reynolds number behind a normal shock. Use of this Reynolds number is a first-order attempt to account for the equilibrium real air effects between flight and wind tunnel and is particularly applicable to blunt entry vehicles dominated by high-entropy flow. This approach was sufficiently straightforward to incorporate into the entry flight mechanics trajectory design (ref. 7). Thus, entry trajectories which were consistent with reusable TPS material capabilities were obtained as illustrated in figure 1. The reusable TPS requirement was a constraint on the geometric configuration and primarily on the entry trajectory corridor. Previous manned entry vehicle trajectories, such as Apollo, were only constrained by acceleration ($\sim$dynamic pressure) and control.

This simplified model was also used to eliminate the largest contribution to unnecessary conservatism in previous manned entry vehicle TPS design: the difference between design and actual requirements. The value of this activity is illustrated in figure 2 by comparison of the Shuttle Orbiter and the Apollo command module experience. The small difference between the STS-1 environment and the design environment was within the preflight uncertainty of the environment and TPS performance (ref. 6). Also, comparison of the Apollo orbital test environments with the Shuttle Orbiter environment is a valid illustration of the heat-load penalty incurred as a result of the reusable TPS requirement. For a given insulation material, the required thickness is roughly proportional to the square root of the heat load.

DESIGN METHODOLOGY

As with previous manned entry vehicles, the foundation for the definition of the entry aerothermodynamic environment for the Shuttle Orbiter was based on wind-tunnel data taken on geometrically scaled models of the Orbiter. Extensive parametric testing was not performed; rather, testing was performed only where the best local flow parameters of significance to the high-heating flight regime could be approached. Despite the fact that wind-tunnel enthalpies are on the order of one-fiftieth of flight (a suitable dimensionless enthalpy parameter for this scaling does not exist), a wind-tunnel free-stream Mach number of about 8 provides the best simulation of the Orbiter entry heating flight regimes (ref. 1). Early aerothermodynamic model testing was performed with a phase-change paint test technique, but the bulk of the design test data were obtained with thermocouple-instrumented models at the Arnold Engineering Development Center, Tunnel B.

The flight design entry heating data were obtained by analysis and correlation normalized by wind-tunnel data. Correlations of equilibrium boundary-layer solutions (and turbulent correlations) obtained for simple (two-dimensional) flowfields (refs. 3 and 8) were applied and normalized at wind-tunnel conditions. These normalized correlations were then applied to flight conditions along an entry trajectory (ref. 4). This process is illustrated schematically in figure 3. It should be noted that the Orbiter entry configuration is not a true blunt entry vehicle nor is it a slender flight vehicle. The flow dynamics vary along the vehicle from the high-entropy blunt-body nose flow to an asymptotic approach toward low-entropy slender-body flow (ref. 9).

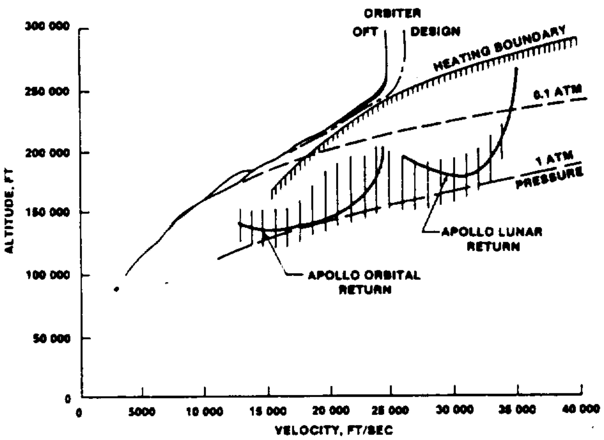


FIGURE 1.- ENTRY FLIGHT REGIMES: APOLLO COMMAND MODULE AND SHUTTLE ORBITER.

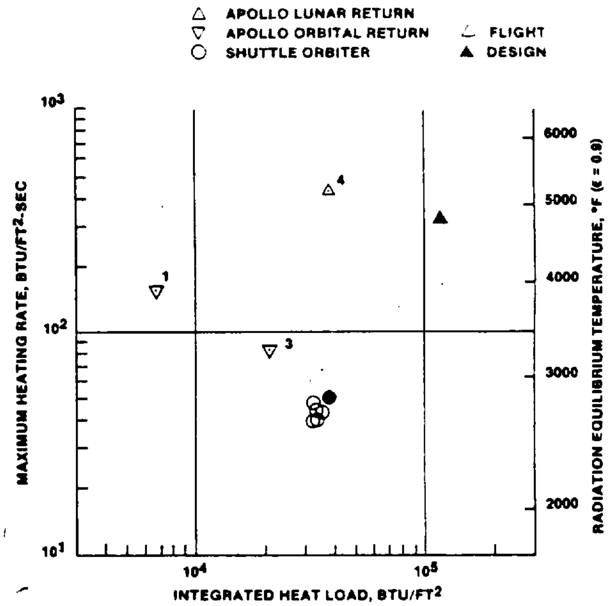


FIGURE 2.- TPS DESIGN AND FLIGHT TEST ENVIRONMENTS.

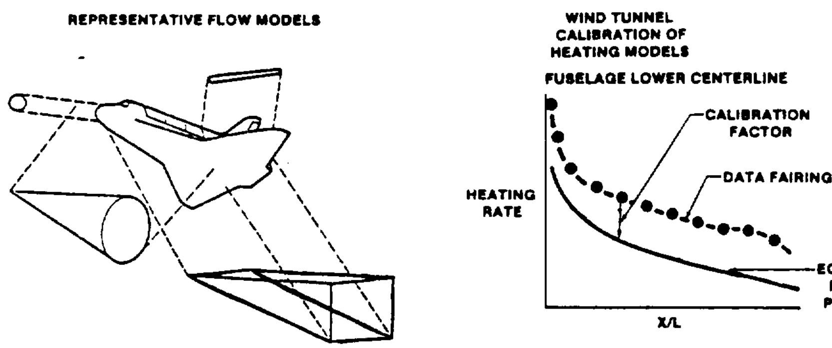


FIGURE 3.- DESIGN HEATING METHODOLOGY.

Smooth-body boundary-layer transition at any location on the vehicle was found to correlate at wind-tunnel conditions by momentum-thickness Reynolds number divided by local Mach number (ref. 4). This correlation was then applied to flight in terms of the same parameter. The results were not drastically different from those for the simplified model. It should be noted, however, that the Orbiter shape had to be "smoothed" to obtain a laminar entry heating vehicle. It had been observed experimentally that configurations without a continuously differentiable windward surface geometry gave rise to premature boundary-layer transition (refs. 1 and 10). This is an overall configuration effect as opposed to a local surface-roughness tripping effect.

TECHNOLOGY ADVANCEMENT

Although there can sometimes be a subtle distinction between state-of-the-art and advanced technology, aerothermodynamics is in the midst of a revolutionary change from a predominantly experimental simulation base to a heavy reliance on numerical simulation. In the case of the Orbiter, entry heating numerical simulations (fig. 4) provided benchmark information for incorporation into the design methodology (refs. 9 and 11 to 18). This information included the scaling of three-dimensional flows and heating from wind tunnel to flight as well as addressing the influences of finite-rate chemistry on the flow and heating. Although numerical flowfield computations have not yet encompassed the entire Orbiter, if the Shuttle program were initiated today, this capability would be the foundation of the design methodology.

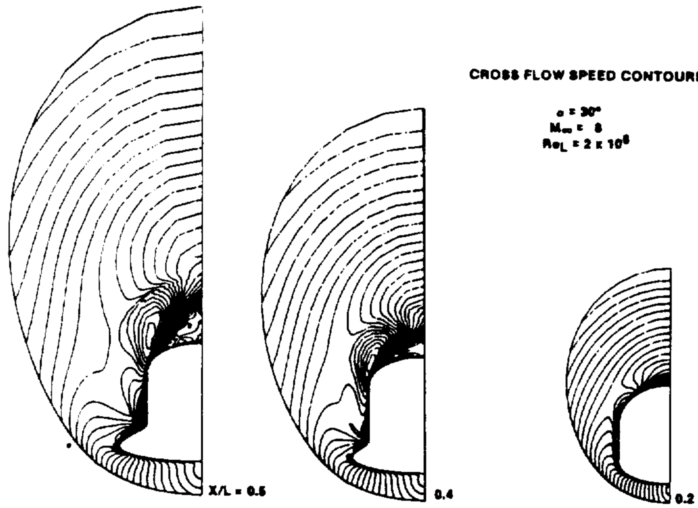


FIGURE 4.- ORBITER FLOWFIELD RESULTS.

Parametric analyses, tests, and data correlations were performed to obtain a better understanding of critical flow phenomena and the sensitivity of the environment and system. Off-nominal testing and analysis were discouraged as a main-line activity (to reduce development cost), but in-house and university studies (refs. 19 to 21) accomplished the required activity. The numerical flowfield simulations were extremely valuable for quantifying the sensitivities to given uncertainty parameters (ref. 6).

Early in the Shuttle program, arc-jet testing of candidate Orbiter TPS materials pointed to the significance of atom recombination surface catalysis to the Orbiter entry heating. Resource limitations prohibited completion of the necessary test data and analyses for the design. However, surface catalysis was characterized before flight (ref. 22). The process for obtaining flight predictions of this phenomenon is illustrated schematically in figure 5. In previous entry vehicle design, this phe-

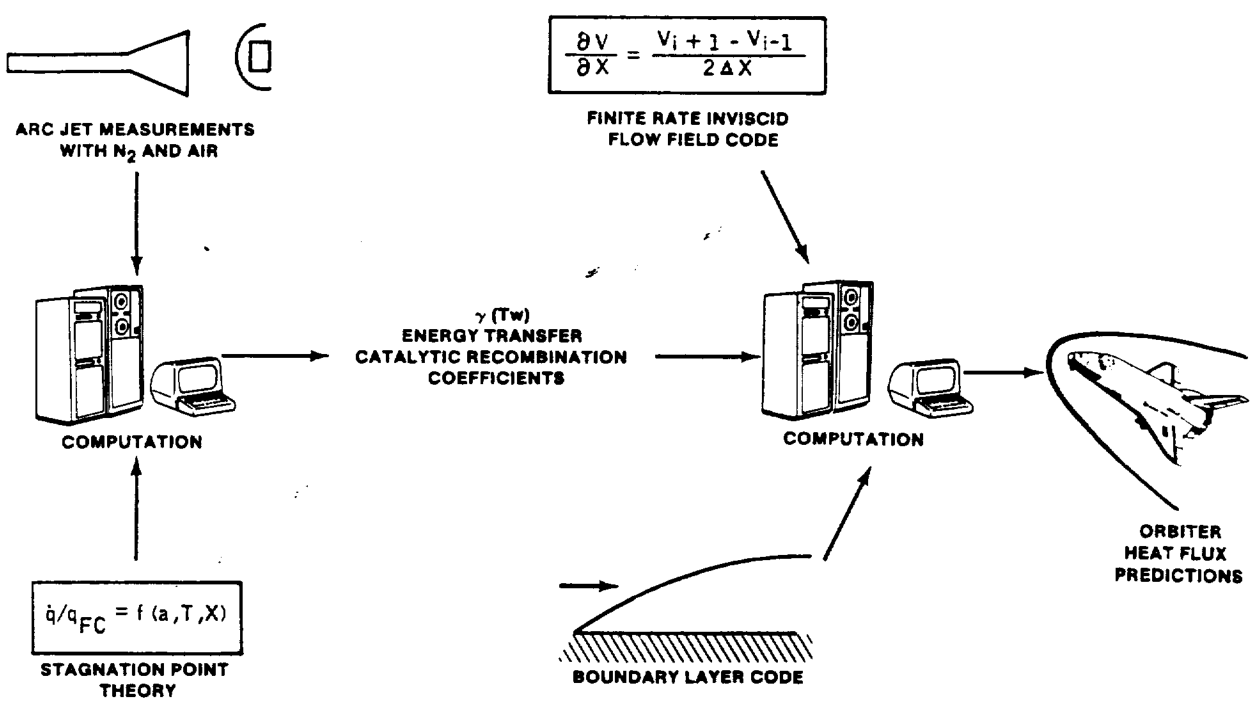


FIGURE 5.- SURFACE CATALYSIS FLIGHT PREDICTION PROCESS.

nomenon had always been masked by the complex processes associated with ablation.

A number of technology questions and issues have arisen as a result of the development of the Orbiter entry heating model. Several of these are addressed under the particular problem area.

SELECT PROBLEMS

BOUNDARY-LAYER TRANSITION

The phenomena of turbulent flow and boundary-layer transition have been under intense investigation for more than a century with somewhat limited success. This limitation is possibly measured by the anxiety which develops when engineers are required to predict boundary-layer transition outside the range of experimental data. The approach to predicting smooth-body transition has already been discussed. Early assessments of the influence of roughness on boundary-layer transition on the Orbiter did not indicate a problem; however, concern arose based on slender-body experience, the large difference between wind-tunnel and flight wall/gas temperature ratio, and the significance of early boundary-layer transition to the TPS. The ensuing activity pushed geometric similitude in wind-tunnel models of entry vehicles to new limits and incorporated pretest chilling of the model to cryogenic temperatures (refs. 23 to 25). Specialized testing, correlation, analysis, and debate finally led to an acceptable level of confidence that roughness associated with the Orbiter TPS tiles would not significantly alter boundary-layer transition from the smooth-body design methodology predictions. The approach used to establish the influence of distributed tile roughness is illustrated in figure 6.

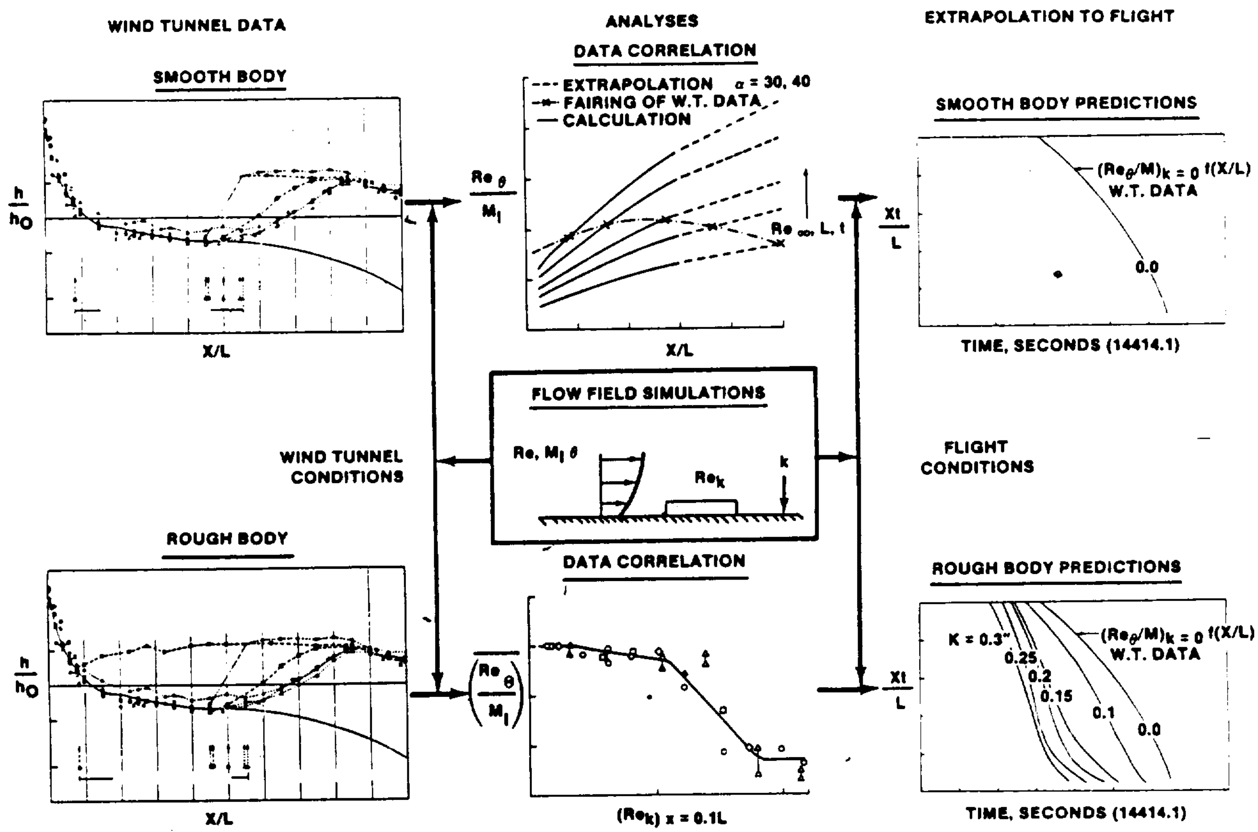


FIGURE 6.- LOGIC FOR PREDICTING BOUNDARY-LAYER TRANSITION ON THE ORBITER.

LEEWARD HEATING

Previous experience with entry vehicle leeward TPS design had generally resulted in a very conservative approach because of the large uncertainty in the hypersonic near-wake flowfield. This uncertainty was of particular importance to the Orbiter because of its large size and the fact that more than half the exterior surface is in a separated-flow regime during significant entry heating. The uncertainty with regard to the leeward environment still exists. However, the conservatism in the leeward TPS was minimized by a reliance on experience with previous manned entry vehicles. This experience is tantamount to assuming a blunt-body controlled flow in that the leeward wind-tunnel data were normalized by heat transfer to the stagnation point of a sphere and applied directly to flight. This problem remains empirical and awaits advances in numerical fluid mechanics simulation capability and efficiency.

SHOCK/SHOCK INTERACTION

Although the Shuttle Orbiter at angle of attack is a relatively clean configuration, there are areas of complex flows which cause concern as to local entry heating and in particular the scaling of wind-tunnel data to flight. One of these areas is the intersection of the fuselage shock and the wing shock. After rather sophisticated wind-tunnel testing, data correlation, and first-order analysis, it was judged that the angle of attack and the wing sweep of the Orbiter did not indicate an overly severe local heating problem for the wing leading edge (ref. 26). However, it was discovered in the pursuit of this problem that scaling of wind-tunnel data to flight when the flow has encountered two shocks (inboard of the shock/shock interaction) resulted in an amplification relative to single-shock scaling (ref. 27). The entropy change obtained by a dual-shock process can be less than that obtained for a single shock. This dual-shock scaling was incorporated in the preflight certification heating environment.

TILE GAP HEATING

Much to the chagrin of the aerothermodynamicist, the Orbiter entry TPS has thin gaps between the 6-inch-square surface insulation tiles. The resulting heat leak afforded by these gaps is a complex coupling of convective heating, radiation exchange, and predominantly conduction down the sidewall of the tile. On the basis primarily of arc-jet tests (which attempt to simulate this coupled environment/system interaction) and analysis, this heat leak can generally be accommodated by an increase in the average insulation thickness. The exception occurs when a pressure gradient causes a hot breeze into the gap (refs. 28 to 30). In this case, it became necessary to stuff the gaps to prevent flow intrusion along with the associated heating. It should be noted that since the nonadiabatic flow of air through a gap is driven by the pressure distribution and the pressure level, the importance of gap convective heating is greatest late in the trajectory after peak surface heating. This behavior was first realized when calculations were performed to ascertain the elevon/wing seal requirements (ref. 21). A postflight assessment is that the late turbulent flow regime is of greater significance to gap convective heating.

NONEQUILIBRIUM EFFECTS

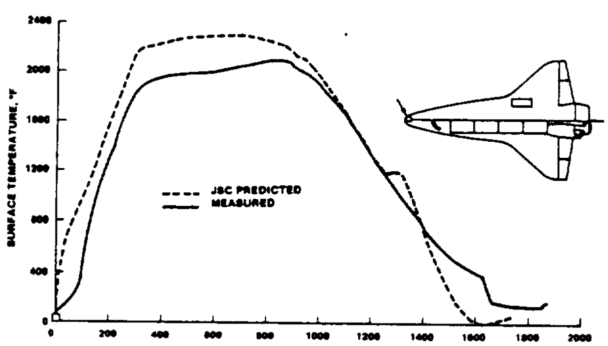
Although significant entry heating occurs in the continuum gas dynamic regime, manned entry vehicles fly at sufficiently low pressure levels that chemical and thermodynamic nonequilibrium phenomena are a concern (refs. 31 and 32). This concern was particularly significant for the Orbiter since it was constrained to lower pressures by the heating rates required for a reusable TPS (fig. 1). A considerable effort was required to confirm that the finite-rate air chemistry does not significantly alter the Orbiter windward flow dynamics (ref. 14). This same question has not yet been answered for the leeward region, where the potential influence of finite-rate chemistry on the gas dynamics is much greater. The finite-rate air chemistry and thermodynamics do, however, significantly alter the entry heating depending on the catalysis characteristics of the particular surface coating. This aspect is discussed in the Orbital Flight Test (OFT) Program results.

FLIGHT TEST RESULTS

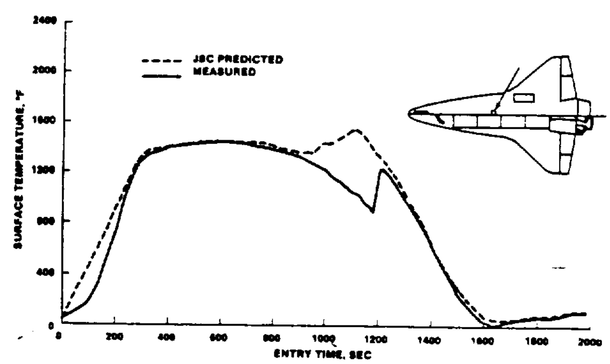
The success of the Space Shuttle Program is very evident from the flight experience to date. An assessment of the job done in defining the entry heating and the flight capability of the Orbiter requires rather extensive analysis of the OFT data. The predominant source of entry heating data consisted of surface thermocouples mounted all over the Orbiter (ref. 33). These thermocouples were installed in the same fashion as in ground arc-jet and radiant tests of the TPS. The OFT Program has provided a large amount of high-quality data for ascertaining the entry heating on the Orbiter configuration. In turn, these data have given rise to a large number of publications comparing predictions and data with a definite trend toward convergence. However, the most important achievement in entry heating has been the contribution toward an adequately designed system (refs. 5 and 34) and well-designed entry trajectories (ref. 7).

Figure 7 is a comparison of selected flight measurements with preflight predictions (refs. 5 and 35). All predictions of boundary-layer transition were conservative, although some were close (refs. 6 and 23 to 25). A detailed presentation of the Orbiter flight boundary transition data is contained in reference 36. The data indicate a definite "tripping" and rapid transition, although whether the cause is distributed roughness (ref. 36), single governing roughness (ref. 37), or configuration (ref. 1) is under debate. Predictions of laminar convective heating are generally conservative (ref. 38), although the extent to which this is due to flowfield assumptions or to surface catalysis effects is under study (refs. 37 to 41). Fortunately, a series of Shuttle flight experiments with catalytically coated tiles (refs. 42 and 43) has provided vivid illustration of finite surface catalysis effects (fig. 8). Turbulent heating levels were very well predicted on the basis of normalization to wind-tunnel data. This agreement was somewhat expected because of the lower sensitivity of turbulent heating to local flow parameters when compared to the laminar case. It should be noted that there is an apparent trend for the entry heating in the highest temperature surface areas to increase (refs. 40 and 44) with flight experience. This trend would indicate changes in surface properties such as emittance or catalycity. Except for this observation, the flight data are quite repeatable.

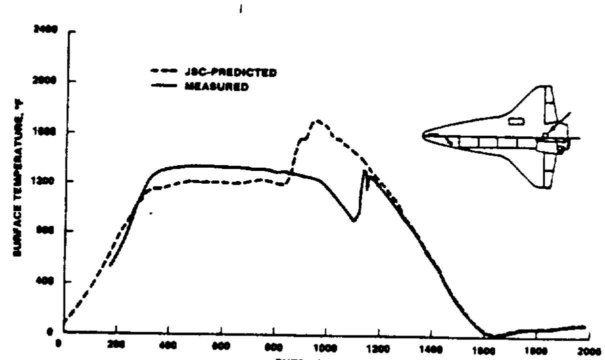
In the light of the complexity of the Orbiter flowfield, the various phenomena involved, and the limitations of wind tunnels in simulating the flight environment, it is fortuitous that the simplified model works quite well. On the leeward side of the vehicle, where the simplified model equals the current level of sophistication, agreement is also reasonable. Figures 9 and 10 illustrate the normalized film heat-transfer coefficient (inferred (ref. 45) from surface temperature measurements) as a function of Reynolds number and angle of attack, respectively. As can be seen, the flight data are quite repeatable and the potential for heat transfer is quite sensitive to angle of attack.



(a) FORWARD WINDWARD CENTERLINE.



(b) MIDBODY WINDWARD CENTERLINE.



(c) AFT WINDWARD CENTERLINE.

FIGURE 7.- COMPARISON OF STS-3 FLIGHT DATA WITH PREFLIGHT TEST PREDICTIONS.

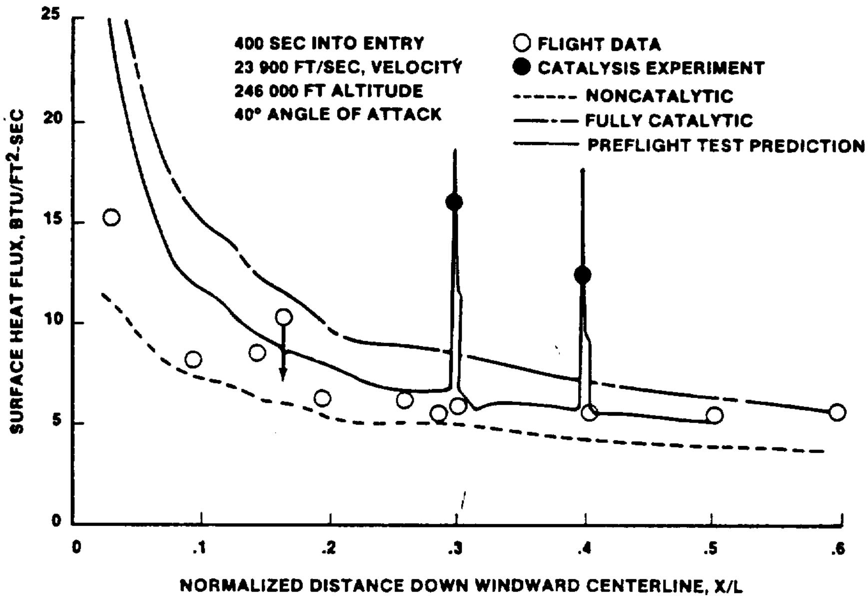


FIGURE 8.- ORBITER INFERRED AND PREDICTED HEAT FLUX, STS-3.

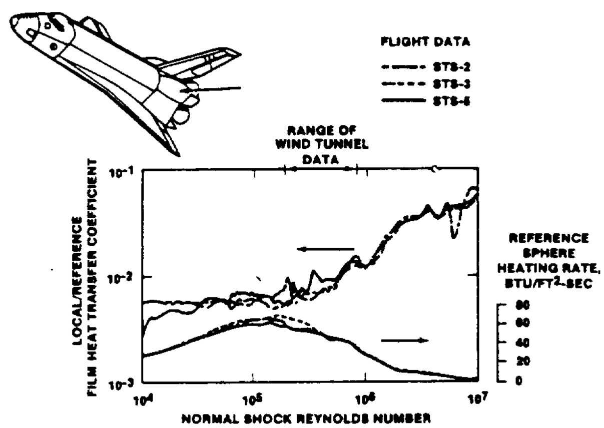


FIGURE 9.- LEEWARD SURFACE FLIGHT DATA VERSUS REYNOLDS NUMBER.

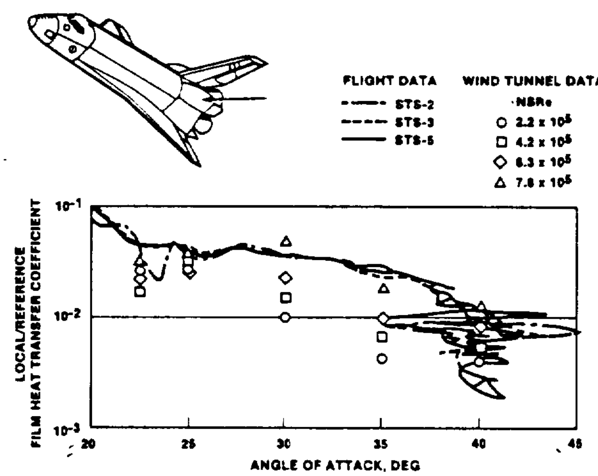


FIGURE 10.- LEEWARD SURFACE FLIGHT DATA VERSUS ANGLE OF ATTACK.

CONCLUSIONS

The definition of entry heating to the Space Shuttle Orbiter was an exciting challenge to the aerothermodynamics community from the standpoint of technology, engineering, and management. It was met by a balanced effort of varying levels of sophistication weighted heavily with experience and adherence to basic engineering principles such as similitude. The use of nominal heating predictions for design was not a low-risk approach but one that helped to provide vehicle performance and an adequate TPS. The treatment of boundary-layer transition is without precedent, except perhaps for the design of a wing for the P-51 airplane.

The reliance on both numerical and wind-tunnel simulations has afforded an efficient means of defining the entry environment and an adequate level of preflight confidence. The high-quality flight data provide opportunity to refine the operational capability of the Orbiter and serve as a benchmark both for the development of aerothermodynamic technology and for use in meeting future entry heating challenges.

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