SPACE SHUTTLE ORBITER ENTRY HEATING AND TPS RESPONSE: STS-1 PREDICTIONS AND FLIGHT DATA

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SUMMARY

The first Orbital flight test of the Space Transportation System, STS-1, was a highly successful demonstration of the technology associated with reusable manned spacecraft. In particular, this paper addresses aerothermodynamic development flight test data, transmitted after entry blackout, which confirm engineering predictions of boundary layer transition, numerical simulations of the Orbiter flow field and tend to substantiate preflight predictions of surface catalysis phenomena. The thermal response of the thermal protection system was as expected. The only exception is that internal free convection was found to be significant in limiting the peak temperature of the structure in areas which do not have internal insulation.

INTRODUCTION

The Space Shuttle Orbiter is the first reusable entry spacecraft built on a foundation of technology and experience gained from the Apollo, Gemini, and Mercury programs (fig. 1). One of the most critical elements to the development of this capabiltiy is the reusable thermal protection system (TPS) mounted on the aluminum structure. The TPS has to be reusable to reduce operational costs and of low mass to achieve necessary and desirable vehicle performance. Experience indicated that the untaxed potential and significant unnecessary mass in a TPS can be attributed to limited understanding and the associated compounded conservatism due to uncertainties in trajectory, environment, system properties, system performance, and system requirements. This program incurred the risk associated with the development of the first reusable TPS and simultaneously the risk associated with significant reductions in conservatism, e.g., the entry design environment was based on the use of nominal heating obtained from the state-of-the-art methodology. The first risk was overcome by a substantial investment in the TPS development while the second risk was treated by the development of understanding for preflight confidence, e.g., aerothermodynamic technology, the subject of this paper. The second risk was also tempered by selecting initial flight trajectories which are not quite as severe as the design entry trajectory. The products of this approach to the Orbiter design and development are an efficient TPS and an aluminum structure which experiences signficant thermal strain and stress as a result of the entry heating. The thermal heat load to the structure is a minute fraction of the aerodynamic heating to the TPS, which is in turn a small fraction of the energy dissipated by atmospheric braking.

In this paper, representative aerothermodynamic and TPS thermal response data obtained on the first atmospheric entry test flight (STS-1) of the Space Shuttle Orbiter are compared to preflight predictions. These predictions are based on rather sophisticated computational and experimental investigations which have complemented the design and development activities as "benchmark" information. Although much of this information was utilized in the design, development and preflight assessment process, the predictions presented here are not the design values nor have they been extended over all regions of the vehicle as required for the design heating rates and TPS response characteristics (refs. 1 & 2). The prediction methodology presented here has also been used to evaluate the sensitivity of preflight predictions to uncertainties in independent parameters and establish system performance uncertainties (ref. 3).

ENTRY HEATING PREDICTIONS

Two features of the Shuttle present particular challenges to the aerothermodynamicist: the temperature limits of reusable TPS materials and the complex geometry of the Orbiter vehicle. The combination of these features in particular pushed the state-of-the-art beyond previous experience even though the definition of the aerothermodynamic environment associated with entry from low earth orbit has been addressed for about thirty years.

Design Approach

In the beginning of the Shuttle program considerable debate ensued as to the most appropriate aerothermodynamic methodology to use for defining the entry heating. The practical state-of-the-art in flow field modeling was limited to two-dimensional flows used in conjunction with ground test facilities which were not capable of simulating all of the significant parameters. NASA/JSC and the prime contractor, Rockwell International (RI) agreed to place a heavy reliance on hypersonic wind tunnel testing of geometrically scaled models to simulate the three-dimensional features of the flow dynamics while using appropriate two-dimensional flow models calibrated by wind tunnel data to simulate flight-related high velocity, real gas phenomena. This methodology was subsequently applied to flight with equilibrium air thermodynamic and transport properties. This approach is schematically illustrated in figure 2 and is the foundation for the design heating methodology.

Orbiter Flow Field Simulations

It is obvious that the flow of air around the Orbiter during entry is three-dimensional and therefore the use of two-dimensional flow models calibrated with wind tunnel data is questionable when extrapolated for use at flight conditions. As such, complementary computational fluid mechanics activities at NASA/ARC and JSC were applied to the development of Orbiter Flow Field Simulations (OFFS) to obtain more reliable techniques for extrapolating wind tunnel data to flight. This rather extensive effort is documented in references 4 through 10. The wind tunnel data on the Orbiter served as good verification for computations performed at wind tunnel conditions (ref. 9). This paper is the first comparison between flight predictions based on these numerical simulations and STS-1 flight data. The results presented here are based on three-dimensional inviscid computations with two-dimensional boundary layer solutions applied along a surface streamline as illustrated in figure 3 (ref. 10). A "coupled" three-dimensional flow field capability which is based on numerical solutions to the "Parabolized Navier-Stokes" equations (refs. 11 & 12) enables computation of flow around the Orbiter chine, wing fillet and lee side. All flow field computations performed to date are either for flight conditions corresponding to the design trajectory or wind tunnel tests.

Surface Catalysis

At entry flight conditions, heat transfer to the Orbiter is realized not only for kinetic thermal energy of the air (as at wind tunnel conditions) but also potential energy stored in chemical changes such as latent heat of dissociation. In general, the air, processed by a hypersonic shock, is not in chemical equilibrium. Since it is necessary to know the chemical composition, finite rate air chemistry flow field computations have been performed for select design trajectory conditions (ref. 13). These results had been incorporated as boundary conditions for finite rate boundary layer computations (ref. 8) to obtain heat transfer. Heat transfer to a surface for a real gas out of chemical and thermodynamic equilibrium also depend on properties of the surface such as the surface catalytic recombination and chemical energy accommodation rates. Surface catalytic recombination rates for the Orbiter TPS have been determined from arc jet testing and analysis (ref. 14) and applied as boundary conditions to finite rate boundary layer computations (ref. 15) coupled to the finite rate inviscid computations (refs. 6, 7, & 13) to obtain more accurate predictions of flight heating. This process is illustrated schematically in figure 4. Data obtained on STS-1 began after peak heating and after the major significance of finite catalysis effects. Hopefully STS-2 data, particularly with an experiment dedicated to this phenomenon, will provide much more useful information.

BOUNDARY LAYER TRANSITION

Quantitative studies of turbulent phenomena and transition from laminar to turbulent flow have been underway for over a century. However, the only approach for defining turbulent heating and boundary layer transition for the Orbiter was and is empirical correlation (fig. 5). In spite of the large dimensions of the Orbiter, the Reynolds numbers (associated with the high heating portion of atmospheric entry) are low enough to permit laminar flow if the configuration is properly controlled (ref. 16). Discontinuous surface radii of curvature are to be avoided (ref. 17). Once the entry configuration is picked, given all of the desired operational entry constraints for the Orbiter, the minimum TPS requirements are obtained by flying just outside the boundary layer transition flight conditions (ref. 18). Selecting a proper configuration and restricting the trajectory to a laminar flow regime has eliminated on the order of 1000 kg of mass from the Orbiter TPS.

Smooth Body

Parametric wind tunnel testing of the Orbiter configuration led Rockwell to correlate boundary layer transition data with a local momentum thickness Reynolds number Re_θ divided by the local Mach number M_l. This correlation parameter varied with location on the vehicle but surprisingly only slightly with angle-of-attack in the range of interest. This parameter was very effective in correlating the available data on this configuration over the range of hypersonic wind tunnel test conditions. These tests were also capable of simulating the predicted values of this parameter at flight conditions for the appropriate angle-of-attack. Because this approach has been shown to be in virtual agreement with the use of a simplistic normal shock Reynolds number (ref. 16)--which worked quite well for the Apollo configuration--Re_θ/M_l was agreed upon as a suitable parameter for correlating smooth body boundary layer transition. It should be emphasized that the main requirement for smooth body boundary layer transition was geometric similitude (including angle-of-attack) and shock layer flow Reynolds number and Mach number simulation. Wall-to-total temperature ratio was found to have no discernible effect on smooth body transition.

Real Body

The major portion of the Orbiter windward surface is covered with TPS tiles, nominally 15 cm (6") square with nominally a 1 mm (.045") gap. Since it was not clear how to analytically account for the counteracting influences of a "cold" and "rough" surface on boundary layer transition, a parametric experimental program, as close to similitude as possible, was pursued (refs. 19-21). It was, and is still, not clear whether distributed or single point roughnesses dominate the boundary layer transition. A 0.0175 scale Orbiter heat transfer model, for which an existing smooth body transition data base existed, was modified to include as much detailed geometric simulation as possible. Randomly distributed protruding tiles were formed in the model to provide a realistic simulation of misaligned TPS tile heights k. The tile gaps were beyond the simulation capability of this model. Also the wall-to-total temperature ratio T_W/T_O was varied throughout the range of interest by cooling the model prior to testing. By varying both the height of the randomly distributed tiles and the temperature ratio, at the same Reynolds number and angles-of-attack used during the smooth body tests, the effects of roughness and cooling could be established.

The combined effects of tile height and T_W/T_O on boundary layer transition location can be seen in figure 6. Note that Re, M and angle-of-attack remain constant during the tests shown in this figure. Even so, the location of transition moves forward as k is increased and as T_W/T_O is decreased.

In the final analysis, this data was best correlated in terms of a departure of Re_θ/M_1 from smooth body transition as a function of Re_k (Reynolds number based on step height k, and conditions at the height of the step for a smooth surface flow.) The results of this transition correlation are shown in figure 7 as applied to the design trajectory. The tile step height data on the Orbiter was never obtained directly. However, the RMS step height, measured on a number of vibro-acoustic test simulation panels (before and after launch simulation), was on the order of .8 mm (.030"). This value was used for preflight predictions although as can be seen in figure 7, step heights below 1.2 mm (.05") do not significantly alter the boundary layer transition from smooth body correlations. The overall logic for predicting boundary layer transition on the Shuttle Orbiter is illustrated in figure 8.

TPS THERMAL PERFORMANCE

The windward surface (bottom) of the Orbiter is protected by a high temperature, low density ceramic tile TPS. These brittle tiles require a thin (0.406 cm) strain isolation pad (SIP), composed of Nomex nylon felt. The system re-radiates most (>95%) of the incident convective heating by maintaining a high coating (reaction-cured glass) temperature. The low density ceramic (5.6 g/cc) is approximately 90% porous; therefore, a very effective insulation. Its thermal diffusion properties are temperature and pressure dependent, but this diffusion is predominately one-dimensional.

The gap between the tiles represents a significant, local departure from one-dimensionality, due to the complex coupling of sidewall coating conduction, radiation interchange, and gap-flow convection from non-adiabatic air (ref. 22). In general, the gap convection is not proportional to the surface heating. Further, the importance of gap heating increases with Reynolds number, particularly as the external flow becomes turbulent. The gaps are designed to be held to a small enough dimension (1.14 mm width), however, that their contribution to the total thermal diffusion to the Orbiter structure is small (∿ 25%).

The TPS thermal analysis is characteristically treated as a one-dimensional diffusion with suitable modification for the gap and radiant contribution. This thermal analysis is calibrated to arc jet test simulations of local heating histories. The basic TPS thermal analysis logic is illustrated schematically in figure 9.

FLIGHT PREDICTIONS AND RESULTS

Predictions

All of the extensive numerical Orbiter flow field simulations described above have been performed either at wind tunnel conditions or at select points along the design trajectory for benchmark purposes. Although the Orbiter entry flight trajectories are all within a relatively narrow band, it was necessary to develop techniques for extrapolating this information to the STS-1 flight test conditions. To achieve this end, state-of-the-art two-dimensional flow models have been (and are being) calibrated to the benchmark simulations. The procedure is similar to the design methodology presented in figure 2 with the exception that the wind tunnel test data is replaced with flow field simulations that are quite close to the flight conditions of interest. If the Shuttle Orbiter design was initiated today, the design methodology would be performed in this manner. The turbulent heating was calculated in the same manner as the design methodology, i.e., with the Spalding and Chi theory calibrated to wind tunnel data.

Surface Temperatures

The primary surface environment information obtained from the Orbiter flight test program is through "surface thermocouples" which essentially measure the temperature of the TPS tile coating. Since the dominant heat transfer processes are aerodynamic heating and re-radiation, the surface temperature measurements are virtually heat transfer measurements. However, to properly account for conduction and thermal capacity, the measured temperatures are compared directly with predicted temperatures. Figure 10 shows this comparison for data obtained along the windward pitch plane of the Orbiter. These predictions are based on the extrapolation of three-dimensional flow field computations for the design trajectory through the use of two-dimensional oblique shock flow models. The forward region exhibits the response to laminar as well as turbulent heating and presents a clear indication of a boundary layer transition. Aft of the mid-fuselage boundary layer transition had occurred prior to the available data. The agreement between predictions and data is quite good.

Predicted and inferred heating rates are shown in figure 11 for a representative mid-fuselage location. Here it can be seen that only tenuous conclusions can be drawn concerning the anticipated finite catalysis phenomenon. Confirmation of this phenomenon must await additional flights with complete data. It should be noted that state-of-the-art methodologies normalized to wind tunnel data are significantly above these predictions at flight conditions. The obvious transition in the state-of-the-art methodologies presented in figure 2 was used only for preflight assessment, whereas the TPS design assumed smooth body transition.

Boundary Layer Transition

The boundary layer transition data obtained on the instrumented half of the STS-1 Orbiter vehicle are fantastic. Most surface temperatures show a clear indication of the onset and completion of the transition process. In select regions of the vehicle the measurements show an incipient transition, a reversal toward laminar values and then a final transition process. These are generally not isolated measurements but rather this effect can be seen as a definite flow pattern in regions of the vehicle. Since the Orbiter is undergoing a decrease in angle-of-attack as well as changing flight conditions, it is not clear whether this behavior is inherent to the transition phenomena or reflects the vehicle behavior. Time contours for the incipient and final boundary layer transition times are illustrated in figure 12.

TPS Thermal Response

In general, the TPS thermal response and aluminum temperatures were consistent with predictions. Figure 13 depicts the temperature transients at three body points on the bottom of the vehicle. At each Development Flight Instrumentation (DFI) plug location, thermocouples were located in the tile coating, several locations within the tile, at the tile-SIP interface, and on the aluminum skin. Most of the flight data were available only for the time after 1100 seconds of entry, due to a data recorder malfunction.

In figure 14, thermal response for two locations where the total aluminum bondline temperature transients are available, were simulated by the numerical model. Note that the adiabatic backwall analysis (see BP 1600) does not follow the flight data. Using backface radiation and free convection, however, the model matches the two data curves perfectly. This was a post-flight modification to the math model. These models were driven (at the surface) by analytically-derived convection coefficients h and local recovery temperatures.

Figure 15 provides a means of comparing bondline temperature-response predictions for STS-1 and the design trajectory as well as STS-1 data for a typical mid-fuselage station (i.e., BP 1500). At this location the major temperature difference between STS-1 and the design trajectory is due to the initial temperature. The data and predictions (labeled JSC predictions) indicate that peak allowable bondline temperatures would not be exceeded for the design trajectory. However, bondline temperature predictions at the time of maximum stress (between TAEM and landing) do not provide a conservative outlook.

CONCLUDING REMARKS

The general agreement between these preflight predictions and the temperature measurements obtained on STS-1 leads to the conclusions summarized in figure 16. The use of computational fluid mechanics as a valuable tool in the design and development process has been demonstrated here. Although the STS-1 measurements point to the significance of finite surface catalysis, a firm conclusion requires a full set of flight data. Boundary layer transition on the windward side of the Orbiter occurred just as it was expected to. The quality of this data is excellent. The TPS thermal response was as predicted with the addition of internal free convection for un-insulated structure areas. The TPS appears to be generally adequate from a thermal response standpoint; which implies that the Orbiter has a warm structure.

REFERENCES

1. "Space Shuttle Orbiter Entry Aerodynamic Heating Data Book," Rockwell International Space Division, Downey, CA, SD73-SH-0184C, Oct.1978.

2. "Space Shuttle Program Thermodynamic Design Data Book, Thermal Protection System," Rockwell International Space Division, Downey, CA, SD73-SH-0226, Vol. 2C, July 1977.

3. Goodrich, W. D,; Derry, S. M.; Maraia, R. J.: Effects of Aerodynamic Heating and TPS Thermal Performance Uncertainties on the Shuttle Orbiter, in Entry Heating and Thermal Protection, Vol. 69 of Progress in Astronautics and Aeronautics, Walter B. Olstad, ed. (1980) pp. 247-268.

4. Li, C. P.: "A Numerical Study of Laminar Flow Separation on Blunt Flared Cones at Angle-of-Attack," AIAA Paper 74-585, June 1974.

5. Kutler, P.; Reinhardt, W. A,; and Warning, R. F.: "Multishocked Three-Dimensional Supersonic Flow Fields with Real Gas Effects," AIAA Journal, Vol. 11, May 1973, pp. 657-664.

6. Rakich, John V,; and Mateer, G. G.: "Calculation of Metric Coefficients for Streamline Coordinates", AIAA Journal, Vol. 10, No. 11, Nov. 1972, pp. 1538-1540.

7. Rakich, John V.; and Lanfranco, Martin J.: "Numerical Computation of Space Shuttle Laminar Heating and Surface Streamlines", Journal of Spacecraft and Rockets, Vol. 14, No. 5, May 1977, pp. 265-272.

8. Tong, H.; Buckingham, A. C.; and Morse, H. L.: Nonequilibrium Chemistry Boundary Layer Integral Matrix Procedure, NASA CR-134039, July 1973.

9. Goodrich, W. D.; Li, C. P.; Houston, C. K.; Meyers, R. M.; and Olmedo, L.: "Scaling of Orbiter Aerothermodynamic Data Through Numerical Flow Field Simulations," NASA SP-347, Part 2, March 1975, pp. 1395-1410.

10. Goodrich, W. D.; Li, C. P.; Houston, C. K.; Chiu, P. B.; and Olmedo, L.: "Numercial Computations of Orbiter Flow Fields and Laminar Heating Rate," Journal of Spacecraft and Rockets, Vol. 14, May 1977, pp. 257-264.

11. Li, C. P.: "Application of An Implicit Technique to the Shock-Layer Flow Around General Bodies," To appear in AIAA Journal (1982).

12. Li, C. P.: "Numercial Simulation of Reentry Flow Around the Shuttle Orbiter Including Real Gas Effects," Paper Presented at the Symposium on Computers in Flow Predictions and Fluid Dynamics Experiments. ASME Winter Annual Meeting, Nov. 1981, Washington, D.C.

13. Rakich, John V.; Bailey, Harry E.; and Park, Chul: Computation of Nonequilibrium Three-Dimensional Inviscid Flow Over Blunt-Nosed Bodies Flying at Supersonic Speeds. AIAA Paper 75-835, June 1975.

14. Scott, Carl D.: Catalytic Recombination of Nitrogen and Oxygen on High Temperature Reusable Surface Insulation. AIAA Paper 80-1477, June 1981.

15. Scott, Carl D.: Space Shuttle Laminar Heating with Finite-Rate Catalytic Recombination, AIAA Paper 81-1144, June 1981.

16. Ried, R. C., Jr.; Goodrich, W. D.; Strouhal, G.; and Curry, D. M.: "The Importance of Boundary Layer Transition to the Space Shuttle Design," Proceedings of the Boundary Layer Transition Workshop held Nov. 3-5, 1971. Aerospace Report No. TOR-0172 (S2816-16) -5, Dec. 20, 1971.

17. Young, C. H.; Reda, D. C.; and Roberge, A. M.: "Hypersonic Transitional and Turbulent Flow Studies on a Lifting Entry Vehicle," AIAA Paper 71-100, Jan. 1971.

18. Curry, D. M.; Tolin, J. W., Jr.; and Goodrich, W. D.: "Effects of Selected Trajectory Parameters on Weight Trends in the Shuttle Thermal Protection System," NASA TMX-58113, Jan. 1974.

19. Goodrich, W. D.; and Stalmach, C., Jr.: "Effects of Scaled Heatshield Tile Misalignment on Orbiter Boundary-Layer Transition," Journal of Spacecraft and Rockets, Vol. 14, October 1977, pp. 638-640.

20. Bertin, J. J.; Idar, E. S., III; and Goodrich, W. D.; "Effect of Surface Cooling and Roughness on Transition for the Shuttle Orbiter," Journal of Spacecraft and Rockets, Vol. 15, March - April, 1978, pp. 113-119.

21. Bertin, J. J.; Hayden, T. E.; and Goodrich, W. D.: "Comparison of Correlations of Shuttle Boundary-Layer Transition Due to Distributed Roughness," AIAA Paper 81-0417, Jan. 1981.

22. Scott, C. D.; and Maraia, R. J.: Gap Heating with Pressure Gradients, in Entry Heating and Thermal Protection, Vol. 69 of Progress in Astronautics and Aeronautics, Walter B. Olstad, ed. (1980) pp. 269-286.

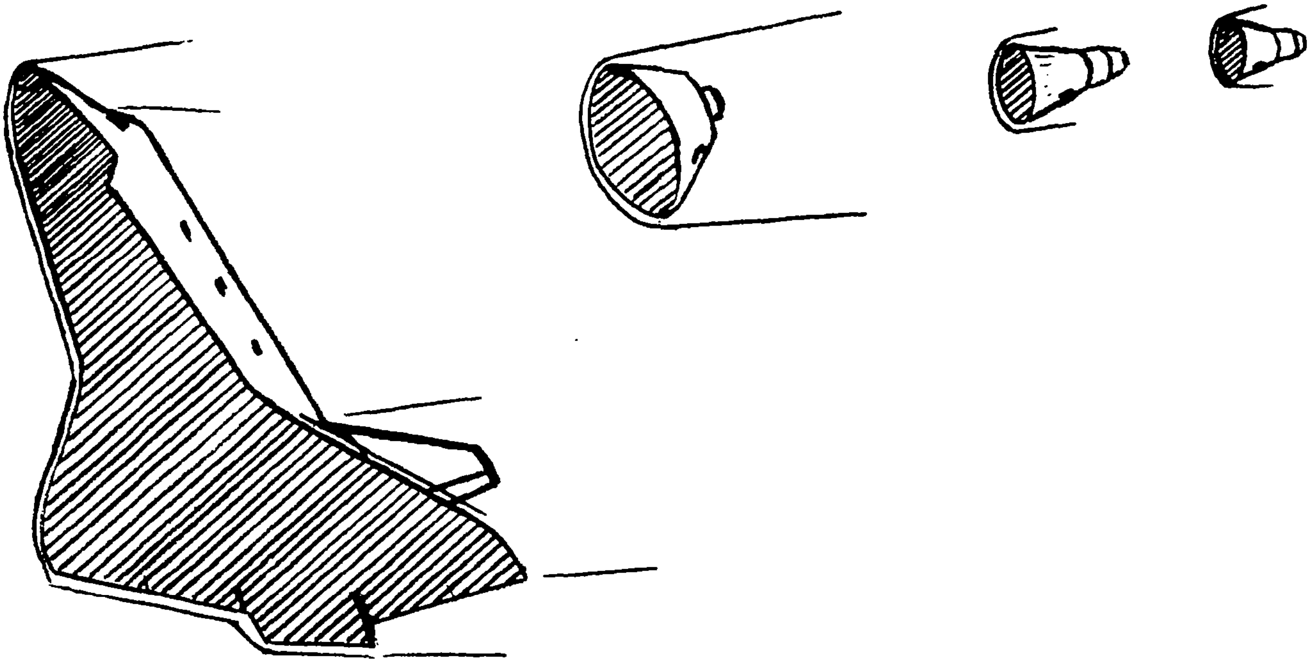
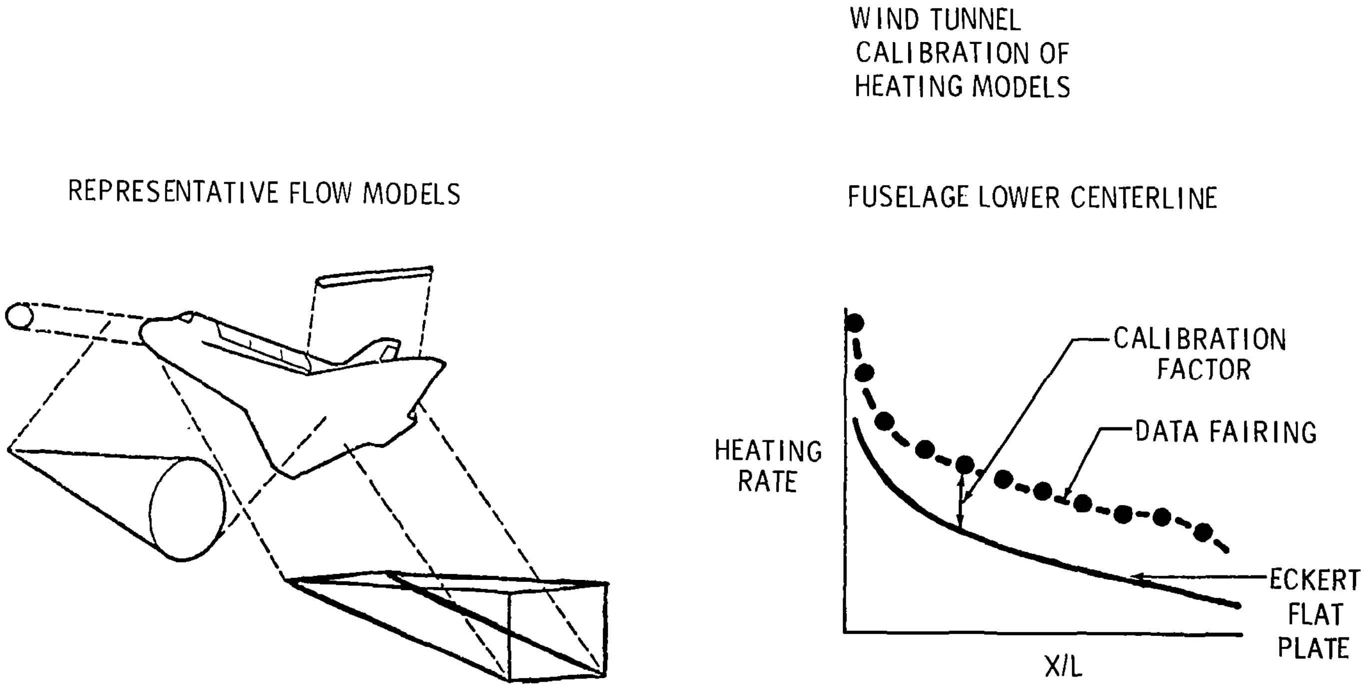


Figure 1.- Manned orbital entry spacecraft.



WIND TUNNEL CALIBRATION OF HEATING MODELS

REPRESENTATIVE FLOW MODELS

FUSELAGE LOWER CENTERLINE

Figure 2.- Design heating methodology.

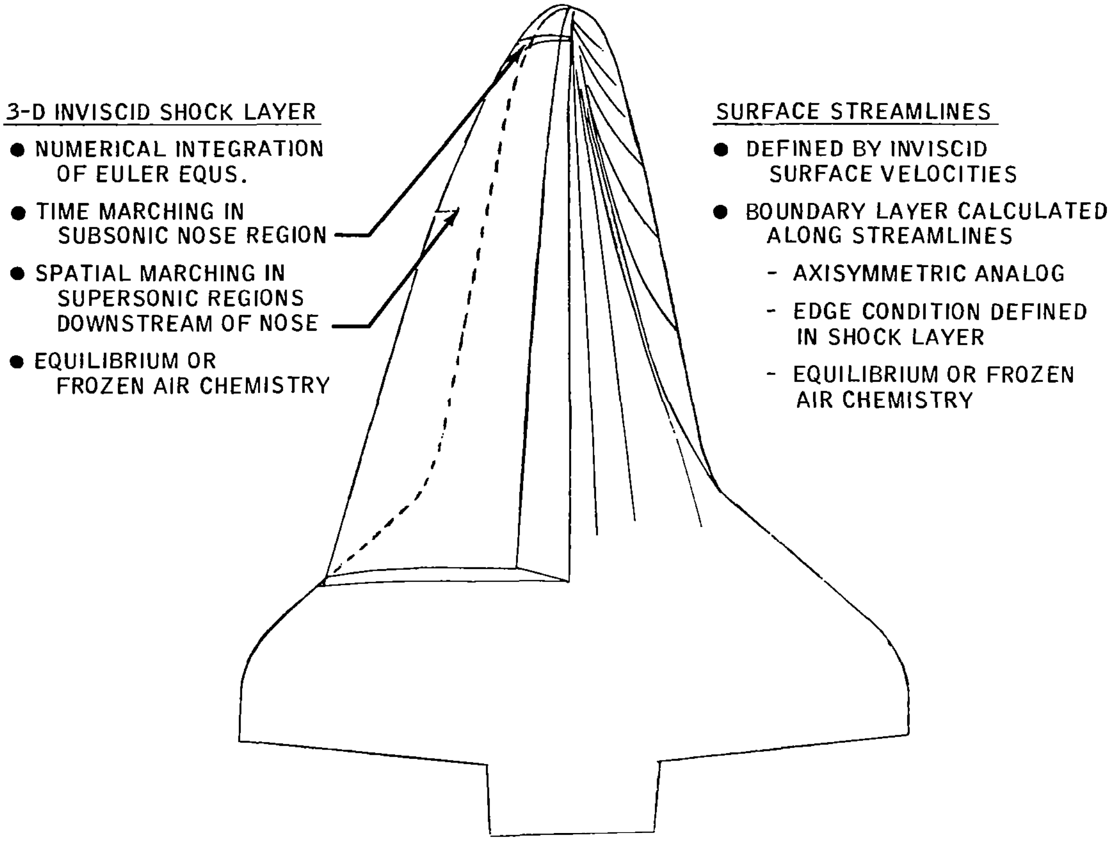


Figure 3.- Illustration of flow field simulation technology as applied to orbiter.

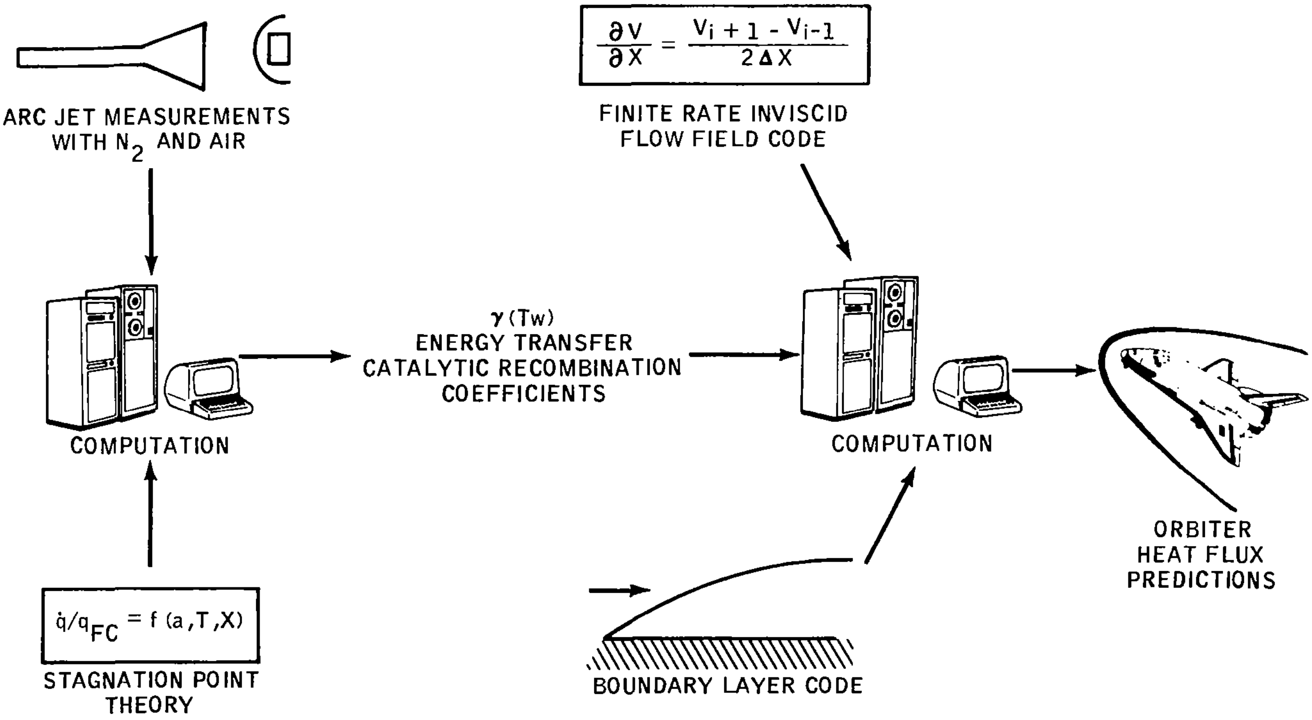


Figure 4.- Surface catalysis flight prediction process.

Figure 5.- State of the art in hypersonic B.L. transition.

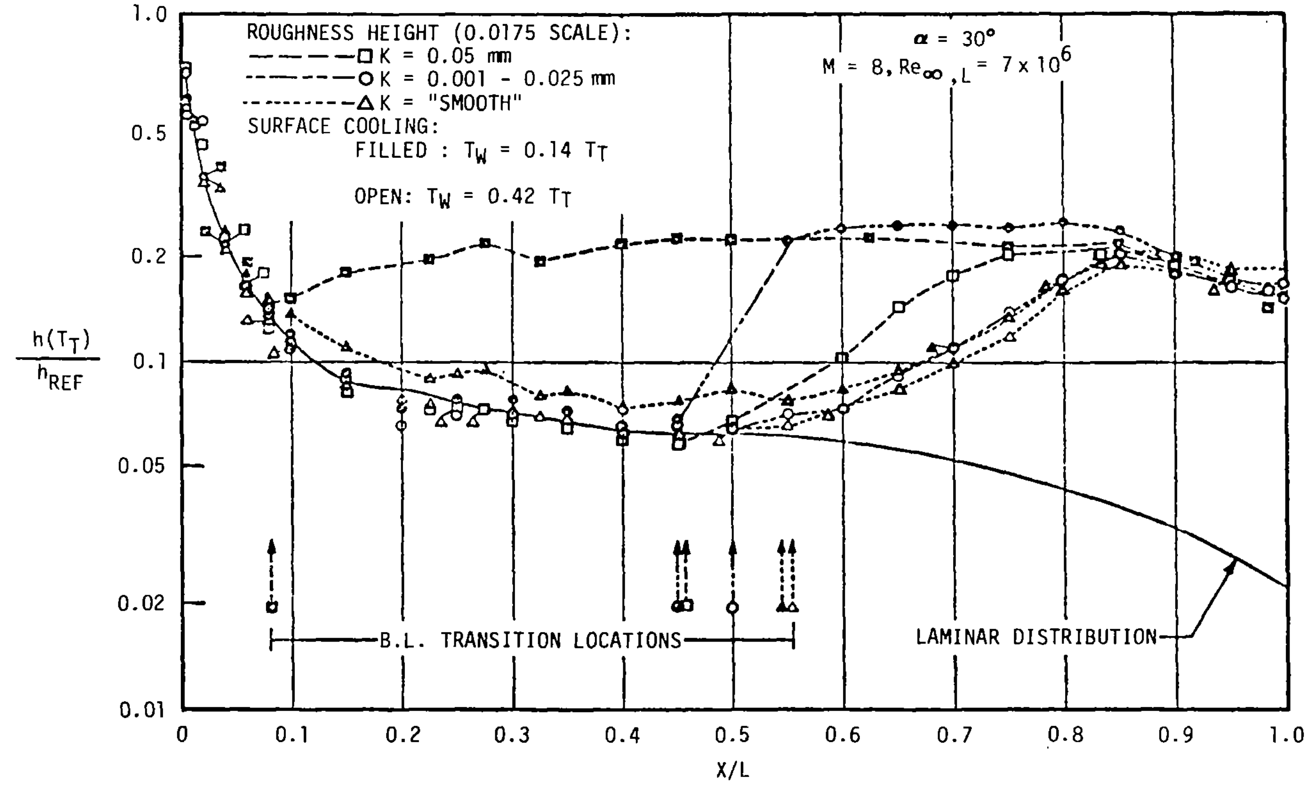


Figure 6.- Orbiter B.L. transition with scaled tile roughness.

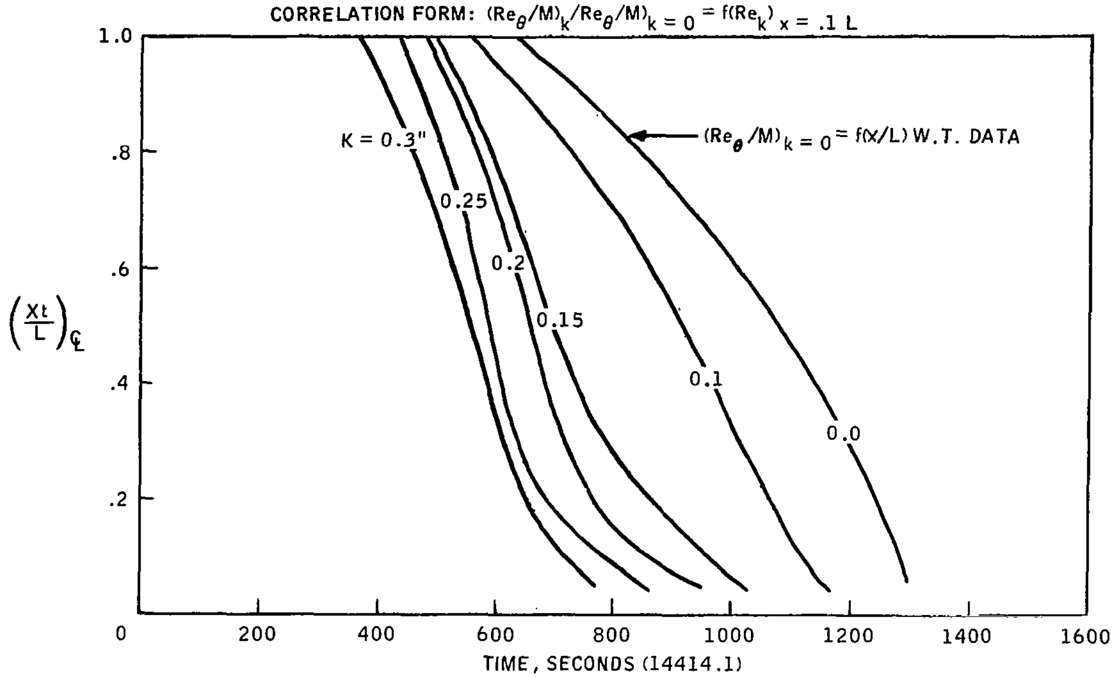


Figure 7.- History of roughness induced orbiter B.L. transition.

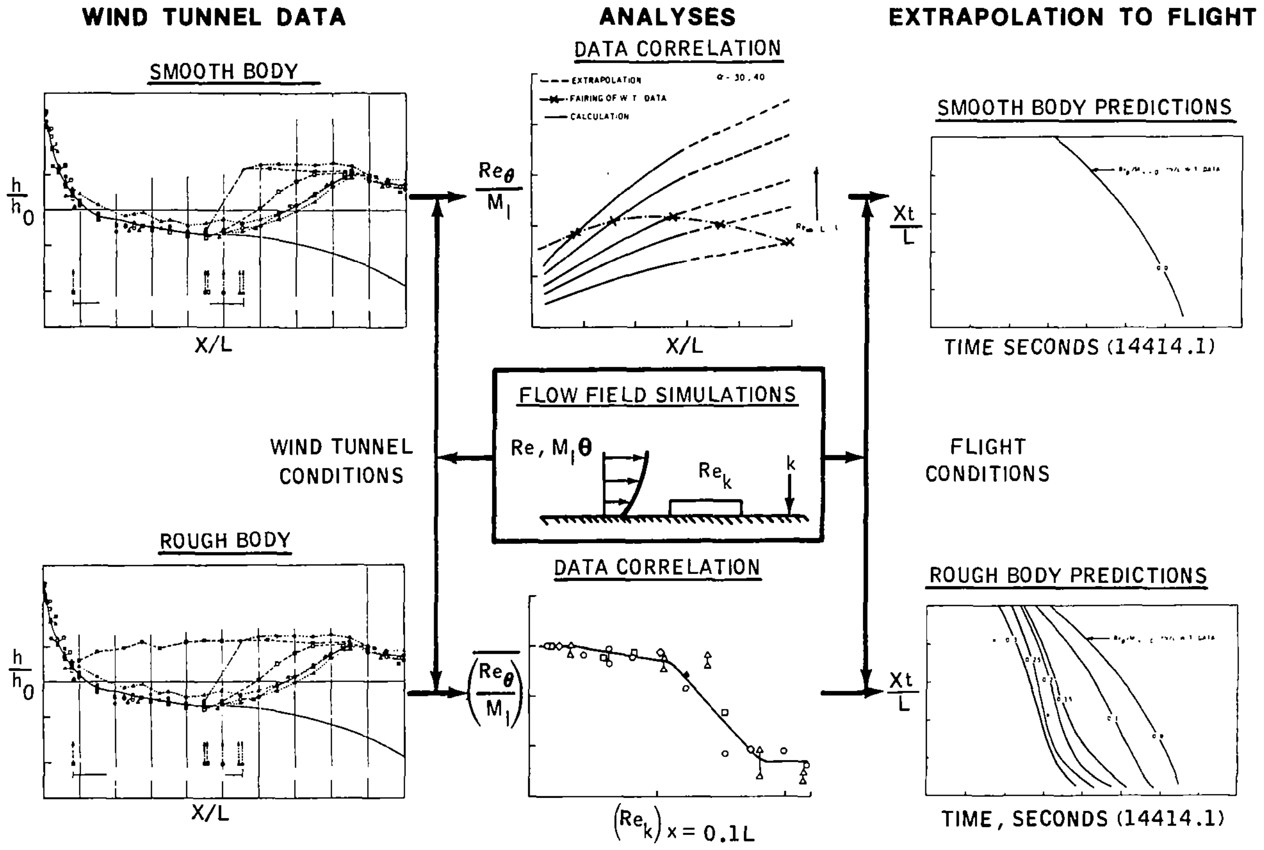


Figure 8.- Logic for predicting B.L. transition on orbiter.

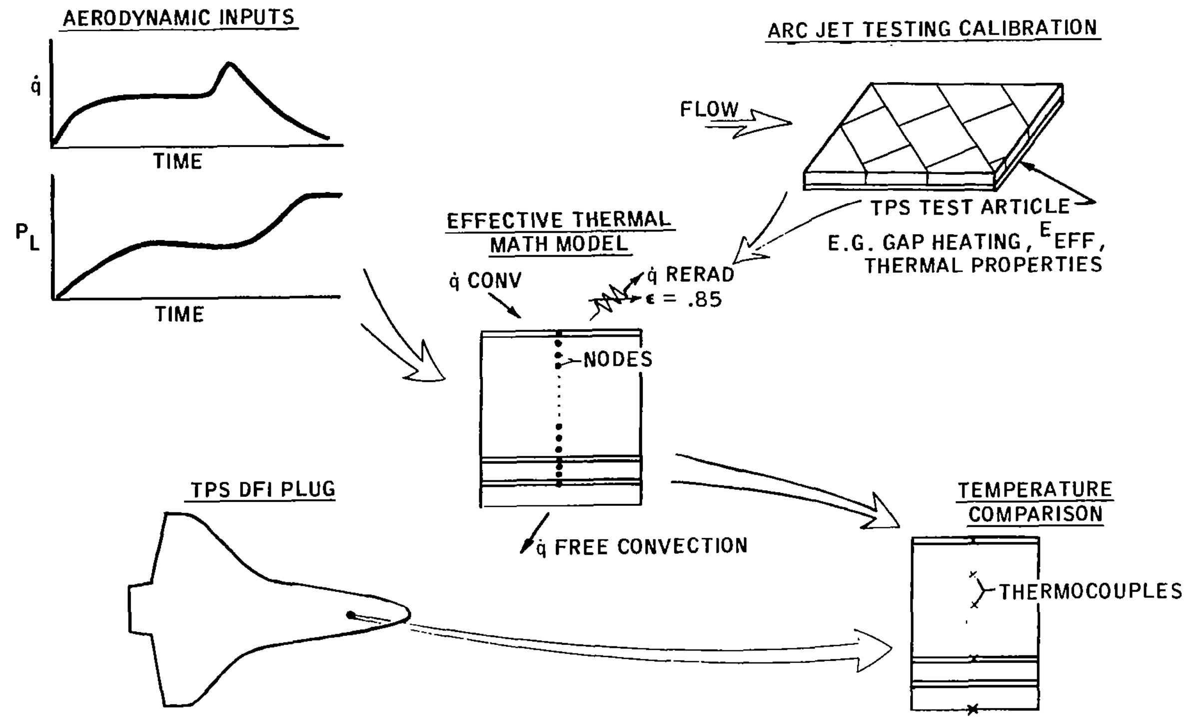


Figure 9.- TPS thermal analysis logic.

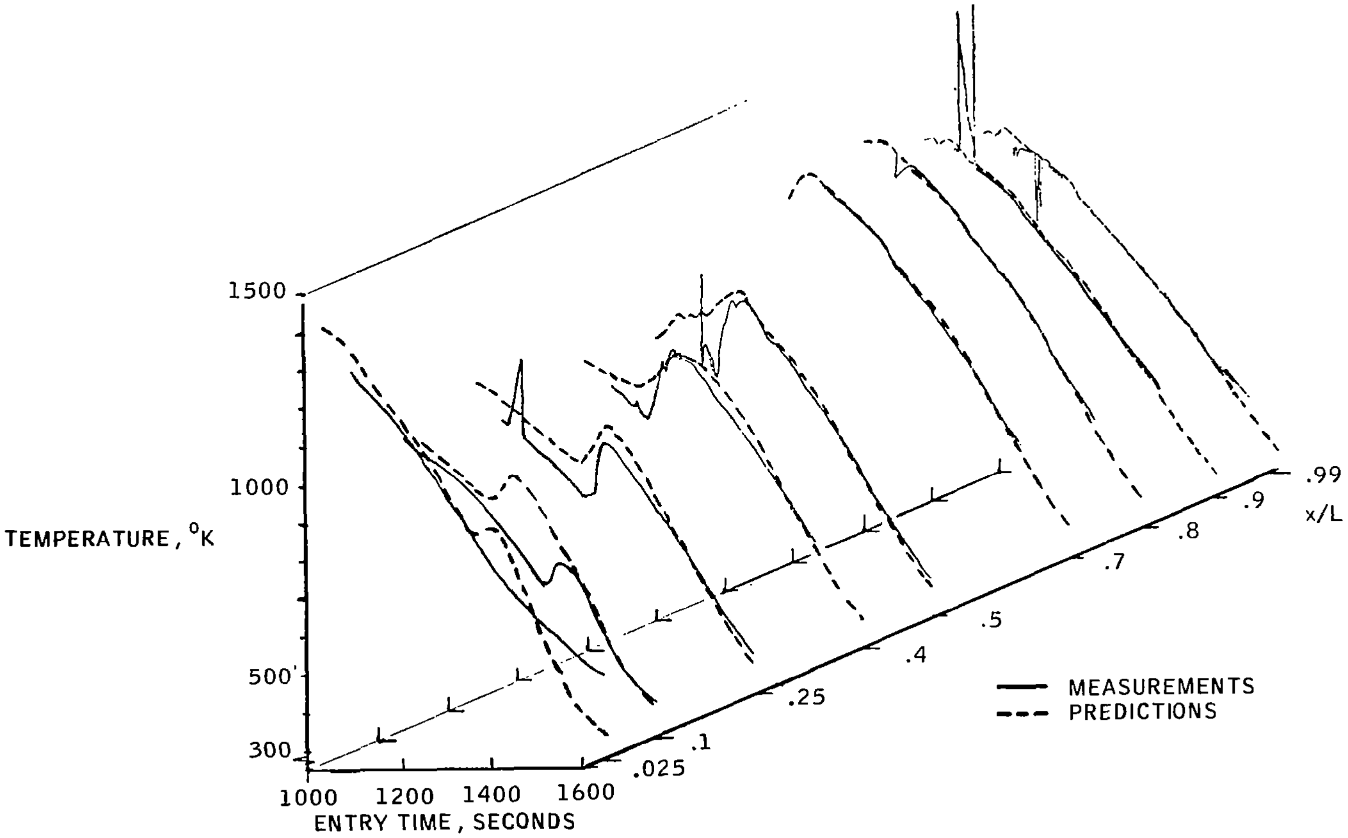


Figure 10.- STS-1 surface temperature measurements and predictions, windward centerline.

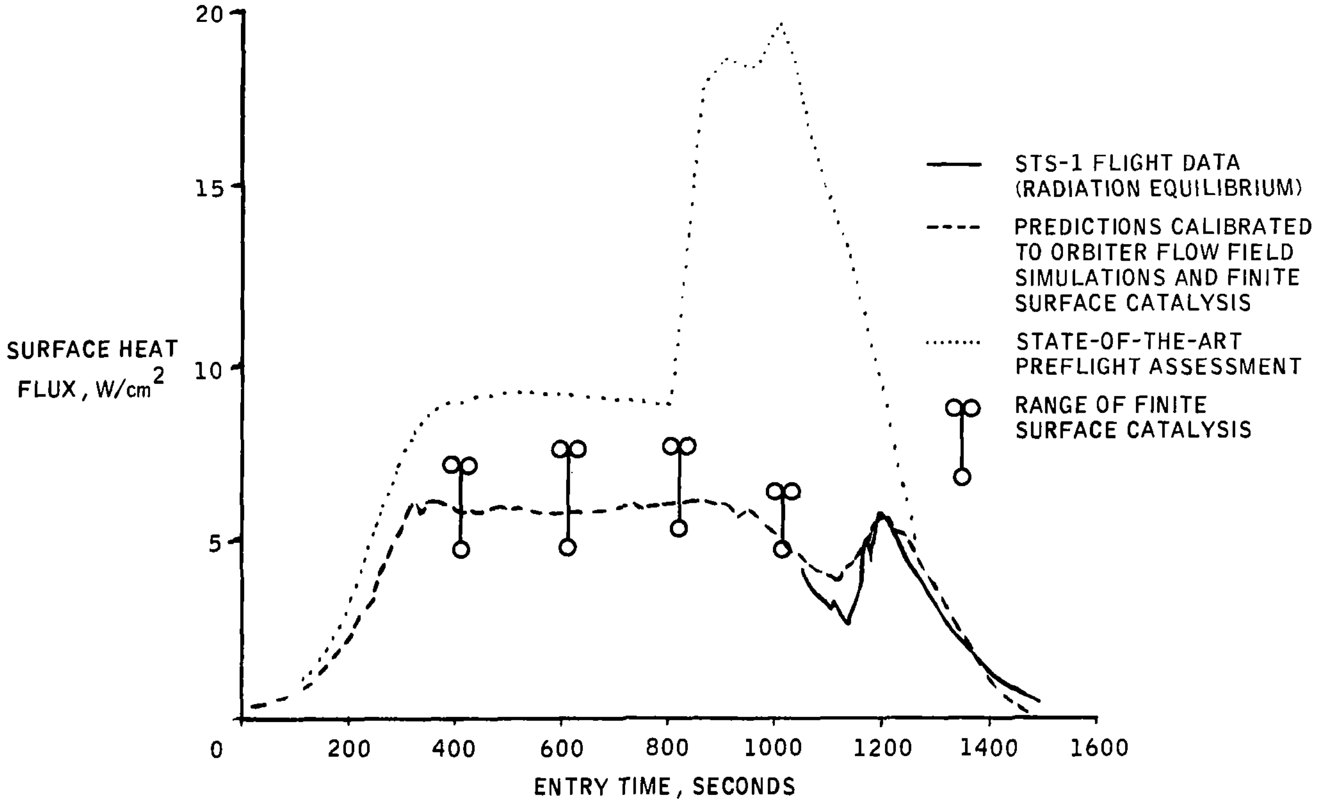
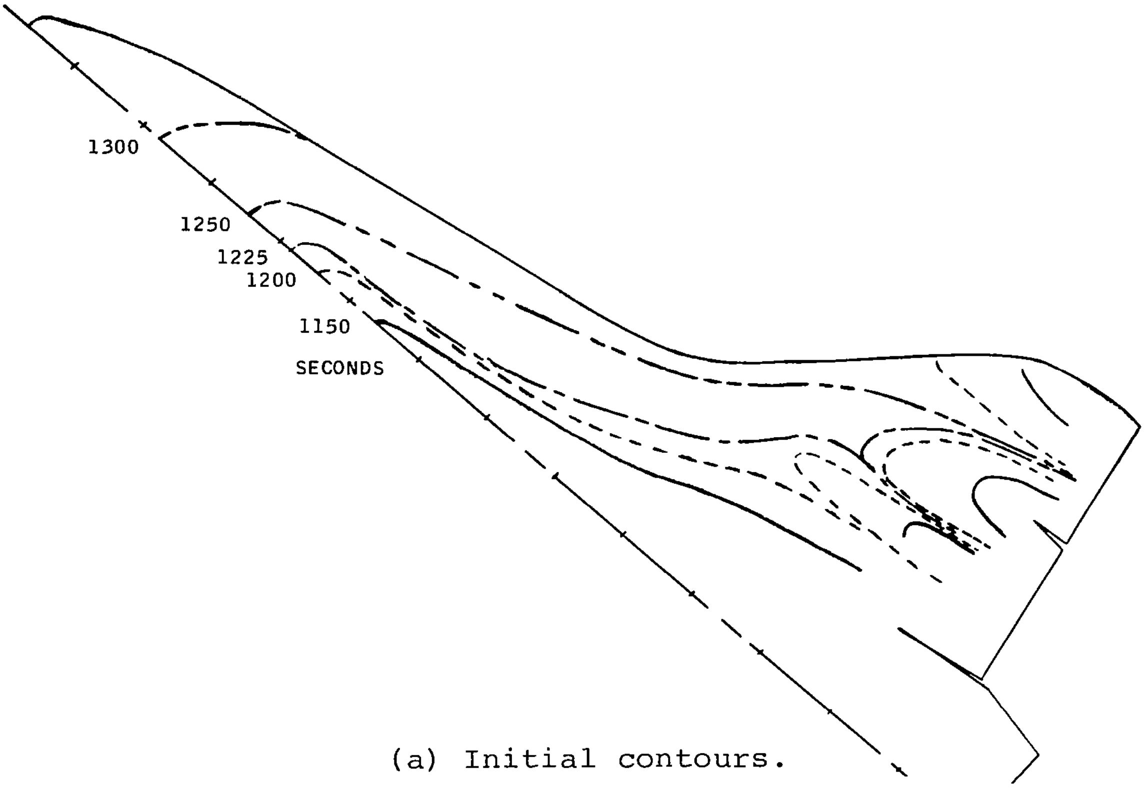
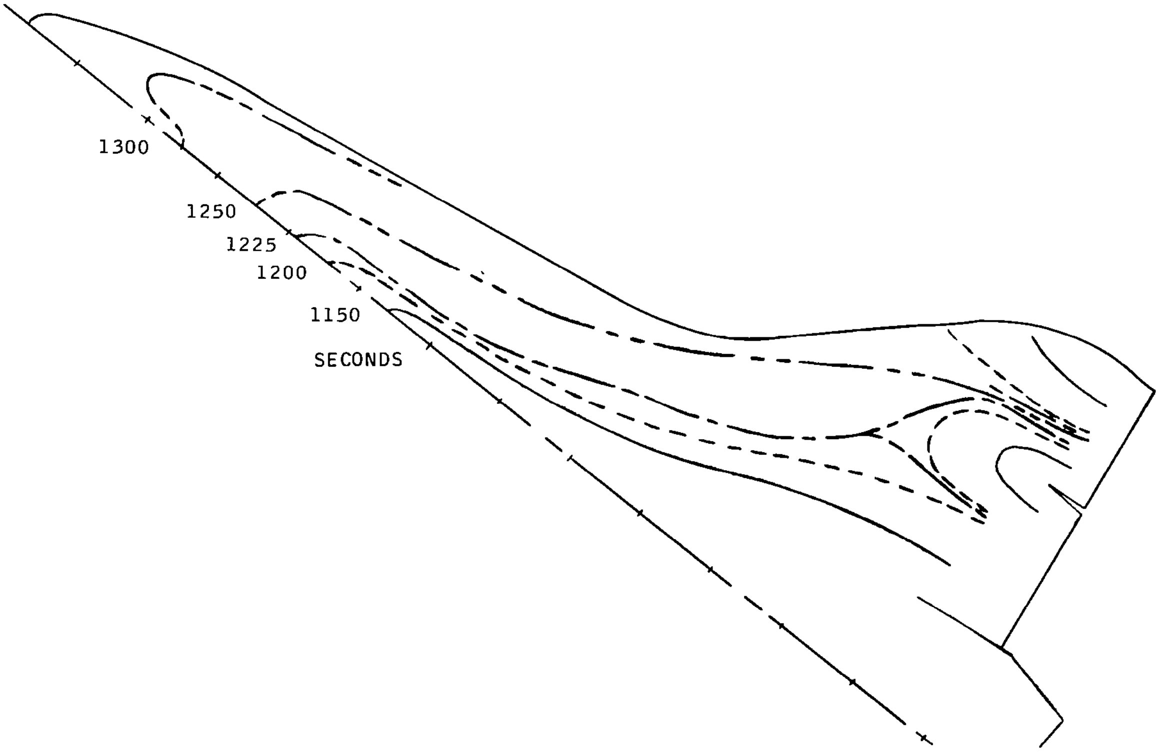


Figure 11.- STS-1 entry heating data and preflight predictions, windward centerline x/L = 0.4.



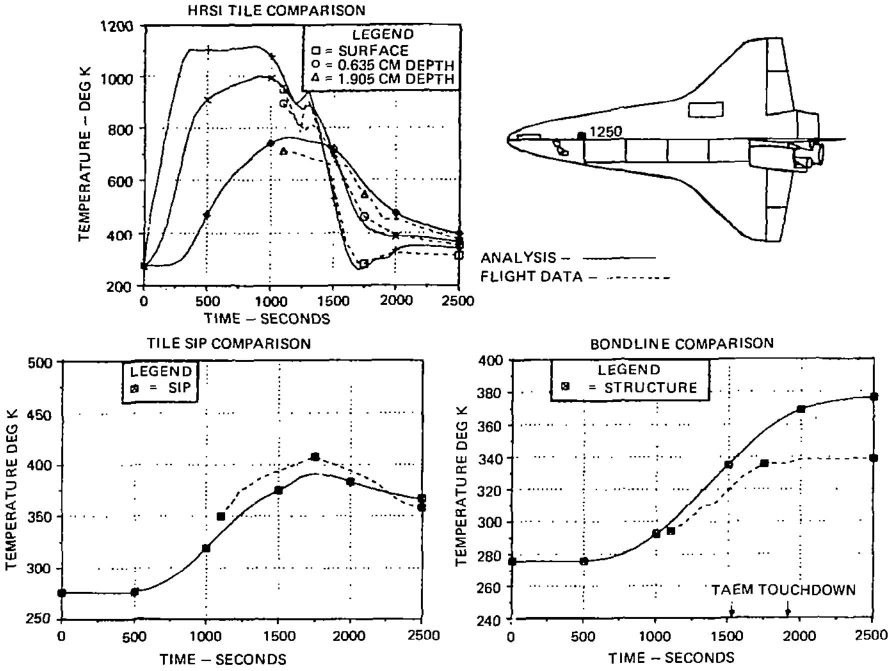
(a) Initial contours.

Figure 12.- Boundary layer transition tune contours, STS-1.



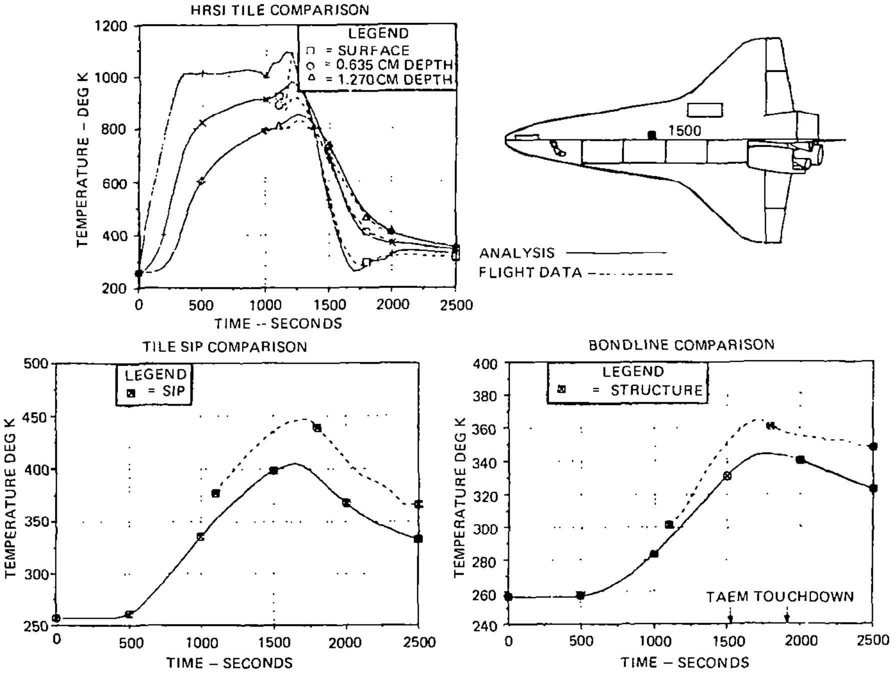
(b) Final contours.

Figure 12.- Concluded.



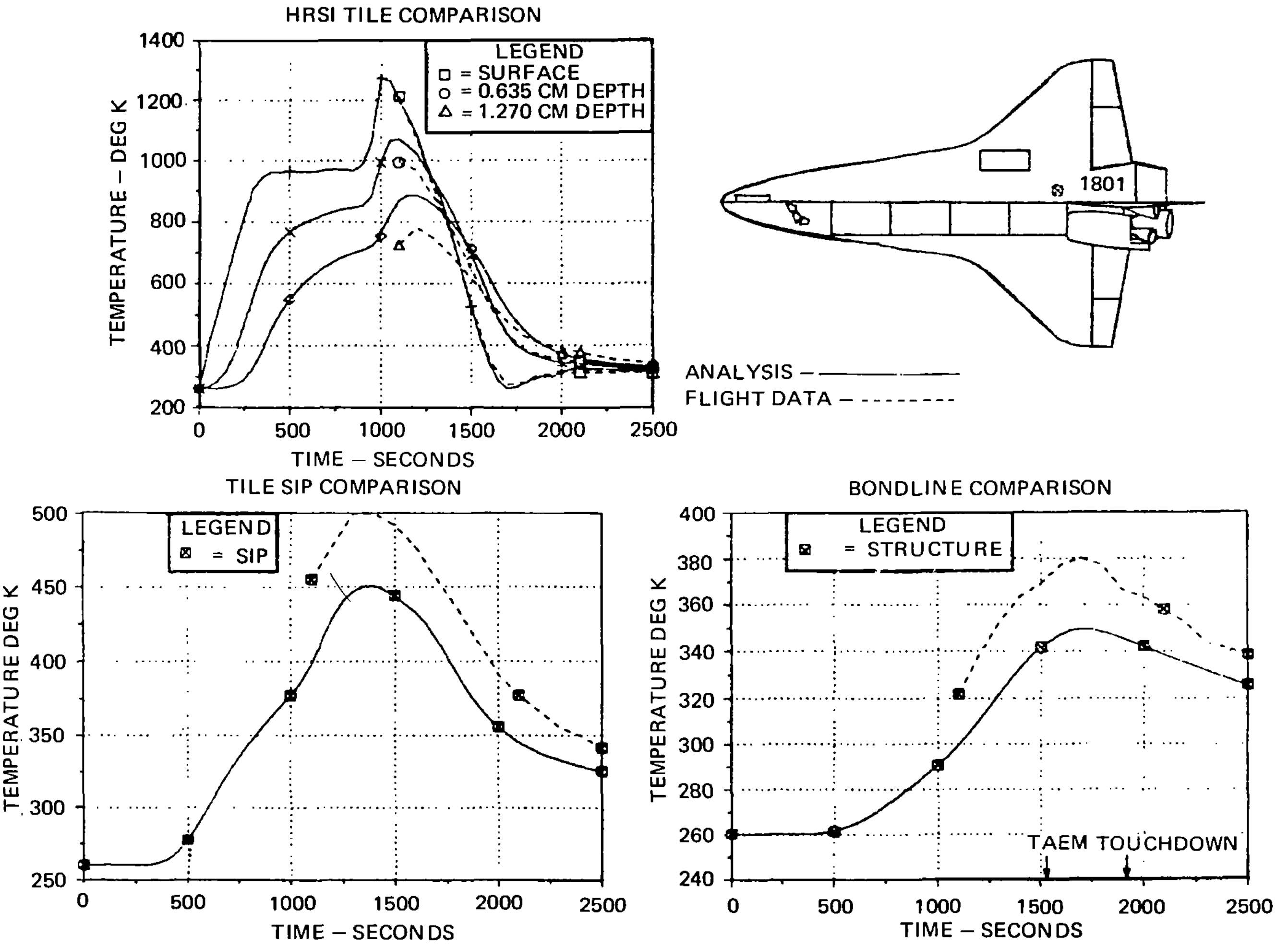
(a) At BP 1250.

Figure 13.- TPS plug temperature comparisons for STS-1.



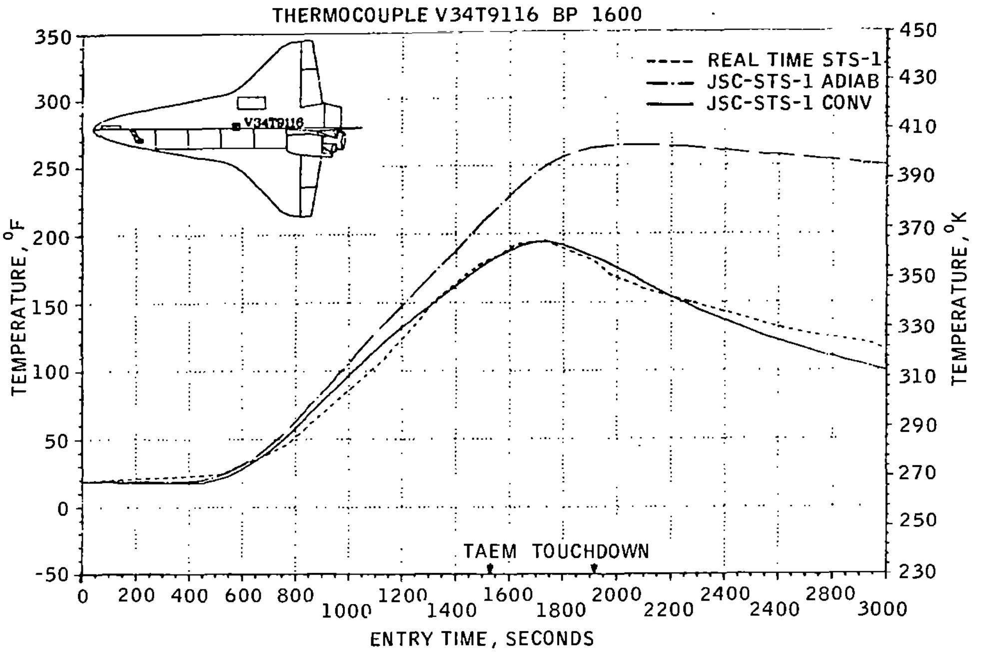
(b) At BP 1500.

Figure 13.- Continued.



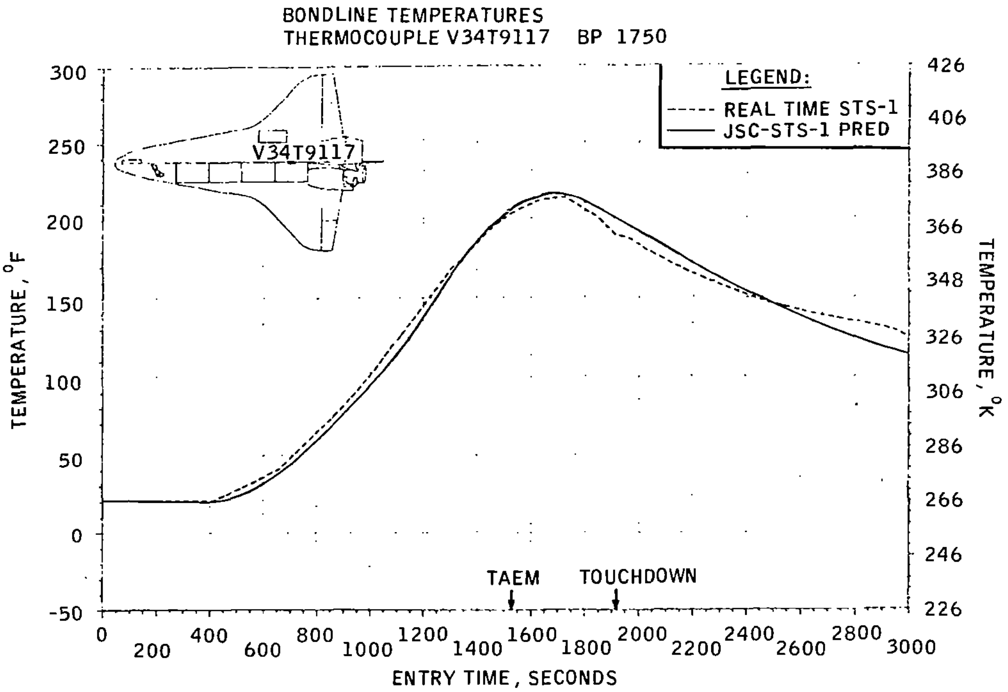
(c) At BP 1801.

Figure 13.- Concluded.



(a) At BP 1600.

Figure 14.- Bondline temperature comparison with STS-1 data.



(b) At BP 1750.

Figure 14.- Concluded.

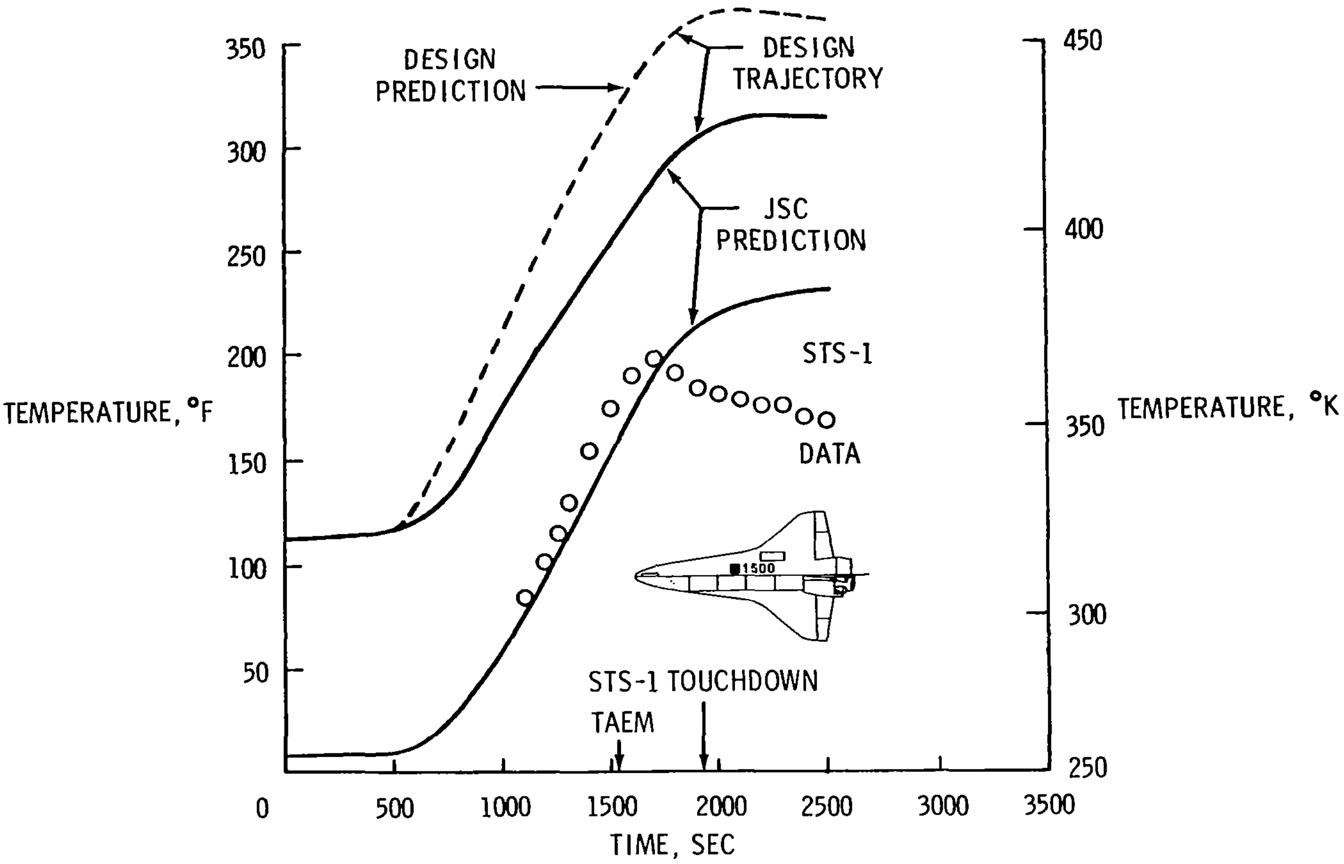


Figure 15.- Entry bondline thermal response, midbody windward.

- COMPUTATIONAL FLUID MECHANICS SIMULATIONS HAVE BEEN A VALUABLE TOOL FOR THE ORBITER DEVELOPMENT
- PREDICTED SURFACE TEMPERATURES AGREE WITH OR EXCEED MEASUREMENTS
- BOUNDARY LAYER TRANSITION OCCURRED AS PREDICTED
- FINITE SURFACE CATALYSIS IMPLIED BY MEASUREMENTS
- TPS THERMAL RESPONSE AS PREDICTED
    - INTERNAL FREE CONVECTION SIGNIFICANT
- THE ORBITER HAS A "WARM" STRUCTURE

Figure 16.- Conclusions.