1-4

Recent Comparisons of Aerothermodynamic Results by CFD and FEM Coupling Analysis with OREX Flight Experiments

by

Yukimitsu Yamamoto
National Aerospace Laboratory,Japan

ABSTRACT

Accuracy of CFD is investigated by comparing numerical results with the measured flight temperature data on the TPS material of OREX. Flow is caluculated by the non-equilibrium Navier-Stokes code and internal thermal response is computed by FEM. Coupling CFD and FEM along the OREX flight trajectry, temperature increase of the TPS during re-entry is favorably predicted. In FEM analysis, the effects of temperature and directional dependence of heat conduction coefficient and radiation effects of TPS material are evaluated. These works have been done as the joint research of NAL and NASDA

1. Introduction

For the development of space transportation vehicles, it is required to predict accurately their aerothermodynamic environments during re-entry, espeacially in high temperature hypersonic flight regime. OREX (Orbital Reentry Experiments) is the first flight experiments planned as a part of the HOPE (H-II Orbiting Plane) projects. OREX was launched by the H-II rocket on February 4, 1994, from Tanegashima Space Center of Japan. The flight experiments were succssfully conducted as almost planned and various kinds of flight data, concerning to aerothermal environment, were aquired[1]. On these experiments, one of the most important purposes is the evaluation of aerothermodynamic heating, which has a large effects on TPS design of re-entry vehicles.

However, in the hypersonic re-entry flight condition, dessociations and ionization of the air are caused due to high temperature environments and real gas effects must be considered in the analysis of aerothermodynamic heating. On the other hands, advanced CFD (Computational Fluid Dinamics) has now potential to simulate such real flow and become a powerful tool for the aerothmal predictions.[2] In our study, based on the OREX flight trajectry data, temperature response of OREX TPS material are analyzed by the non-equilibrium Navier-Stokes CFD code and internal thermal response is computed by FEM.

Data exchange of surface temperature and heat transfer is made alternatively, every 10 seconds along the OREX flight trajectory. Caluculated temperature increase is compared with the mearured flight temperature on the TPS material, such as C/C nose, C/C TPS and ceramic tiles. The purpose of our study are 1) to analyze OREX TPS flight temperature hisory, 2) to well understand the aerothemodynamic environment and the coupled flow thermal-structural interactions, and 3) to investigate the applicability the real gas CFD code as the tool for the evaluation aerothermodynamic heating.

2. Numerical Algorithm

Basic equations used in the present analysis, are Navier-Stokes equations with thin layer assumption. The differencing is based on the upwind TVD flux-split method.[2] Real gas effects are evalueted by using 7 species chemically non-equilibrium one temperature model. In the present, preliminaly analysis, uncertainty of the real gas modeling must be eliminated, and the heat transfer dose not change between one (chemically non-equilibrium) and two (thermochemically non-equilibrium) temperature models. So, the aerothermal analysis are made by one temperature real gas CFD code. Detailed description of numerical algorithm is presented in Ref.2. As the boundary conditions, non-catalytic wall surface is assumed and wall temperature is given by FEM analysis at each trajectory points.

In the present study, internal temperature increase is calculated by FEM, using heat transfer distributions on the surface. In FEM analysis, the effects of temperature and differential directional dependence of heat conduction coefficients of each TPS materials are considered and radiation effects of each TPS materials are also evaluated.

3. Numerical Results

OREX geometry is shown in Fig.1 with the detailed dimensions. The forebody shape is composed of a spherical nose, cone and a circular shoulder. OREX weight is 760 kg just befor the re-entry. Table 1 indicates OREX re-entry flight trajectory focused on the present study. This table shows the flow data and C/C nose cap stagnation point temperature history at evey ten seconds. The altitude changes from 105Km to 48Km and Mach number from 27.0 to 9.1. At each trajectory points in the table, flow is computed by using the chemicalhy non-eguilibrium Navier-Stokes code. Computational mesh consists of 41 points distributed streamwise along the body and 60 points between the body and outside of the bow shock wave.

Figure 2 shows thermo-couple locations for temperature measurements, where comparison with numerical predictions are made. Fig 2(a) indicates the measurement points just behind C/C nose cap. Temperature are measured at the center of C/C nose cap (Termocouple No. TH1) and at the $\theta = 20$ deg points (TH2, TH3, TH4) from the axis. At the right hand side of the figure, outline of OREX structure system is drawn. It is noticed that heat shield plate is set behind the C/C nose cap in order to protect thermal radiation from the internal nose. For the C/C TPS panels, circumferentially different three measurement points (TH7, TH8, TH9) are set, as shown in Fig.2(b). In the left of the fingure, temperature history of three thermo-couples are plotted. On the ceramic tile, three point (TH22, TH23, TH24) data in Fig 2(c) are used for comparisons. In this case, thermo-couples are embedded in the ceramic tile surface. The depth of measurement center from the surface is about 1.5 mm. Also, in the left side of Fig 2(c), temperature history is plotted. It is known that maximum temperature reachs about 1000°C.

In Fig.3, a series of temperature contours are shown at trajectory points listed in Table 1. We use chemically non-equilibrium one temperature code for flow analysis. So, translational and rotational temperature are plotted in the figure. About the altitude of 90 km, it is noticed that the rarefaction effects are conspicuous and shock stand off distance becomes large with the increase of the altitude. Maximum temperature reaches more than 20000 K in high altitudes flight, where high temperature region beyond 12000 K is also large. With the decrease of the altitude, this high temperature area disappears and maximum temperature in the shock layer drops gradually.

In Fig.4, FEM grids of TPS material are shown. Grids are drawn in a enlarged form to the inner direction. OREX TPS are composed of 4mm thick C/C nose cap, 1.5mm thick C/C TPS and 20mm thick ceramic tiles. Thermal properties of each TPS are presented in Table 2. In the present FEM analysis, the effects of temperature and differential directional dependence of heat conduction coefficient of TPS materials are considered. Also, radiation effects (emissivity of 0.84 on the OREX C/C materials and 0.8 on the ceramic tile)are evaluated. Intenal radiation is assumed to be zero for the C/C nose cap region, because heat sheald after the nose cap protects the inner radiation. For the other TPS material surface, emissivity of internal radiation is assumed to be 0.7.

CFD-FEM coupling analysis are made along the OREX trajectory every 10 seconds. Computational procedure are as follows.

(1) At the flight time of 7361.0sec and an altitude of 105Km, flowfield is calcutated using free stream conditions of Table 1. Wall temperature distribution is given by the constant value of temperature of 332 K on the whole surface. This assumption is considered to be valid, because on the C/C nose cap temperatures at TH1,2,3 and 4 is almost the same level at 332 K and, on the other area, temperature is almost constant at 302 K. On the ceramic tiles, temperature increases in short time and reach to radiation equilibrium state, so, initial temperature difference on ceramic tiles may be ignored.

(2) From the flow calculations, heat transfer distributions are determined and surface temperature after 10 seconds is computed by FEM analysis.

(3) Based on the freestream conditions after the 10 seconds and the wall temperature distributions obtained by step(2), flow fields are calculated by CFD code and heat transfer distributions are computed at the new altitude.

These procedures are done alternatively and temperatude increase of TPS materials is evaluated at each altitude in order.

In Fig.5, temperature increase of OREX TPS material is depicted at each OREX trajectory points. Temperature increase is rapid on the ceramic tile surface due to low conductivity coefficient. However, maximum temperature is caused at an altitude of 56 km on the C/C nose cap stagnation point. At the innner point of C/C nose cap temperature is about 3 deg below than the outer surface. On the inner ceramic surface, remarkable increase of temperature are not observed.

Figure 6 shows the change of heat transfer distributions along the OREX trajectory. It is shown that maximum heating is produced at an altitude of 60 km, where stagnation point heating reaches to 0.383 MW/m^2. Also in the figure, local peak heating is generated at the shoulder due to the local flow acceleration. Figure 7 is the surface temperature distributions at OREX trajectory points. In the early stage of OREX re-entry, temperature on the ceramic tile increases rapidly and may reach to local radiation equilibrium state. Maximum tolerable temperature of C/C and ceramic TPS are 2000°C and 1400°C, respectively.

Fig.8 shows the comparison between measured temperature history and CFD-FEM coupling results at C/C nose cap stagnation point. Measured maxinum temperature reaches about 1570 K, whereas numerical prediction represents almost the same temperature. In our analysis, emissivity of 0.84 and non catalytic surface conditions are assumed. In Fig.9, similar comparison of temperature history are shown at $\theta = 20$ deg point of C/C nose cap. Numerical maxinum temperature is about the same as the measurements.

In flight analysis, aerothermodynamic heating is alternatively estimated by decoupling the flow analysis. In this method, only FEM is used by assuming more complete thermo structual models. The result of stagnation point heating about 1.2 times higher than the CFD-FEM coupling results. The difference may originate in the surface catalycity of C/C nose cap.

Comparison of the C/C TPS temperature is presented in Fig.10. Measured temperature becomes maxinum about 1000°C for all three mesurement points. In this case, numerical reults predict almost the same value as the experiments.

Figure 11 shows the comparison of ceramic tile surface temperature. Measured temperature has the maxinum peak of about 1000°C at the TH23 point and temperature at TH22, and TH24 points follows. In this case, comparison is made at 1.5 mm lower points than surface, corresponding to the thermo-couple center locations. Numerical prediction shows almost similar temperature. However, in the numerical analysis, the maximum temperature appears at slightly lower altitude.

Finaly, comparison of stagnation point heating on the C/C nose cap are shown in Fig.12, where the maximum heating by CFD-FEM coupling analysis are slightly lower than the flight data analysis[1)] and the location of peak heating are shifted to lower altitude. Also, in the figure, prediction by Fay and Riddell's theory and Detra, Kemp and Riddell's calculations are plotted. It is noticed that analytical predictions overestimate the stagnation point heating.

Conclusions

OREX TPS temperature history is analyzed by CFD-FEM coupling analysis. In our study, the approach by one-temperature chemically nonequilibrium flow model is adopted. In this preliminary studies, the applicability of one-temperature real gas CFD code are investigated in detail and its accuracy is evaluated. Numerical results favorably predict the behaivior of temperature increase of each TPS material during OREX re-entry. On the C/C nose cap, calculated maximum temperature at each measurement points coincide with the flight experiment. However, maximum stagnation point heating predicted by flight analysis[1)] differs from the value obtained by CFD-FEM coupling mathods. This may be due to the different treatments of internal thermal structure analysis and the surface catalycity. In the real enviroments, heat sheald effects after the nose cap, etc, have to be introduced in our CFD-FEM analysis. On the other C/C TPS and ceramic tiles, good agreements are also obtained in maximum temperature predictions, although slight time difference of peak appearence exists. In OREX flight experiment, atomospheric data is not gathered, so, the accuracy of standard atomosphere model used in the present CFD computations must be also investigated by using the other available flight experimental data such as pressure coefficients. In addition, the study of the sensitivity of thermal properties and catalytic surface effects must be made.

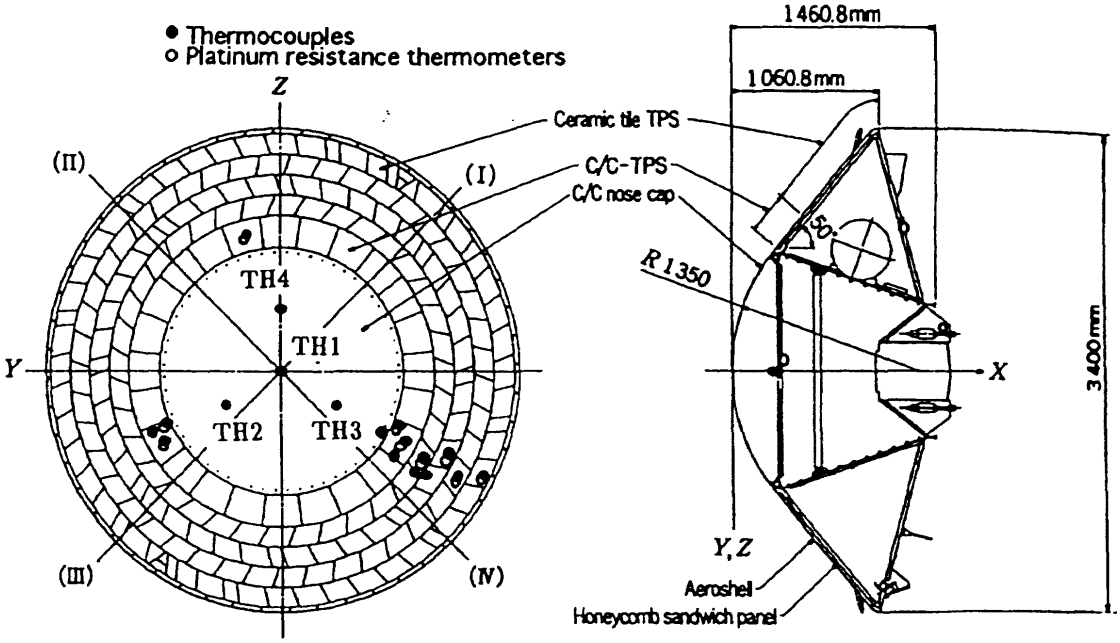
References

1) NAL/NASDA Joint Research Report. 「OREX」 March, 1995 (in Japanese)

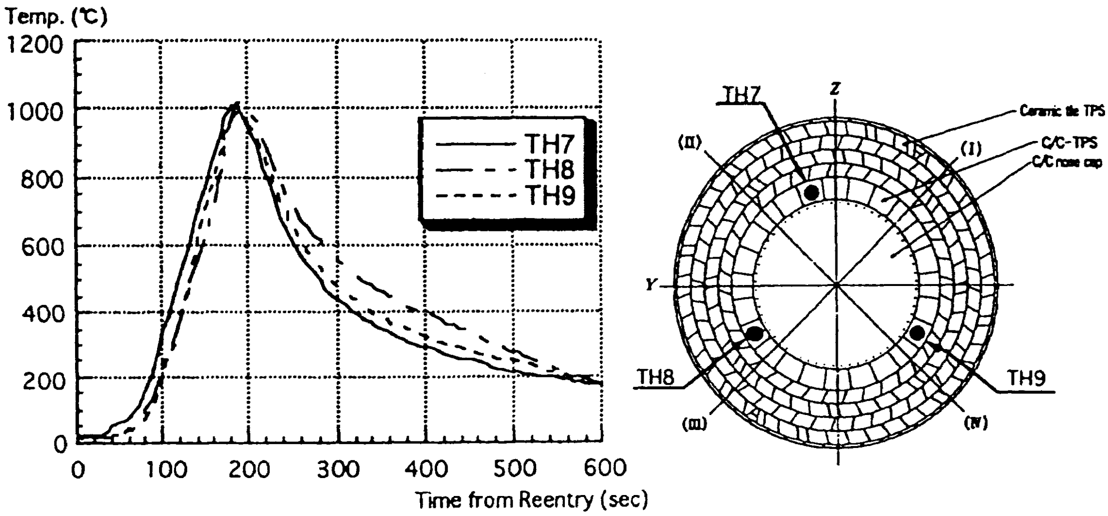
2) Yamamoto,Y,"Numerical simulation of Hypersonic Viscous Flow for the design of H-II Orbiting Plane (HOPE), Part II" AIAA Paper 91-1390, June 1991

3) Yamamoto,Y, Wada,Y, and Yoshioka,M, "HYFLEX Computational Fluid Dynamic Analysis ; Part II. " AIAA Paper 95-2274, June, 1995

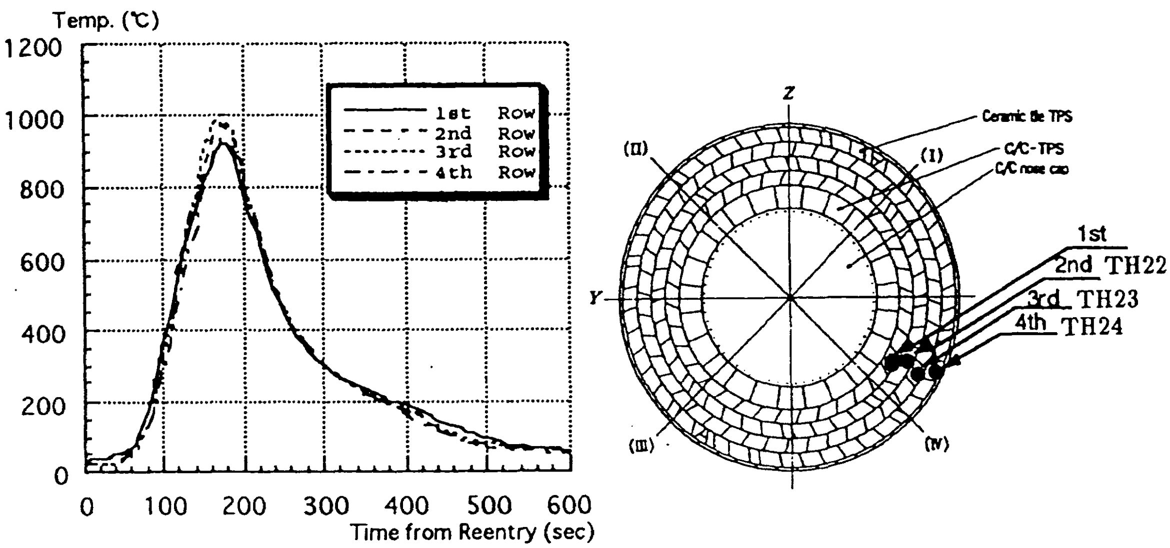
4) Yamamoto,Y, Wada,Y, and Yoshioka,M, "Hypersonic CFD Analysis for the Aerothermodynamic Design of HOPE " AIAA Paper 95-1770, June, 1995



a) C/C nose cap sensor Locations and Structure systems.



b) CC-TPS Sensor Locations and Temperature Histroy



c) Ceramic Tile Sensor Locations and Temperature History

Fig.2 OREX Temperature measurement Location

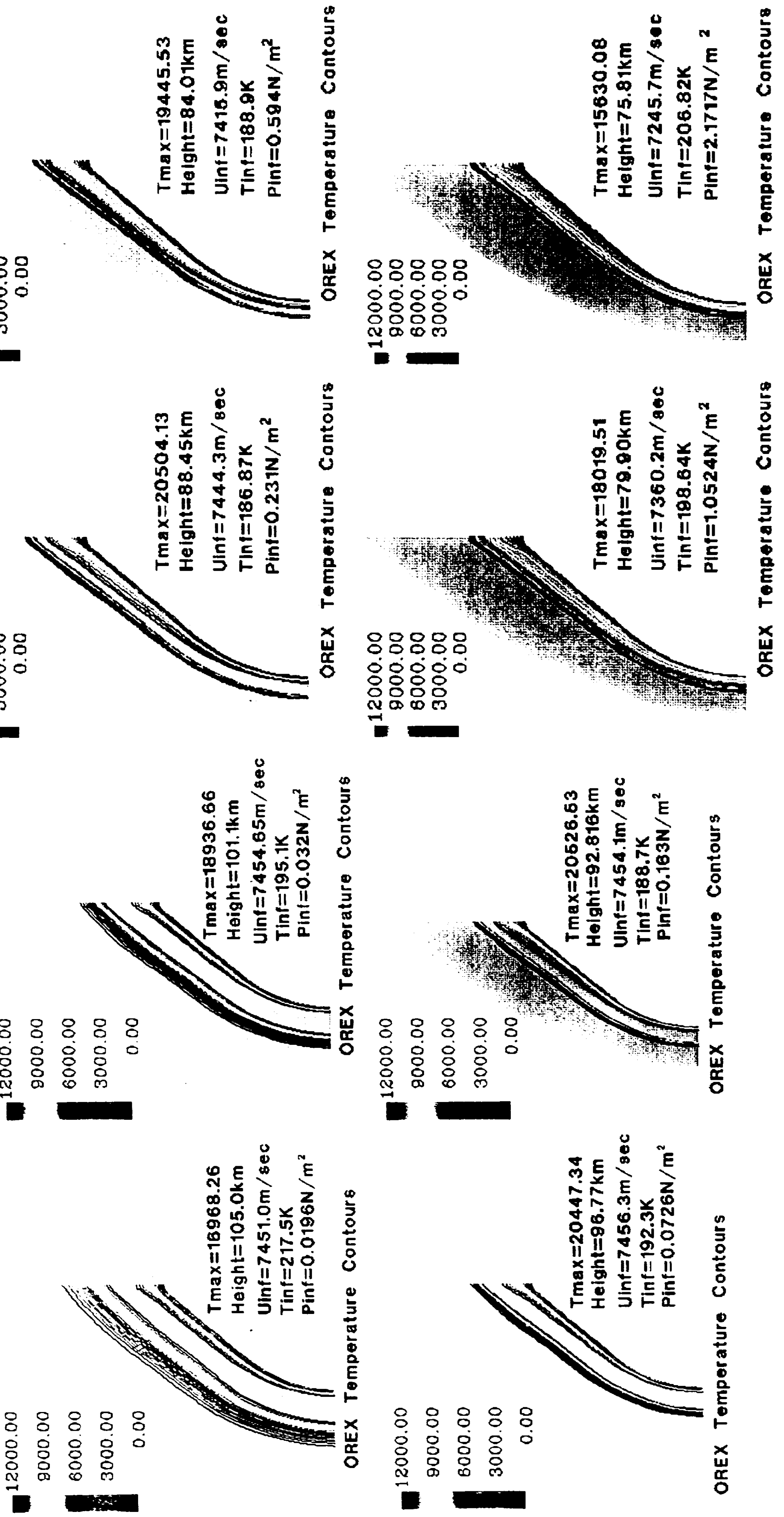


Fig 3. OREX Flow Temperature Contours along at Each Flight Trajectory Points in Table 1

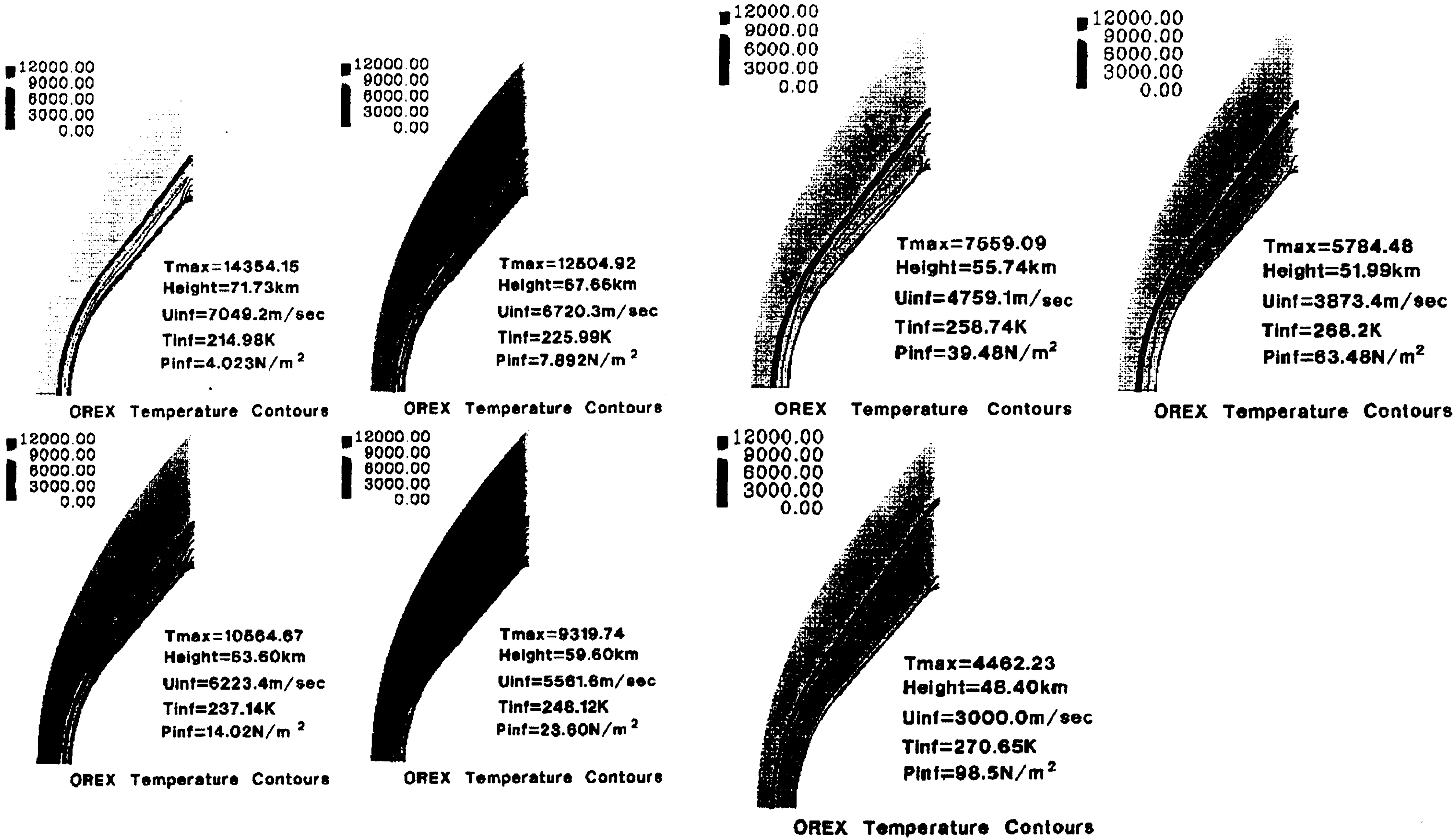


Fig 3. OREX Flow Temperature Contours along at Each Flight Trajectory Points in Table 1

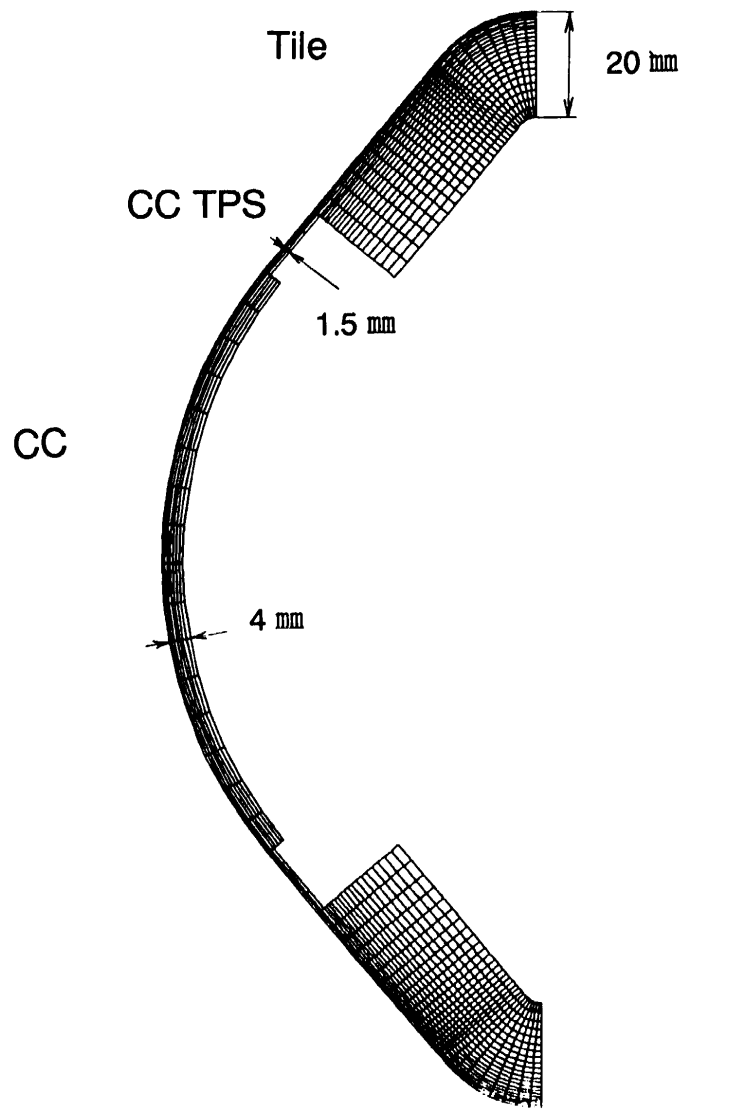


Fig.4 OREX TPS Grids for FEM Analysis Thermal

OREX Thermal Properties of TPS Materials

Material C/C Nose Cap	Density (g/㎤)	Temp (℃)	Specific Heat (kcal/ kg ℃)	Thermal Conductivity (cal/cm·S· ℃)	Emissivity
C/C Parallel Direction	1.50	RT	0.159	78.732	0.84
		500	0.371	131.22	
		1000	0.434	134.96	
		1500	0.544	168.48	
C/C Normal Direction		RT		17.50	
		500		29.16	
		1000		29.99	
		1500		37.44	

Material	Density (kg/ℓ)	Temp (℃)	Specific Heat (J/kg K)	Thermal Conductivity (W/mk) Normal	 parallel	Emissivity
C/C TPS (MHI)	1890	25	615	0 ℃	206.1	0.84
		500	1476	300 ℃	166.6	
		1000	1714	600 ℃	119.0	
		1300	1838	900 ℃	110.2	
		1500	1970	1200 ℃	117.1	

Material	Density (g/cℓ)	Specific Heat (kcal/ kg ℃)		Thermal Conductivity (kcal/mhr ℃)		Emissivity
Ceramic Tile	0.216	0 ℃	0.151	0 ℃	0.040	0.8
		500 ℃	0.212	300 ℃	0.050	
		1000 ℃	0.232	600 ℃	0.065	
		1400 ℃	0.243	900 ℃	0.104	
				1200 ℃	0.153	

Table2 Thermal Properties of TPS Materials

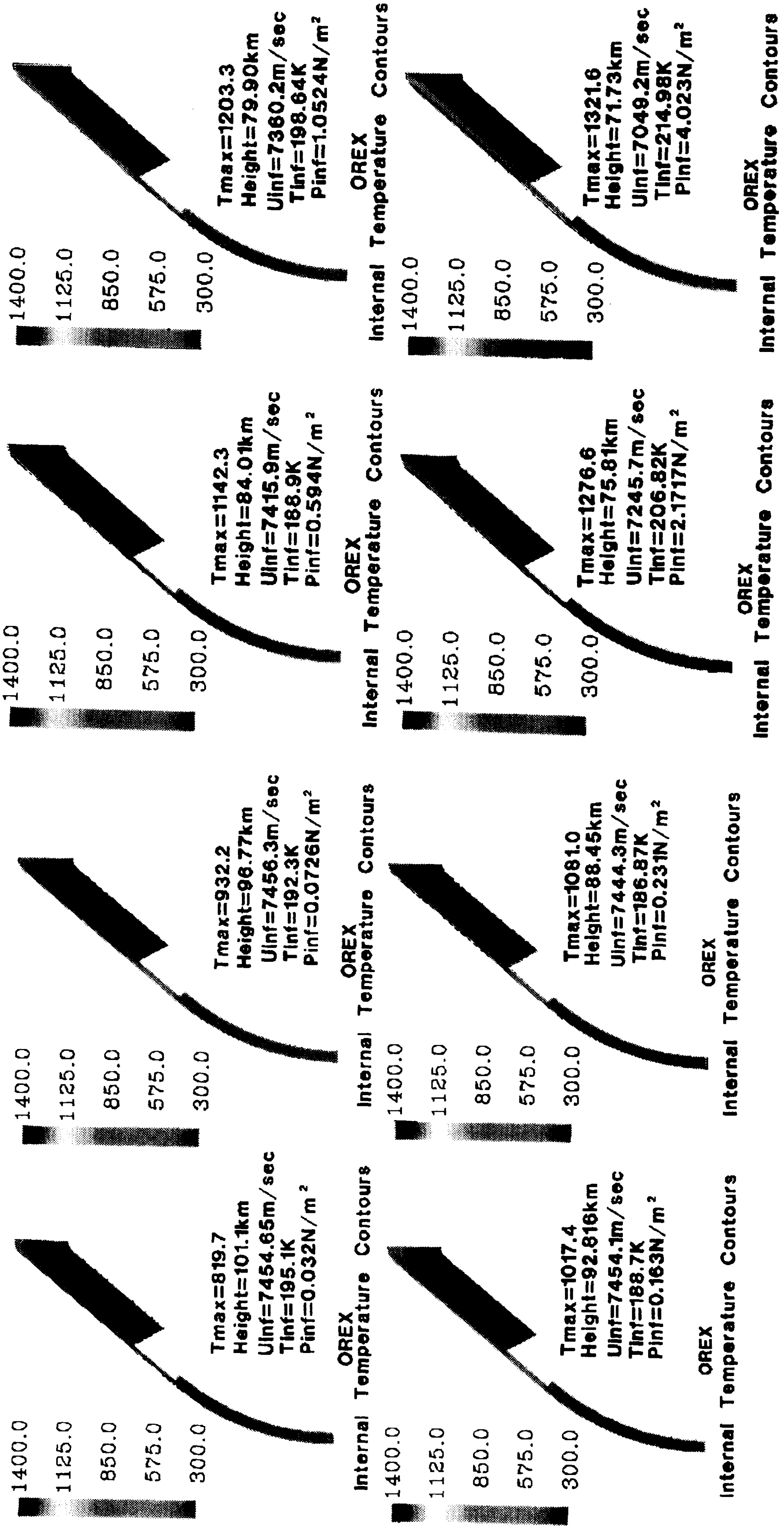


Fig 5. Internal Temperature Contours of OREX TPS at Each Flight Trajectory Points in Table 1

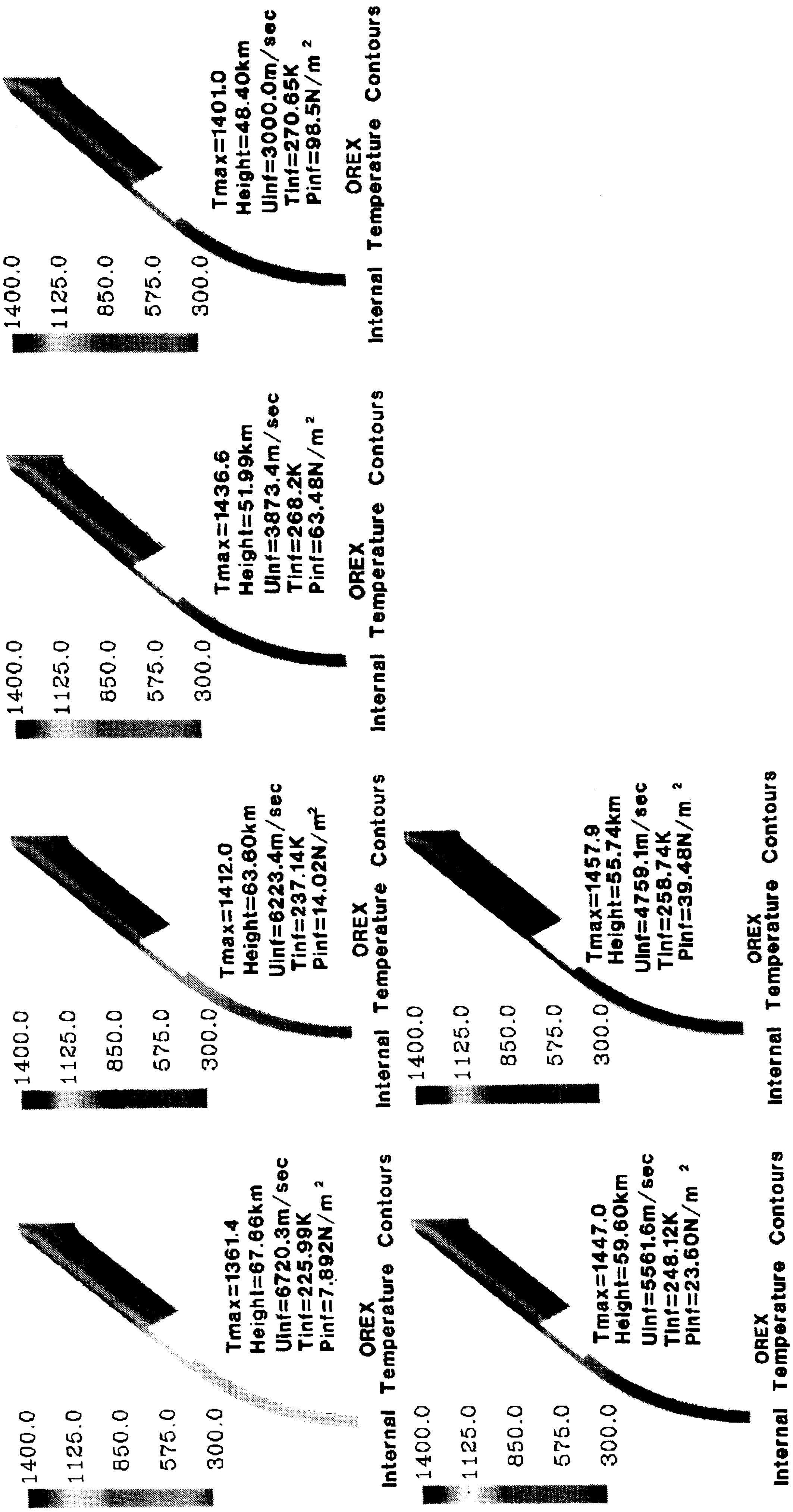


Fig 5. Internal Temperature Contours of OREX TPS at Each Flight Trajectory Points in Table 1

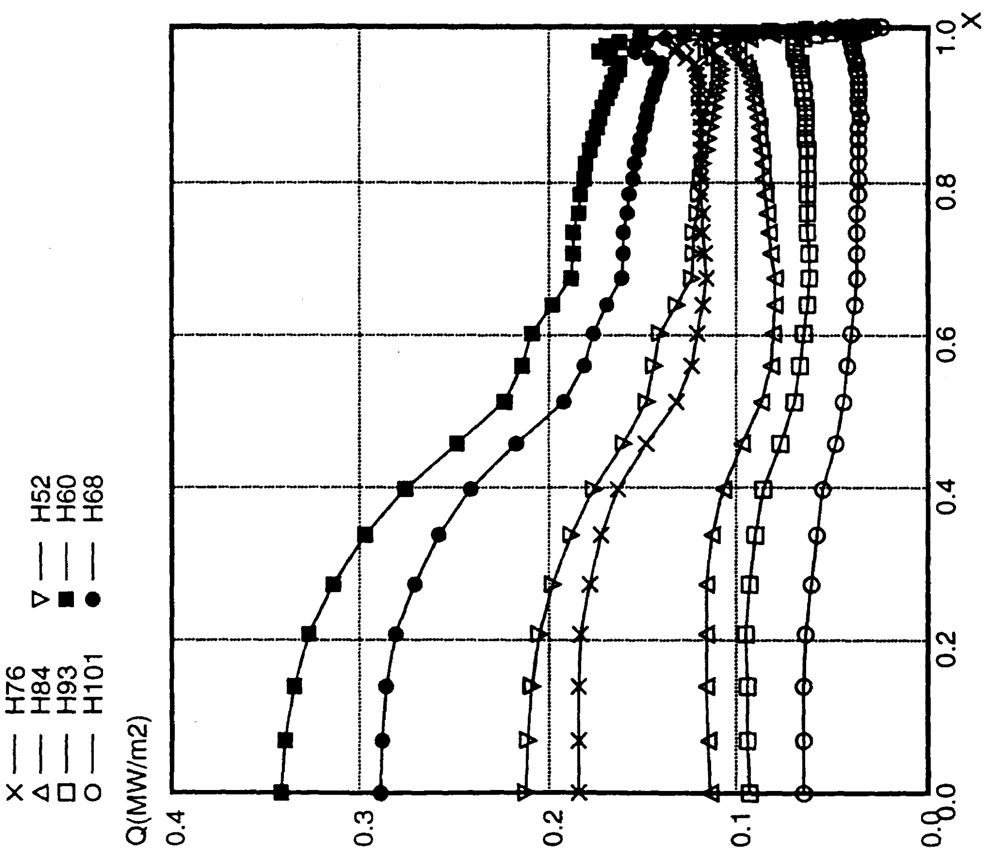


Fig.6 Heat Transfer Distributions along the Vertical Coordinate of OREX at Several Flight Trajectory Points

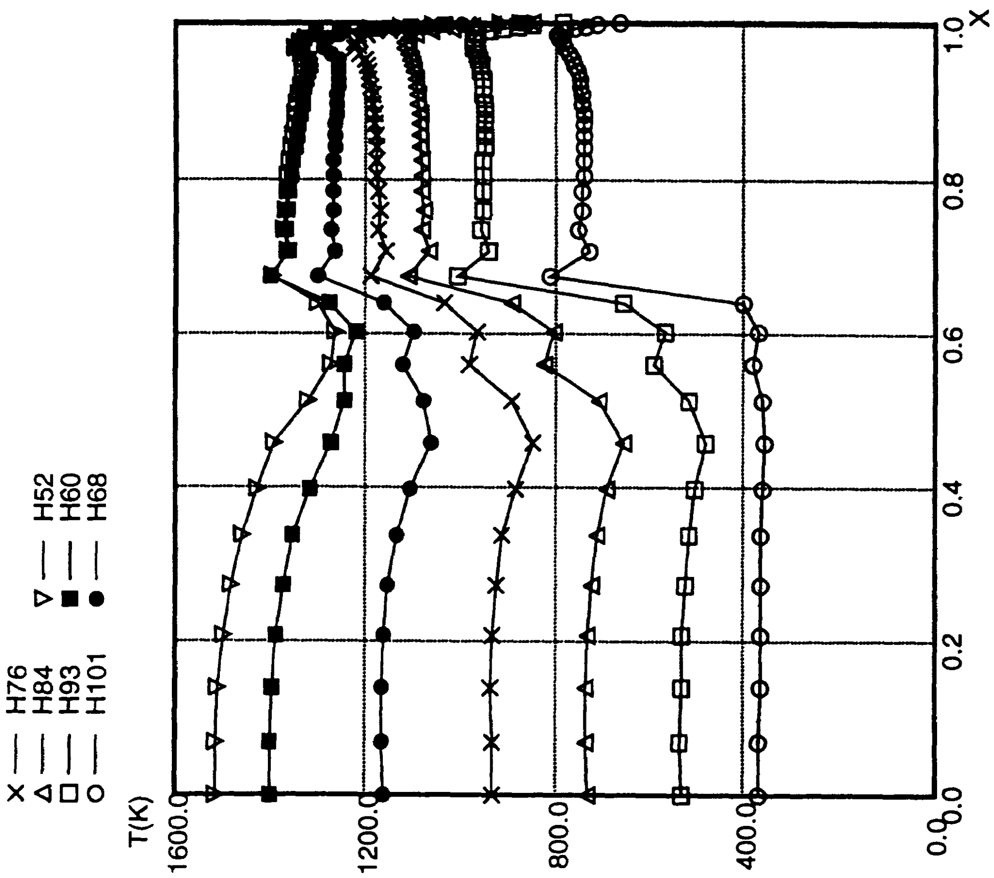


Fig.7 Surface Temperature Distributions along the Vertical Coodinate of OREX at Several Flight Trajectry Points Trajectory Points

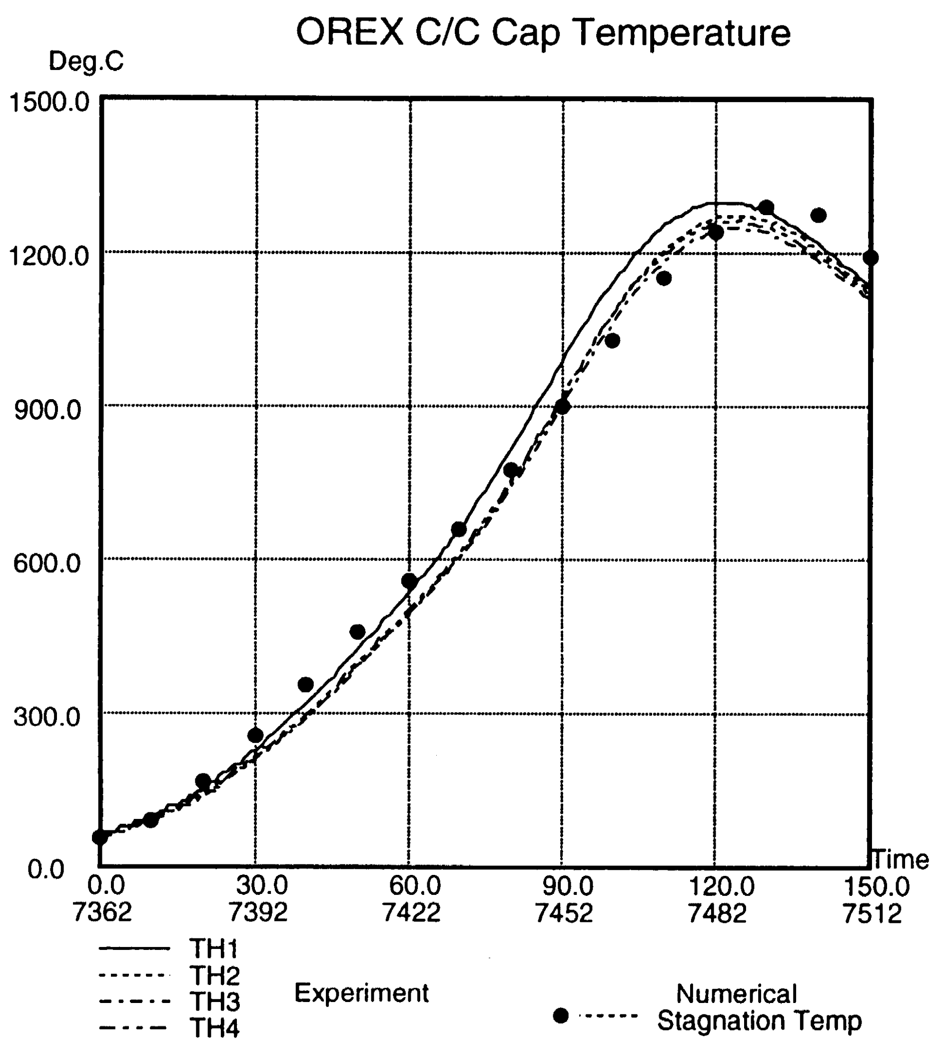


Fig.8 Comparison of C/C Nose Cap Stagnation Point Temperature History

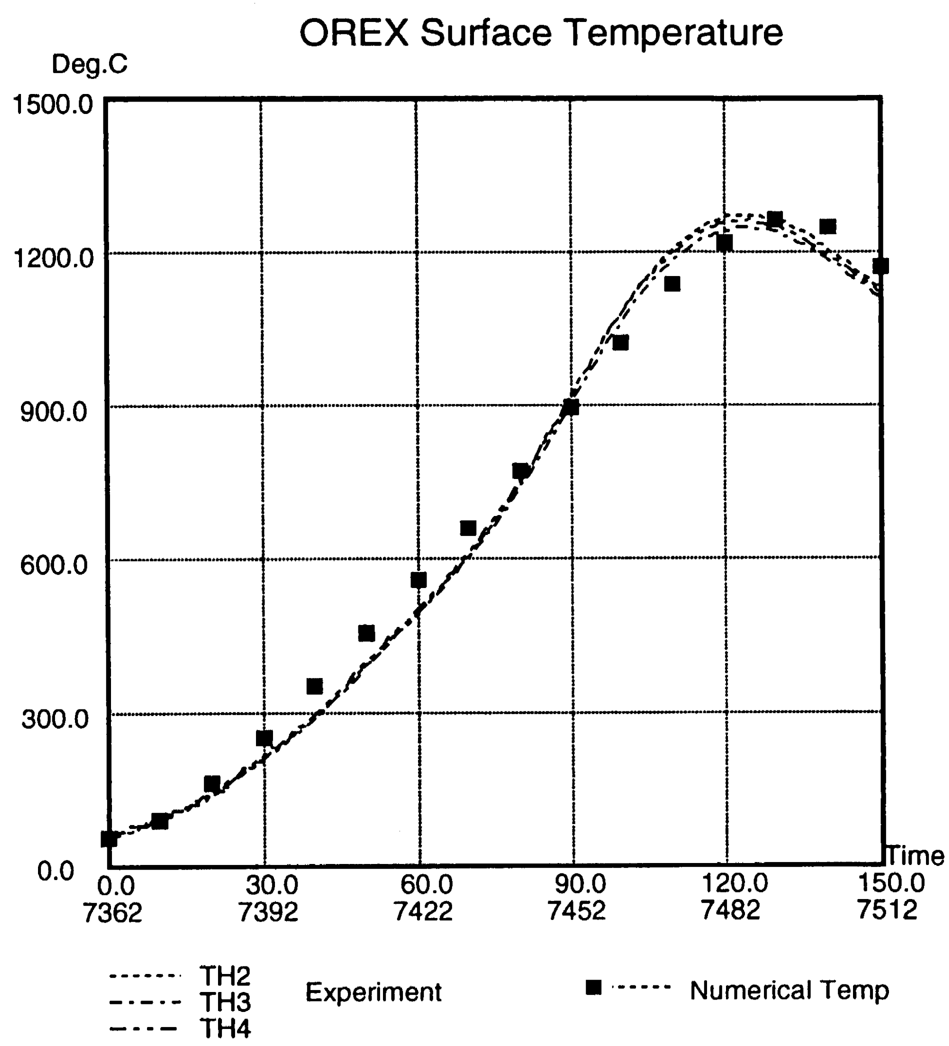


Fig.9 Comparison of C/C Nose Cap Temperature History at θ=20deg

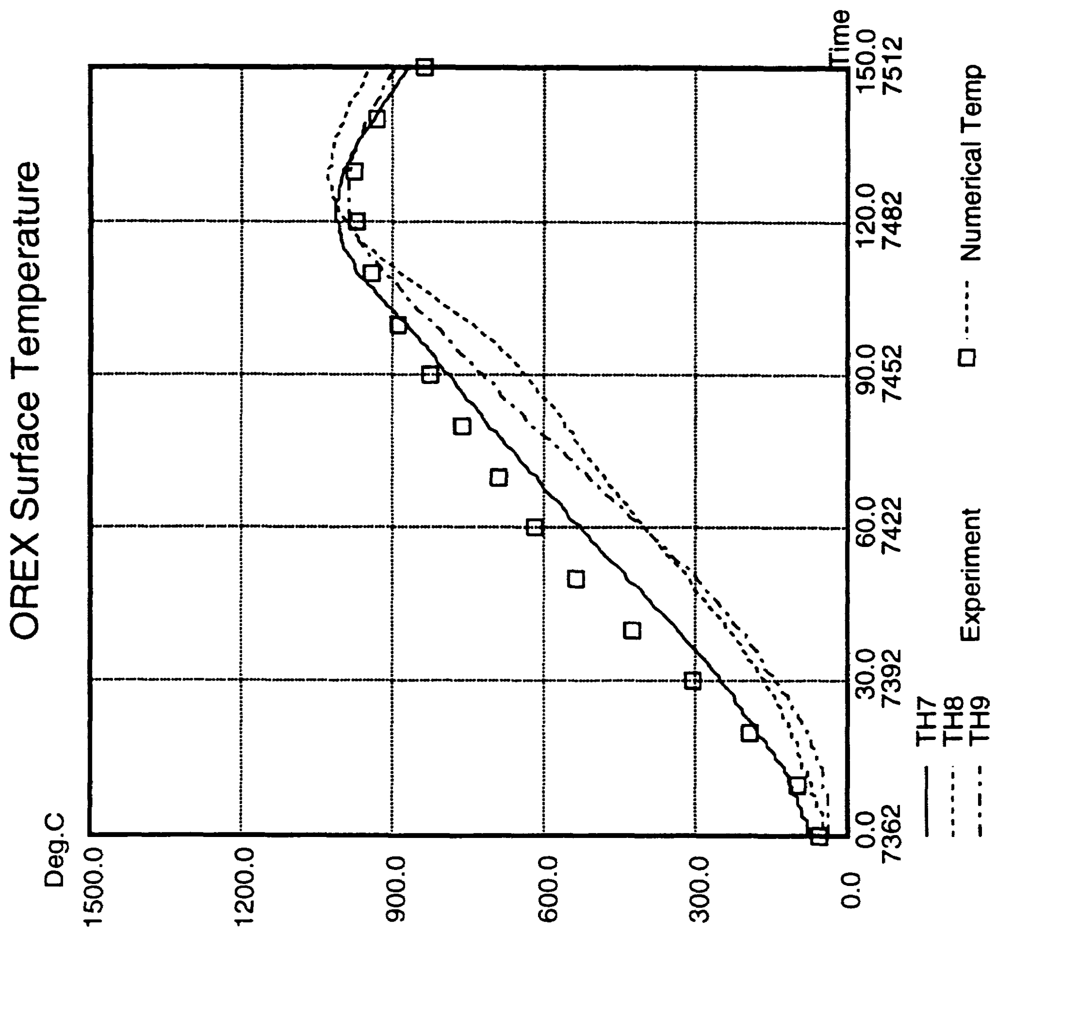


Fig.10 Comparison of C/C TPS Panel Temperature History

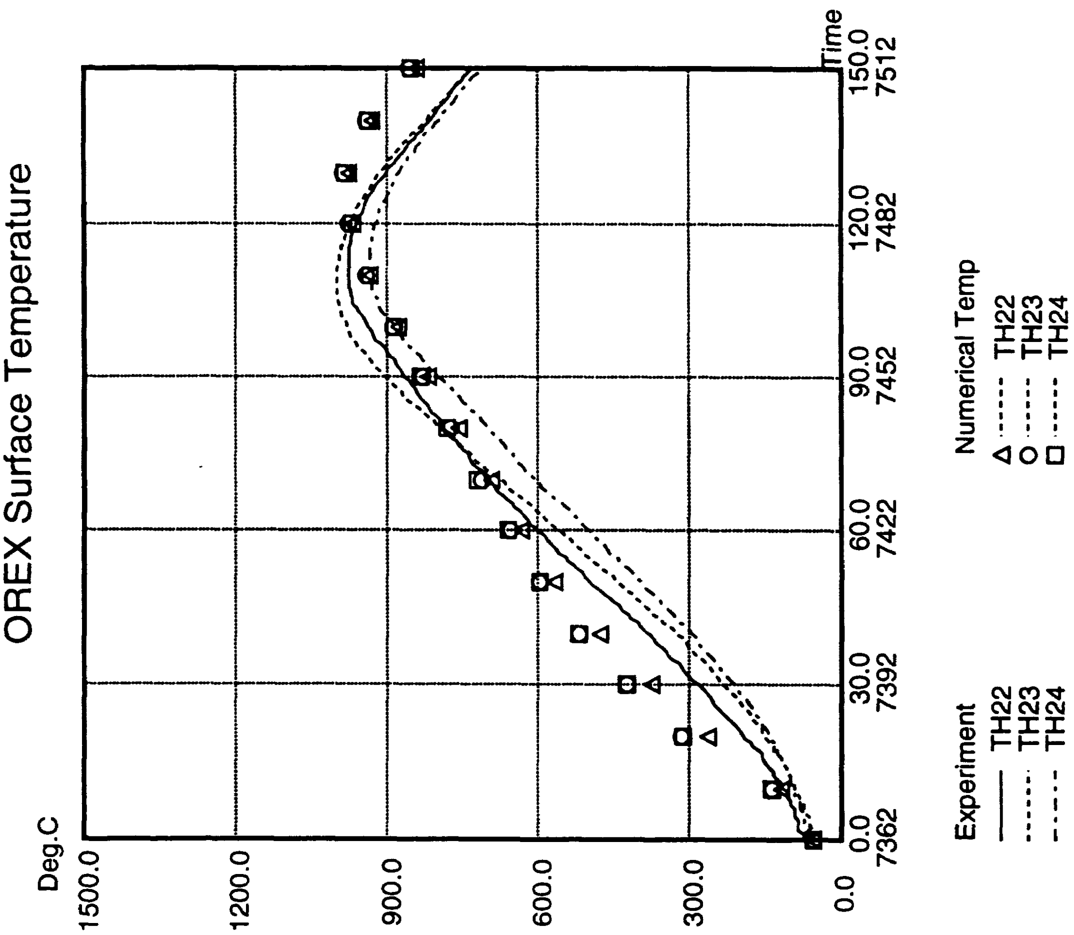


Fig.11 Comparison of Ceramic Tile temperature History

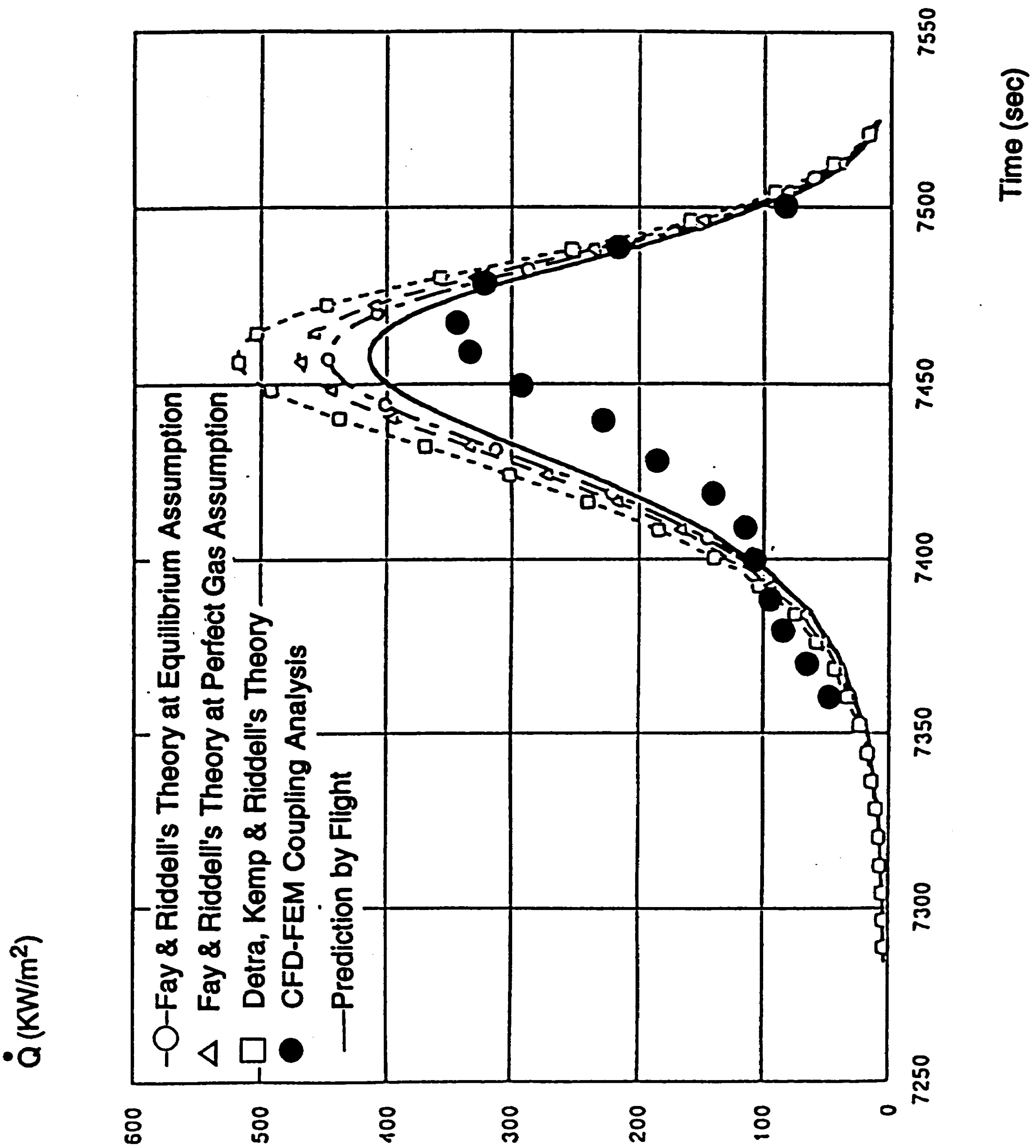


Fig.12 Comparison of Stagnation Point Heat Transfer