Shuttle Entry Air Data System Preflight Testing and Analysis

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Data from the Shuttle Entry Air Data System (SEADS) port arcjet test were correlated using conventional finite difference thermal analysis methods to demonstrate the applicability of such methods to flight analyses. The arcjet tests were conducted to demonstrate the integrity of the SEADS-coated columbium port and provide data required to accomplish SEADS preflight analysis. The successful correlation of the results from finite difference thermal analysis methods and the test data demonstrated these methods for flight analysis. Using these techniques, a preflight analysis of the SEADS was performed and it was concluded that the maximum port temperature will be at a safe level for the first SEADS mission.

Nomenclature

f = heat flux ratio
Q = heat load
q_∞ = free-stream dynamic pressure
$\dot{q}$ = heat rate
T = temperature
α = angle of attack
β = angle of sideslip
ϵ = emissivity
σ = Stefan-Boltzmann constant
θ = time

Subscripts

max = maximum
RCC = reinforced carbon-carbon
ref = reference

Introduction

THIS paper reviews the thermal mathematical model (TMM) development that was required to substantiate methods used for the commit-to-flight (CTF) thermal analysis of the initial Shuttle Entry Air Data System (SEADS) flight. An arcjet test program was conducted at the NASA Johnson Space Center (JSC) Atmospheric Reentry Materials and Structures Evaluation Facility (ARMSEF) to provide test data for model development and to demonstrate the capability of the SEADS-coated columbium port to withstand the entry environment. The entry mission picked for test simulation was STS-9, the Spacelab heavy payload mission, since it closely resembles the worst-case SEADS flight. The STS-9 mission was also the most thermally severe entry flown by the Shuttle to date. The SEADS flight program will obtain flight temperatures using radiometers and nose cap surface pressure and temperature data during the next six flights of Columbia.

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The program to provide TMM development data and additional ground test confirmation was conceived jointly by NASA Langley Research Center (LaRC) and NASA JSC. Subsequently, testing was conducted in the JSC ARMSEF facility during November 1984 to March 1985.[1]

Background

SEADS was conceived as a Shuttle orbiter flight experiment at NASA LaRC. It was developed under the orbiter experimental (OEX) program for two purposes:

1) To provide heretofore unavailable air data (q_∞, T, α, β) from high altitudes and high Mach numbers (altitude 92 km, Mach 26) to sea level on a body of revolution.

2) To provide development and evaluation data relative to SEADS use as a high-precision air pressure monitoring system that might be used for orbiter guidance and control.

SEADS consists of a complete reinforced carbon–carbon (RCC) nose cap assembly with specially designed coated columbium alloy static pressure ports. The ports are flush mounted at 14 locations of the nose cap (Fig. 1). Each port is

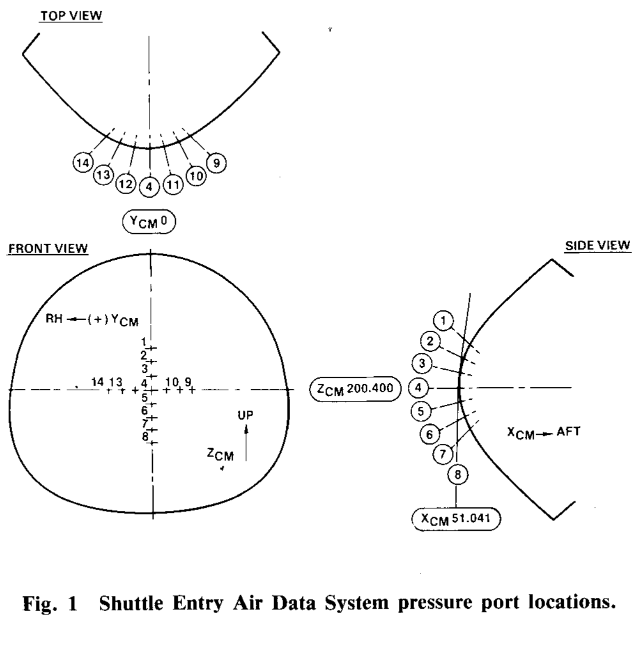

Fig. 1 Shuttle Entry Air Data System pressure port locations.

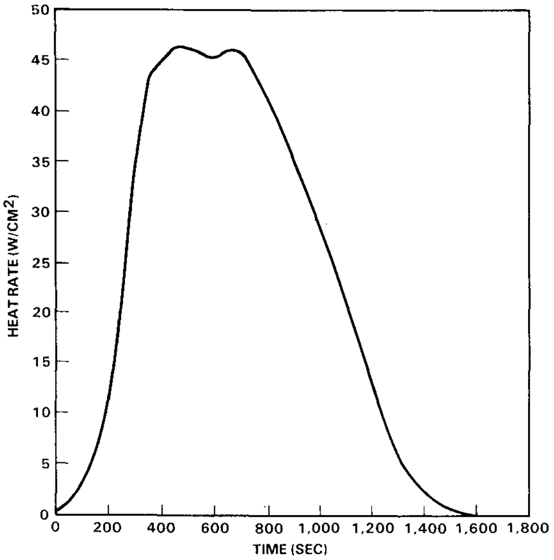

Fig. 2 **Nose cap design 14414.1C heat rate at stagnation.**

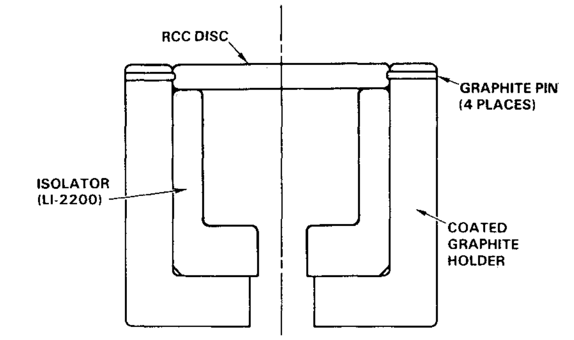

Fig. 3 RCC and C742 coated disc calibration test model.

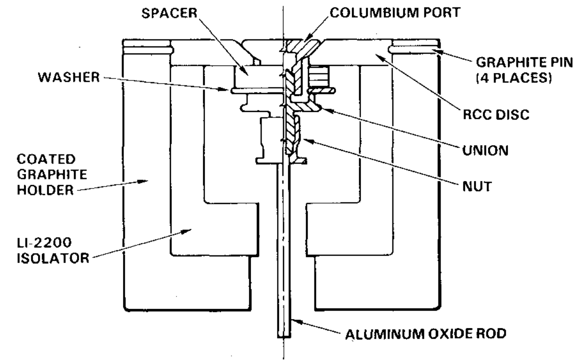

Fig. 4 Columbium port/RCC system test model configuration.

connected through an air manifold to a dual range pressure monitoring system, which has been designed to record nose cap surface pressure continuously from 92 km to touchdown. Six radiometers record nose cap inner mold line temperatures. The SEADS instrumentation system is designed to provide the data required to calculate α, β, and q_∞.[2,3]

Early port design studies and development testing were conducted by the Shuttle subcontractor for the RCC nose cap and wing leading edge panels.[4] Port testing was successfully accomplished during two test phases: first at LaRC and then at the NASA Ames Research Center[5] in arcjet environments intended to simulate orbiter design mission 14414.1C. The design heating, which is shown in Fig. 2, produces a maximum stagnation temperature of 1430°C.

Test Program

Two types of test models were fabricated to obtain RCC and coated columbium alloy port calibration data. The calibration model, shown in Fig. 3, consisted of a 7.21×0.59-cm-thick coated RCC disc with Type C (W—25% Rh/W—5% Rh) thermocouple instrumentation. The RCC material used in the tests is identical to production carbon-carbon used to fabricate the Shuttle orbiter nose cap and wing leading edge panels, and uses a silicon carbide oxidation resistant barrier that both protects the carbon substrate and provides a high surface emittance ($\epsilon = 0.85$). Thermocouples monitor temperatures at both the heated and interior surfaces of the disc, which was positioned in a coated graphite holder by four graphite pins. A 0.035-g/cm^3 foamed silica internal insert served as a near adiabatic isolator for the heated disc.

The system test model was similar to the calibration model but the RCC disc was machined to accept a SEADS-coated columbium alloy port. The port is flush mounted in the disc and identical to the flight article in all respects (Fig. 4). The assembled port is positioned and restrained by a coated columbium union and threaded nut that bear on a RCC spacer and lock the port in place. All port components are coated columbium alloy except for the RCC spacer. The 0.318-cm outer diameter aluminum oxide rod that replaced the columbium pressure tube was retained by the nut and was used to block gas leakage through the port and serve as a support guide for thermocouple lead wires. Test models reached equilibrium temperature after approximately 400 s of exposure in the arc (Fig. 5).

A VH-109 silicide coating provides oxidation protection for all columbium alloy surfaces. The coating thickness can vary from 0.008 to 0.013 cm depending on surface curvature and

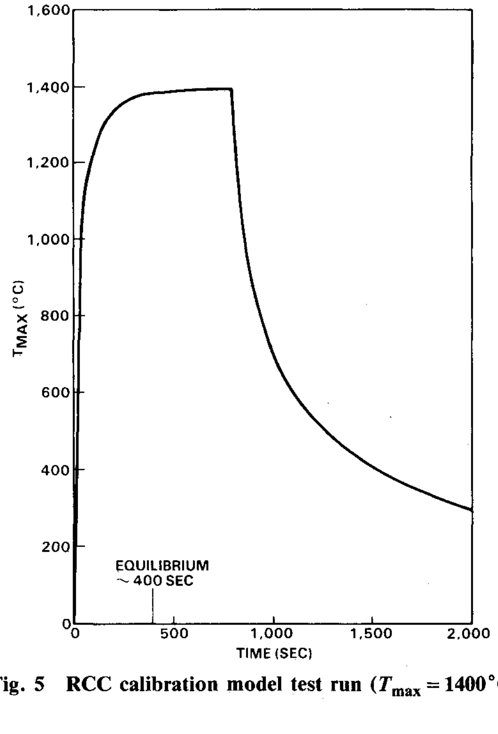

Fig. 5 RCC calibration model test run (T_{max} = 1400°C).

process variables. Union and lock nut threads have been precision machined, and then coated to ensure integrity of the coating at mating thread surfaces after installation.

The test matrix for port tests considered in this paper is shown in Table 1. The initial series of six system model tests was run at a nominal maximum temperature (T_{max}) of 1260°C while the second series of six runs was conducted at a nominal T_{max} of 1430°C. The last test series consisted of three runs at a T_{max} of 1540°C and was intended to provide overtemperature data.

Table 3 Predicted maximum temperature comparison

Columbium T_{max} (°C)		RCC T_{max} (°C)	
Predicted	Observed[a]	Predicted	Observed[b]
1293	—	1260	1259
1493	—	1424	1408
1604	—	1552	1543

[a]Pyrometer readings were irradic and were discarded. [b]Surface thermocouple 1.

Heating Environment

The Shuttle orbiter nose cap must be capable of withstanding the very high predicted heat rate ($\dot{q}$ = 34-51 W/cm²) encountered in the stagnation region. These heat rates result in a surface temperature that exceeds 1260°C, the 100-mission temperature limit of high temperature reusable surface insulation (HRSI) tile. This is the reason that RCC was selected for the Shuttle orbiter nose cap. Table 2 compares the maximum calculated heat rate and RCC T_{max} at stagnation for a number of entry missions flown by two of the four operational orbiters. The design entry mission, 14414.1C, has also been included for reference. As shown in the table, the STS-9 mission flown by Columbia actually exceeded the RCC design heating and T_{max}. Margins inherent in the system design were adequate to preclude failure of the nose cap. However, for a mission like STS-9, the system will degrade at a rate that exceeds the design rate, since the higher temperature levels accelerate RCC substrate mass loss and thus reduce the mission life of the nose cap. The severity of the STS-9 entry environment is a consequence of entry from a 57-deg inclined orbit with the heavyweight Spacelab payload. The more heavily burdened vehicle requires higher and more sustained aerodynamic braking, thus producing a higher peak heat rate, a longer entry timeline, and a higher heat load. This is the reason that STS-9 entry was selected for simulation in the SEADS arcjet tests. The STS-9 flight heat rate at the nose cap stagnation body point is plotted in Fig. 6. Since it is impractical to simulate this transient in an arcjet facility, another plan was devised for SEADS testing.

Previous flight and test experience for coated columbium was limited to 1370°C; therefore, 1370°C was selected as the lowest temperature of interest for the test. As previously discussed, the test matrix included temperatures both less than and greater than this datum. This extension of test temperatures provided comparative data for port integrity evaluation and TMM validation. Using the maximum predicted port temperature for STS-9 of 1440°C, the test scheme illustrated in Fig. 7 was devised. From the plot of port temperature, the time at temperatures greater than 1370°C was calculated as 620 s. The test facility was then set up to provide an exposure of 620 s at a heating environment calibrated to provide a T_{max} of 1440°C. Since the actual test time at T_{max} would exceed the flight time at T_{max}, the test would provide a conservative evaluation of port survival.

Columbium and RCC Surface Heat Rate

Success in correlating the test data with finite difference thermal analysis methods depends on accurately determining surface heating to both coated columbium and RCC. RCC heat rate can be calculated directly from calibration test results obtained from an RCC disc instrumented with surface thermocouples. At equilibrium, and assuming an adiabatic disc, the surface temperature was substituted in the adiabatic wall heat balance equation to calculate heat rate. RCC emittance for these calculations was a function of temperature and is plotted in Fig. 8. Although precautions were taken in the calibration model design to limit heat losses from the RCC disc, some edge and backface radiation losses were evident. These heat losses were estimated to be approximately 8% of the incident heat rate, which was considered acceptable accuracy for the test.

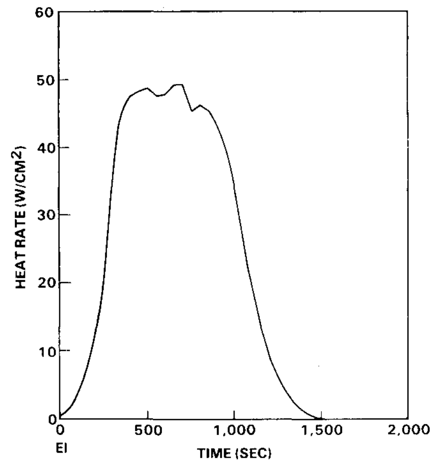

Fig. 6 Shuttle flight STS-9 heat flux.

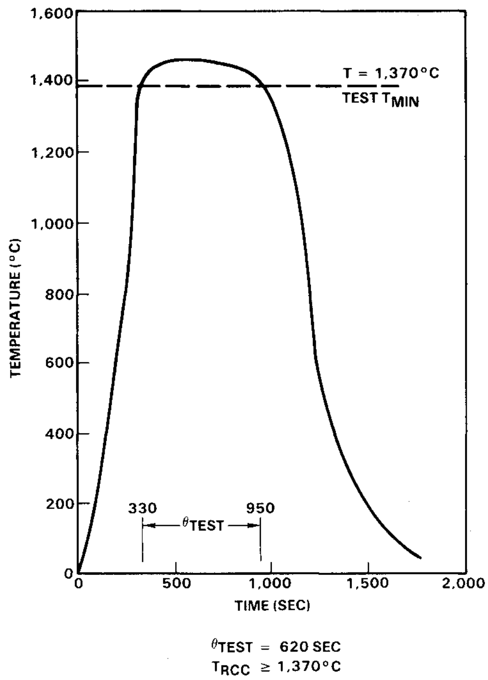

Fig. 7 System test article test duration selection using STS-9 preflight RCC temperature prediction.

It was desirable to use the heat balance method to calculate coated columbium heat rate, but instrumenting a columbium disc for testing in an oxidizing air environment was both formidable and untried with the present model configuration. Success in attaching a thermocouple to the very thin (0.008-0.013 cm) silicide coating using conventional techniques without degrading or destroying the coating integrity appeared unlikely. It was also possible that a conventional thermocouple installation could cause coating degradation that could serve as a nucleation point for oxidation. Since columbium oxidation would produce local heat generation, this would introduce an error of unknown magnitude in the thermocouple measurement that would likely invalidate the measurement.

The C742 catalytic coating (iron-cobalt-chromium spinel), which was originally developed for Shuttle flight testing,[6] provided an alternate method of determining columbium surface temperature. The coating had been used successfully at the Ames Research Center in arcjet tests, which showed

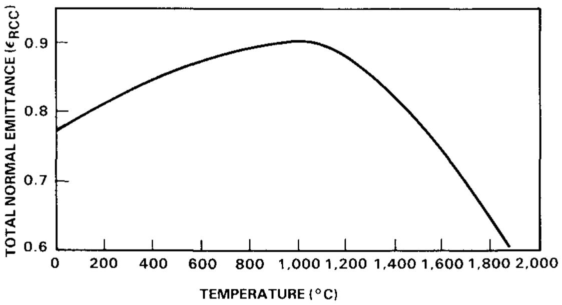

Fig. 8 Reinforced carbon-carbon total normal emittance.

that C742-coated RCC discs exhibited surface catalycity similar to coated columbium.[7] Therefore, the problems of instrumenting coated columbium could be avoided by using an instrumented RCC disc identical to the calibration test model except coated with C742 on the heated surface. Then, calibration model temperature data could be acquired in arc tests and used to calculate surface heat rate by means of a heat balance. The coating emittance used for the calculations was 0.75.[8]

A copper slug calorimeter was used during calibration runs to measure the fully catalytic heat flux data. These data established the fully catalytic heat flux and were used as a datum to compare RCC- and C742-coated disc data. A thin (0.025 cm) nickel coating was plated on the exposed copper surface to limit oxidation.

The facility provided two pneumatically actuated sting arms that allowed test models to be positioned at the arc centerline after arc stabilization. A typical calibration run used the dual arm system by mounting the copper slug calorimeter on the first sting and either a standard or C742-coated RCC calibration model on the second. The calibration sequence first inserted the slug calorimeter in the arc to measure reference $\dot{q}$ ($\dot{q}_{ref}$) while recording enthalpy and pressure data. With the first model removed, the second model was then inserted into the arc and allowed to reach equilibrium. Disc surface heat rate was then converted to $\dot{q}$ using the surface equilibrium thermocouple reading.

Effective heat rate data for the RCC disc model and the C742-coated disc model were first corrected to cold wall temperature, and then plotted as a function of copper slug reference heat flux in Fig. 9. The data are seen to be linear with $\dot{q}_{ref}$, although some data scatter is evident, particularly with RCC. Inspecting the data shown in Fig. 9 led to the following conclusions.

Both RCC and coated columbium, simulated by the C742-coated disc, are less than fully catalytic over the range of arc conditions tested. RCC is approximately 50% of the catalytic value while coated columbium $\dot{q}_{ref}$ is approximately 67%. The JSC RCC data are in the low range of data obtained in arcjet tests at Ames Research Center.[7] The Ames data show coated columbium to be nearly 100% catalytic. The difference in simulated columbium $\dot{q}$ data in the current test might be caused by the differences in the C742 coating or its application method during the two programs.

It should be noted that since direct measurement of coated columbium temperature was not made in the current test program, there was an uncertainty in the analysis since the actual catalytic efficiency of coated columbium was unknown. This uncertainty was considered acceptable since the primary purpose of the program was to demonstrate the analysis methods used. Subsequently, the excellent correlation of analytical predictions with test model thermocouple data proved the validity of the approach. However, for flight it was necessary to take a conservative approach to assess the possibility of the port T_{max} as a potential Shuttle flight safety concern. The assumption made for flight analysis is discussed in a later section.

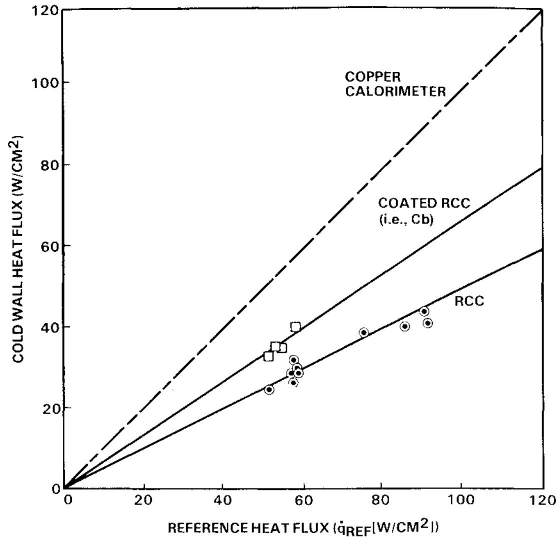

Fig. 9 SEADS calibration model heat rate comparison.

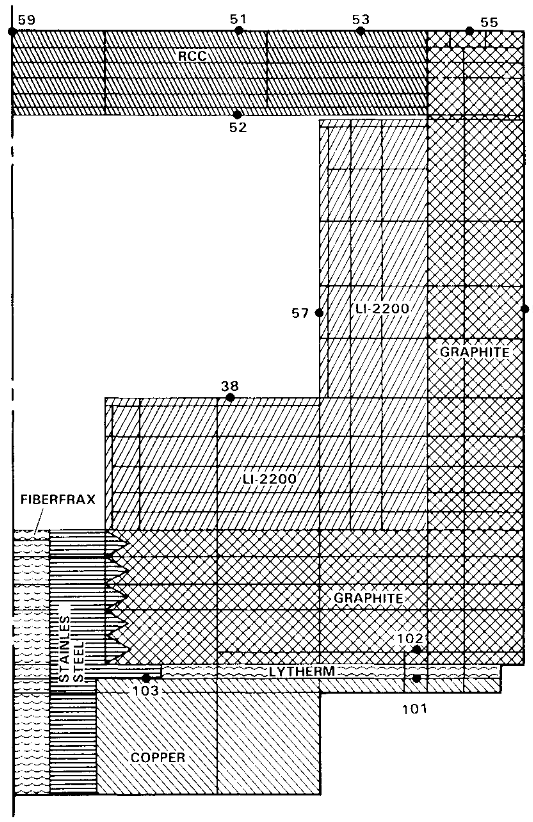

Fig. 10 SEADS calibration TMM.

Test Data Analysis and Correlation

Flight prediction methods were demonstrated by analysis with the aid of detailed TMM's, which were developed to simulate system test configurations. Two TMM's were developed to analyze both the calibration test model and the port system test model shown in Figs. 3 and 4. The calibration TMM is presented in Fig. 10, which shows the nodal arrangement of the RCC disc, LI-2200 sleeve, graphite model holder, stainless-steel model adapter, copper holder, and Lytherm and Fiberfrax insulation. The port system TMM of Fig. 11 was similar to the calibration TMM, except that it included both the columbium port assembly at the center of the RCC disc and the solid aluminum oxide rod that was

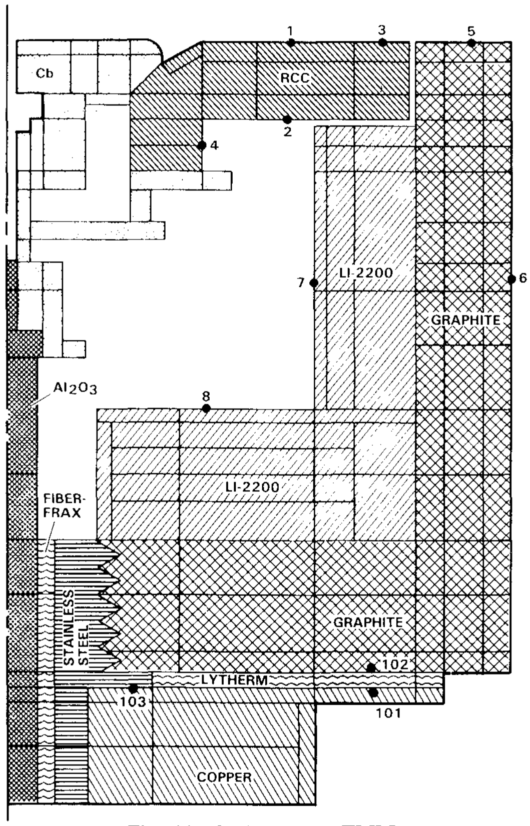

Fig. 11 SEADS port TMM.

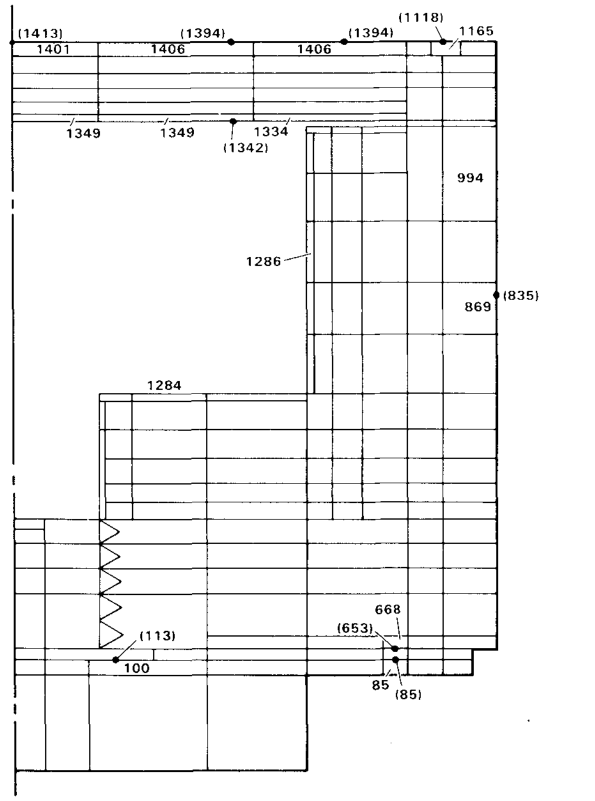

Fig. 13 Calibration model predicted and measured equilibrium temperatures.

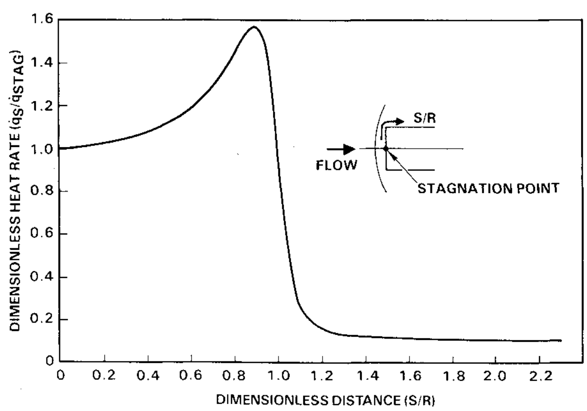

Fig. 12 Heat rate variation near edge of flat-faced cylinder.

supported from the port assembly. Also shown in Figs. 10 and 11 are the locations of the thermocouples.

Transient, three-dimensional analyses were performed using the Rockwell XF0031 heat conduction program.[9] The company-developed computer code is the standard used for Shuttle commit-to-flight thermal analyses and was used for methods validation and subsequent SEADS flight thermal analysis. The view factor required for radiation interchange were calculated by means of the Thermal Radiation Analysis System (TRASYS) Program.[10] The external surfaces of the models were assumed to radiate to a 27°C heat sink. The measured temperature of the copper adapter holder (thermocouple 101) at the sting arm interface was assumed to be a constant temperature heat sink. A contact coefficient of 39 cal/s-°C was assumed at all metal-to-metal interfaces, while a value of 3.9 cal/s-°C was assumed at interfaces with an insulation. These coefficients are common values used for these surfaces with machined parts.

For convenience in the analysis, the surface heat rates were obtained by first determining the measured slug calorimeter heat rate as a function of heater power. The radiation equilibrium heat rate based on the maximum measured surface temperature was then obtained using the design emissivity curve for RCC (Fig. 8). A heat rate ratio was then calculated as

$$f=\frac{\dot{q}_{\mathrm{RCC}}}{\dot{q}_{\mathrm{ref}}}=\frac{\sigma\epsilon_{\mathrm{RCC}}T_{\mathrm{RCC}}{}^{4}}{\dot{q}_{\mathrm{ref}}}$$

This factor varied from 0.37 to 0.45 for RCC in the 1260°C to 1540°C temperature range.

Use of this factor in the program calculated RCC surface temperatures that were low by about 60°C. An increase in surface heat rate by a factor of 1.08 was then used to bring the RCC front face predictions to within 15°C of the test data. The factor accounted for disc heat losses and data scatter in f. Because of the higher surface catalycity of the columbium port, a higher surface heating rate factor was calculated. Based on calibration test data from the C742-coated RCC disc tests, a value of f in the range of 0.6 to 0.7 was calculated. As previously discussed, the catalycity of the C742 coating is similar to that of columbium. For this analysis, a value of 0.65 was used for the surface of the columbium in the port TMM. With both of the TMMs, the model heat rate was known to increase toward the edge and then rapidly decrease on the sidewall. Figure 12 was developed and used in the analysis to account for variation of $\dot{q}$ to the heated surfaces. This curve was derived from the test data of Refs. 11 and 12, and the measured graphite holder top and side surface thermocouple data. The heat rate curve presented in Fig. 12 was based on the calculations of Ref. 13, using density ratios computed using the Nonequilibrium Air Tunnel Analysis (NATA) program,[14] and values of mass flow rate and enthalpy obtained from arcjet test data.

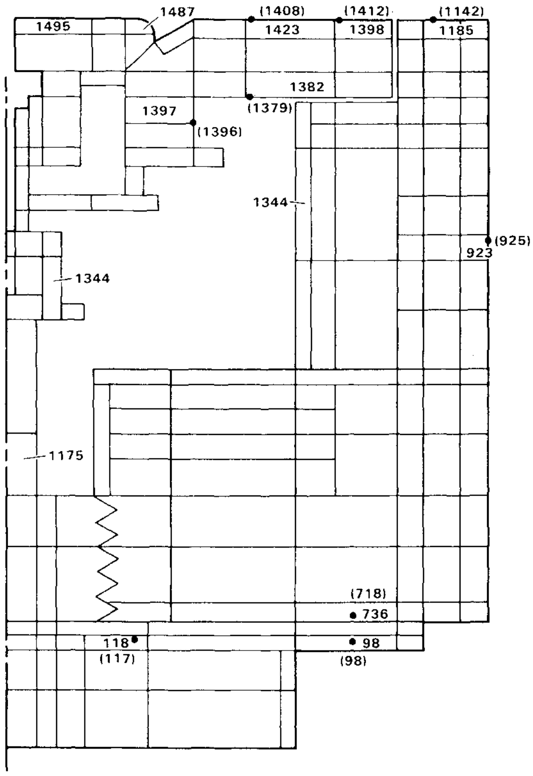

Fig. 14 Port model predicted and measured equilibrium temperatures.

Figures 13 and 14 plot typical TMM results for spatial distribution of predicted temperature for both calibration and port model tests. These predictions were for a nominal test temperature of 1420°C. The test data obtained at selected thermocouple locations are also shown in these figures at thermal equilibrium to provide a direct comparison that shows the accuracy of the analysis in predicting test temperatures. It is seen that model predictions are within 28°C of the thermocouple data while predicted RCC front-face temperatures are within 15°C (1%) of the test data. Figures 13 and 14 show the excellent accuracy of the TMM to predict in-depth temperatures of the calibration and port test models.

Figure 15 compares predicted temperatures as a function of time to test data at a surface temperature of 1420°C. This plot shows predictions at the RCC outer mold line, RCC inner mold line, RCC spacer, and the graphite lower surface temperatures together with thermocouple data. From these figures it is seen that excellent agreement between test data and TMM prediction was achieved. For the test analysis at 1420°C, the predicted peak columbium temperature was about 60°C higher than the predicted peak RCC temperature (Table 3). This temperature difference is not expected in flight as is discussed in the next section. Excellent correlation between prediction and test temperatures was also obtained at the other temperature levels tested: 1260°C and 1540°C.

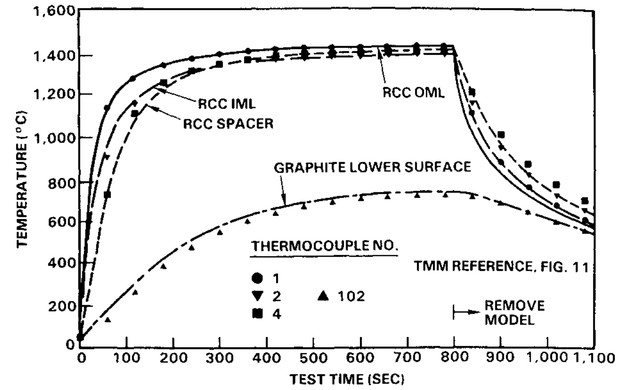

Fig. 15 Comparison of TMM prediction with test data for surface temperature ~1430°C.

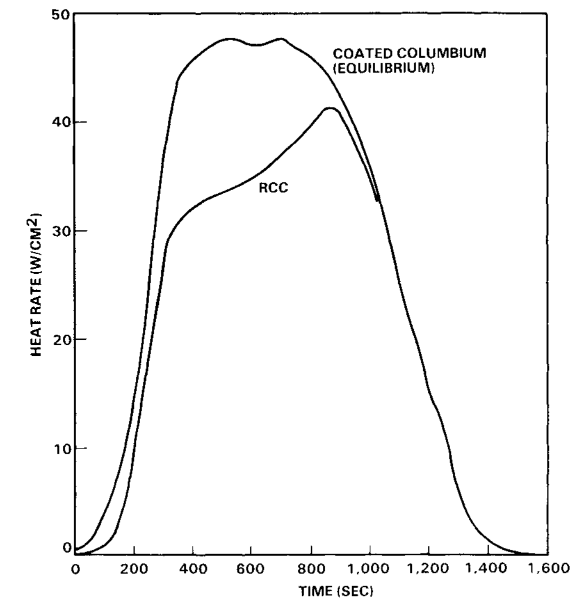

Fig. 16 SEADS port stagnation heat rate for the STS-9 entry trajectory.

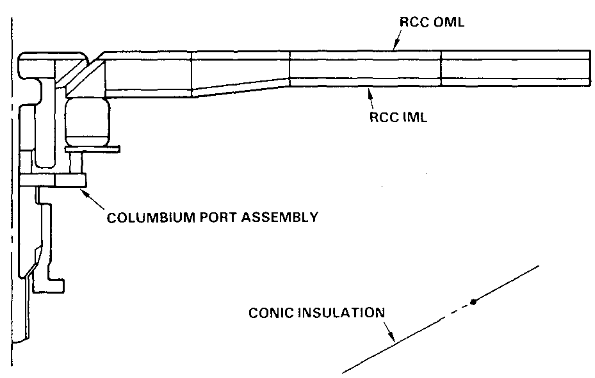

Fig. 17 SEADS columbium port flight analysis TMM.

Flight Temperature Prediction

Aeroheating predictions for both coated columbium and RCC surfaces were required for the flight analysis since each of these surfaces exhibit different degrees of catalycity in the entry dissociated air environment. The Rockwell Aeroheating Program XF0002,[15] which was modified to account for finite catalycity, was used for the analysis as follows.

RCC nose cap radiometer data from STS-5 had been used with a finite catalycity approach to correlate flight temperature transients using the methods presented in Ref. 16. This was accomplished in two steps.

First, an equilibrium heat rate correlation was developed for the heating distribution on a sphere and modified using scale model wind tunnel data to provide an equilibrium boundary layer solution. Next, this correlation was further modified by incorporating a dissociation energy potential term to account for dissociated air species recombination energy in the nonequilibrium boundary layer. Forcing the nonequilibrium equation to agree with nose cap radiometer flight data from STS-5 allowed good correlation between predicted and flight RCC temperatures.

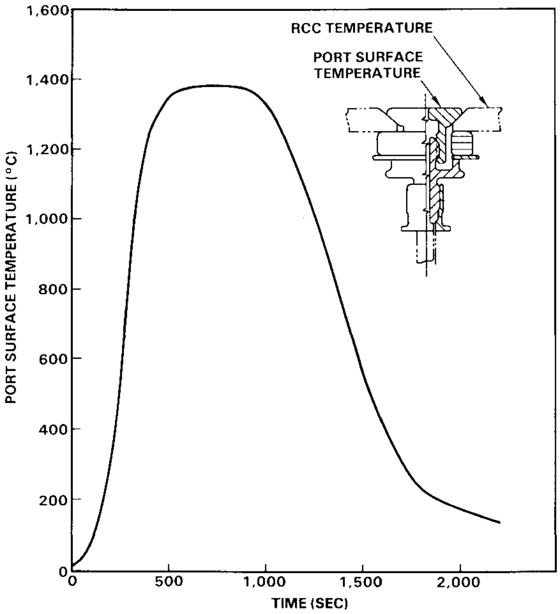

Fig. 18 Columbium port predicted temperature for STS-9.

The equilibrium or fully catalytic heat rate correlation was used to predict heat rate to the high catalicity columbium port. Although this approach had not been confirmed in the current test program, which indicated the simulated columbium surface was less than fully catalytic, it was decided to employ a conservative approach for the flight environment analysis. Coated columbium and RCC $\dot{q}$ histories for the STS-9 mission are compared in Fig. 16. The RCC $\dot{q}$ varies with time as both pure convection and air recombination energy are transferred through the dissociated boundary layer. At peak heating (700 s in Fig. 16), the RCC $\dot{q}$ is found to be 77% of the columbium fully catalytic $\dot{q}$. At later entry times air energy levels decrease, heat transfer occurs by convection only, and RCC and columbium heat rate predictions converge.

The stagnation port TMM used to predict SEADS flight temperatures is shown in Fig. 17. In an earlier study it was found that the relatively complex internal surface geometry and temperature distribution that comprise the nose cap internal radiation environment could be reduced to a single internal node when the analysis of a local zone of the RCC nose cap shell was performed. This temperature, which varied with entry time, was found to be close to the mean internal surface temperatures. Although this assumption was a major simplification, it had been used with good accuracy to correlate RCC flight temperatures measured with a radiometer during STS-5. Accordingly, the same simplification could be justified for the SEADS port TMM; therefore, it was adopted in the port TMM for the flight environment analysis. Columbium port T_{max}, RCC T_{max}, and the port temperature history for STS-9 are shown in Fig. 18. Peak temperature for the port and the adjacent RCC are 1382°C and 1402°C, respectively.

One observation is that port temperature and RCC are predicted to be nearly equal in flight, whereas the port temperature prediction exceeded the RCC temperature in the test. This difference is attributed to the mismatched columbium port and RCC surface heating. During the tests in which both port and RCC are allowed to reach equilibrium in an adiabatic enclosure, the port surface temperature will reach a higher equilibrium temperature because of its higher $\dot{q}$. However, in flight the port is not adiabatic since it radiates to the cooler internal surfaces of the nose cap. Because of the extended surfaces of the port, which act as a fin, the port more efficiently dissipates the surface heating and this results in nearly equal port and RCC temperatures.

Conclusions

The SEADS-coated columbium port was successfully tested at 1260°C, 1430°C, and 1540°C for as many as six entry simulation cycles with little evidence of damage. Effective heating because of catalytic effects were noted with both RCC and simulated columbium systems. The simulation was accomplished during the test using a high catalycity-coated RCC disc. Calculated heat rate data for the latter were less than anticipated, possibly because of anomalous constituents in the coating or the way it was applied for the current test.

The use of conventional finite difference methods for flight analysis were demonstrated by correlating test data with system test model predictions. Use of these methods for the STS-9 flight heating environment showed that the SEADS port is predicted to operate at a safe temperature for the first SEADS mission.

Acknowledgments

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