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THE RESULT OF AN ANALYSIS OF AEROTHERMO- AND AERODYNAMICS OF OREX

軌道再突入実験の空力及び空力加熱解析結果

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ABSTRACT

We are going to perform three experiments preceding to the development of HOPE. We performed OREX taking the opportunity of H-Ⅱ TF#1 on Feb.4,1994. We report a result of one of the main purpose of OREX, acquisition of fundamental data of aerothermo- and aerodynamics during re-entry.

As to aerothermodynamics, we evaluated comparison between wind tunnel test data and values estimated from Fay&Riddell method before a flight experiment. After the experiment, we estimated heating rate induced from flight orbit using Fay&Riddell method validated before. And we calculated a temperature at the stagnation point using thermal-analysis model, then we compared the value with flight data.

As to aerodynamics, we compared flight pressure data with estimated value.

Analysis of aerothermodynamics

Analysis before flight-*hypersonic wind tunnel test*

We conducted a hypersonic wind tunnel test of OREX June 1991. At this time, we used phase-change paint to measure aerodynamic heating rate. We calculated the heating rate using the phase-change speed. We estimated aerodynamic heating rate using Fay&Riddell equation assuming perfect gas, while conducting wind tunnel.

The comparison between this estimation and wind tunnel test result is shown in Fig.1. This shows that the value of wind tunnel test is 30% larger than the Fay&Riddell estimation. Then, to compare these data more correctly we chose the value that we directly measured instead of catalogue value as maerial property of wind tunnel model. Measured values are shown in Table 1. And comparison using measured values is also shown in Fig.1.

Finally we get the result as follows. The aerodynamic heating rate obtained in wind tunnel test is 10% larger than the estimation by Fay&Riddell equation. So, we took an 10% value of Fay&Riddell estimation as an error for designing OREX vehicle. But actually we took a large margin taking 3σ distribution because this is the first re-entry experiment .

The result of flight experiment

estimation of thermal conductivity

Thermal contact resistance at thermocouple is an important factor to estimate aerodynamic heating rate from the result of flight. So we performed thermal analysis to estimate thermal contact resistance between C/C material and thermocouple.

First, we performed heating test of a test piece similar to the part of C/C Nose Cap where the thermocouple is attached. The test piece is made with the same condition with C/C Nose Cap, using the same material, being treated under the same condition and the same thickness and so on. The outline of the test piece is shown in Fig.2. Using this test piece, we performed heating test in a vacuumed chamber. The outline of the heating test is shown in Fig.3. The result of the heating tests are shown in Table 2-3. Table 2 shows the relation between heating rate and measured temperature, and Table 3 shows the temperatures at various points of the test piece.

Next, we estimated thermal contact resistance between C/C material and thermocouple using the data of heating test of test pieces. At this analysis, we used an analysis model shown in Fig.4. We considered thermal conductivity between C/C material and thermocouple, and emissivity and thermal conductivity from the surface. We analyzed three cases. Table 4 shows thermal property we used, and Table 5 shows the cases of analysis. The way of analysis is that we varied the value of thermal contact resistance as a parameter and identified when the analyzed temperature at the thermocoupple agreed with the measured temperature in the heating test. The result of identification of thermal contact resistance is also shown in Table 5.

Estimation of aerodynamic heating rate by analysis model of C/C Nose Cap

We estimated the temperature at the thermocouple of C/C Nose Cap using the thermal contact resistance in Table 5 and the aerodynamic heating rate induced by the best estimated real flight path and Fay&Riddell equation. And we compared the value with the data gained from flight experiment.

The analysis model is shown in Fig.6. It is a 3-D and 1/36 peel part model of full C/C Nose Cap. We considered thermal conductivity between C/C material and thermocouple, and emissivity and thermal conductivity from the surface. Analysis conditions are as follows:

Heating condition :

We use heating rate distribution obtained by Lees equation. And we use the value obtained by Fay&Riddell equation along the best estimated real flight path as the value of heating rate at the stagnation point, and we deal this value as Q.

Side temp. of test piece :

adiabatic considering symmetry.

Emission inside :

We took the temperature of inside insulation as that of emission inside.

Emission of Nose cap :

Emission outside is ε_c, and inside is ε_i. Measured values on the ground are both 0.84.

Thermal contact resistance :

We used Table 5, and represented by R.

Initial condition : Initial temperature is 20 degree.

Material property : We used Table 4.

Analysis time : 7284-7540 sec. after lift-off.

On these conditions we analyzed in several cases. The cases we analyzed are shown in Table 6. The analysis result of each case is shown in Fig.7-13.

Case1:(Fig.7)

This is a nominal case, using the gained data directly. Emission is the value measured on the ground test, but it may not be an absolutely real data, because the way of measuring is not established yet. This may be why analyzed value is lower than the measured value at the top of temperature. Analyzed value increases around 7420 sec. This may be why the thermal contact resistance is too large at low temperature. At higher temperature, we use the value induced from a paper as thermal contact resistance, so both values are close. The peaks of both temperature almost agree.

Case2:(Fig.8)

We analyzed the effect of variation of emission. Emission may vary at high temperature, so we analyzed taking 0.7 instead of 0.84 as emission. The result is that the peak temperatures of analyzed and measured value almost agree.

Case3:(Fig.9)

We noticed a large inclination at lower temperature at case 1, 2. So assuming that the thermal contact resistance at lower temperature we gained on the ground test before is too large, we analyzed taking 1/2 value of thermal contact resistance gained on the ground test. The result is that the analyzed value comes close to the measured value.

Case4:(Fig.10)

Furthermore, we analyzed taking 1/10 value of thermal contact resistance. The result is that the analyzed value almost agreed with measured one. From this result, we can estimate thermal contact resistance to be 1/10 of the one gained on the ground test. This is also reinforced by the value reported on the paper.

Case5:(Fig.11)

In this flight we could not get the whole temperature data at the thermocouple on the insulation. We got only half a data at this point, so we have some doubt about reliability of this data. For this reason, we assumed emission inside C/C Nose Cap is zero to get the data of heat conduction into insulation. The result is that trend of temperature variation is the same as that of case 1, but the peak of temperature is higher because heat doesn't run away.

Case6:(Fig.12)

Because of the doubt of the reliability of the data at thermocouple on the insulation, we analyzed taking the temperature data below the insulation instead of that on the insulation. In this time we also took insulation into consideration as analysis model. And we took 1/10 value of thermal contact resistance. The result is that the trend of curving of both value almost agree, and the peak of analyzed temperature is a little higher.

Case7:(Fig.13)

On the base of Case 6, we analyzed taking the 88% value of aerodynamic heating rate estimated by Fay&Riddell equation to conform the peak temperature of analyzed value to that of measured one. The result is that analyzed value and measured value almost agree.

From these result of analysis of Orbital Re-entry Experiment, we could get the following conclusions.

1.We can estimate the aerodynamic heating rate of OREX to be 88% of the value obtained from Fay&Riddell equation.

2.It appeared that error of emission and estimation error of heat movement inside C/C Nose Cap effected the estimation of aerodynamic heating rate very much.

3.We can estimate the value of thermal contact resistance to be 1/10 of that induced on the ground test.

But the value of thermal contact resistance is effected greatly by the way of attachment of thermocouple, and some papers reported that it varied in the range of 10^3. Then this value is so important that we should accumulate a lot of test data to estimate aerodynamic heating rate correctly.

Evaluation of estimation method of heating rate

Evaluation of time history of heating rate

We evaluate time history of the estimated heating rate by various estimation methods along the best estimated flight path and that of heating rate identified from flight data. We evaluated such methods as:

1.Fay&Riddell equation : assuming perfect gas (being used in the chapter before)

2.Fay&Riddell equation : assuming equilibrium flow

3.Detra, Kemp & Riddell equation

The comparison between heating rate by each method and that from flight data is shown in Fig.14. It shows nominal value and we should evaluate considering estimation error. All the same, we can understand the value by Fay&Riddell equation assuming equilibrium flow is the closest to flight data. This may be because Fay&Riddell equation is defined assuming equilibrium gas. In this case, we use the standard atmosphere as the data of density, so we should also consider the effect of using real atmosphere data.

Evaluation of distribution of aerodynamic heating rate

We adopted Lees distribution as aerodynamic heating rate distribution of OREX for designing. Fig.15 shows heating rate distribution estimated by Lees distribution used for designing the vehicle, the result of CFD assuming perfect gas and non-equilibrium, and flight data at some points. We can see such trend in Lees distribution as decrease of heating rate at the edge of nose cap and re-increase at the first line of tiles. We have also obtained this trend by CFD, so designing using Lees distribution can be valid. And we should consider such factors to estimate heating rate below the first line of tiles as:

1.production of non-equilibrium flow below the stagnation point

2.difference of material property of ceramic tiles based on the deference of tile maker.

3.error of measurement and identification

Analysis of aerodynamics

The outline of pressure sensor

We compared the flight results of two pressure sensors (sensor for middle altitude and one for high altitude) on the OREX with the estimation by various ways. Fig.16 shows the outline of pressure sensors and installation. Middle altitude sensor can measure the altitude 40km-85km, and measurement error is 1114.3Pa. High pressure sensor is used for measuring faint pressure at over 75 km altitude.

Flight result of middle altitude pressure

Analysis condition

We analyzed along the best estimated real flight path, and used 1976U.S.Standard Atmosphere Model. We show this model in Table 7.

Estimation of pressure value

We calculated pressure value at the height of 40, 51.1, 60, 65, 70km with the condition of Table 7 and by such ways as below;

1.Newton method

2.VSL equation;

Assumig non-catalysis and emission of 0.8, we analyzed the cases of ideal gas and non-equilibrium gas.

3.CFD by NS-equation:

Assuming ideal gas at 51.1km altitude

Comparison between flight data and estimated value

We compared flight data of middle altitude pressure sensor with some values estimated by each method above. Fig.17 shows the comparison between flight data and estimated values. We can say each estimated value is almost the same value, but flight data is about 800Pa higher than estimation. This can be within the error of sensor which is 1114Pa, and this may be because of the error of standard atmosphere. The data of high altitude sensor is also shown in the figure and it is connected with the data of middle altitude smoothly.

As reference, fig.18 shows comparison between flight data and estimated value which used the atmospheric data 1km below the flight data. In this case, flight data and estimation agree very well. Fig.19 shows surface pressure distribution at the height of 51.1 and 70km, and Fig.20 used the data 1km below the flight data for estimation.

Conclusion

For aerothermodynamics, heating rate of 88% value estimated by Fay&Riddell agreed with the flight data very well. But we used 1/10 value of thermal contact resistance obtained on the ground test, so it is very important to get a correct value of such value as thermal contact resistance, material property and so on.

For aerodynamics, estimation of several method almost agreed with flight data. But it is important to use real atmospheric data to get a precise estimation.

Table 1. Comparison of Material Property

	Cataloge ①	Measurement ②	② ÷ ①
ρ (g/cm ^{3})	2.1	2.3	1.095
Cp (cal/g·K)	0.3	0.261	0.870
κ (cal/cm·s·K)	3.3×10^{-3}	2.72×10^{-3}	0.824

Table 2. Measurement of heating rate

Voltage(V)	Temp.(℃)	heating rate(W/cm ^{2})
30	338.2	0.27
50	479.3	1.88
115	721.1	7.66

Table 3. Measured temperatures

heating rate / points	0.27(W/cm ^{2})	1.82(W/cm ^{2})	7.38(W/cm ^{2})
#1	331.7	475.3	720.1
#2	339.6	480.6	723.2
#3	336.8	478.0	718.9
#4	332.3	474.5	719.4
#5	321.7	461.2	700.6
#6	325.4	465.9	708.0
#7	272.5	399.6	623.7
#8	72.7	106.7	173.9

Table 4. Thermal Property

	Representative Temp.	Density (g/ ㎝^{3})	Specific Heat(cal/g ℃)	Termal Conductivity(cal/ ㎝·s·℃)	Emissivity
C/C composit (longitudinal)	RT	1.50	0.159	0.2187	0.84
	500		0.371	0.3645	
	1000		0.434	0.3749	
	1500		0.544	0.4680	
C/C composit (transverse)	RT	1.50	0.159	0.0486	
	500		0.371	0.0810	
	1000		0.434	0.0833	
	1500		0.544	0.1040	
Temp.sensor	RT	13.31	0.11	0.0922	-
Adhesive	RT	3.5	0.1169	0.00251	-
Insulation	330	-	-	-	0.74
	470				0.73
	700				0.70

Table 5. Cae of Analysis

case	Measured Surface Temp.(℃)	Thermal Contact Resistance (m ^{2} ·hr· ℃ /kcal)
case1	340	0.0842
case2	481	0.0751
case3	723	0.0370

Table 6. Analysis cases about aerothermodynamics

Case No.	Heating Rate	ε c	ε i	thermal contact resistanc	Inside temp.
①	Q	0.84	0.84	R	Outside
②	Q	0.7	0.7	R	Outside
③	Q	0.84	0.84	R × 0.5	Outside
④	Q	0.84	0.84	R × 0.1	Outside
⑤	Q	0.84	0	R	Outside
⑥	Q	0.84	0.84	R × 0.1	Inside
⑦	Q × 0.88	0.84	0.84	R × 0.1	Inside

Table 7. 1976 U.S.Standard Atmosphere Model

Time after Lift Off(s)	Height (km)	M number	Temp. (K)	Pressure (Pa)	Density (kg/m ^{3})
7445.875	70	23.31	219.585	5.221	8.283×10^{-5}
7457.875	65	20.98	233.292	1.093×10^{1}	1.632×10^{-4}
7470.675	60	17.84	247.02	2.196×10^{1}	3.097×10^{-4}
7493.875	51.1	11.10	270.65	7.046×10^{1}	9.069×10^{-4}
7526.675	40	4.11	250.35	2.871×10^{2}	4.000×10^{-3}

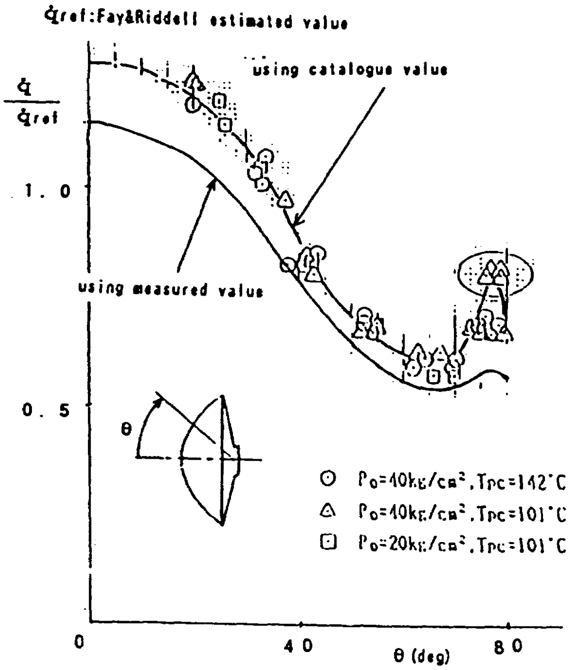


Fig.1 Comparison between tunnel test result and Fay&Riddell estimation

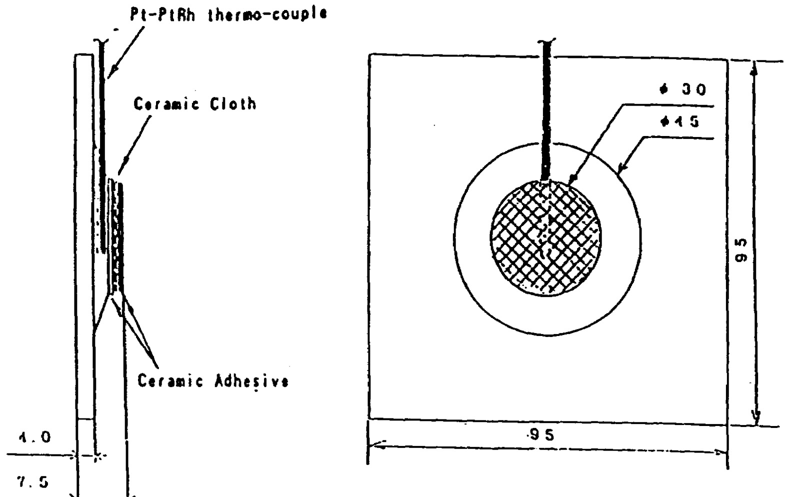


Fig.2 Heat test model

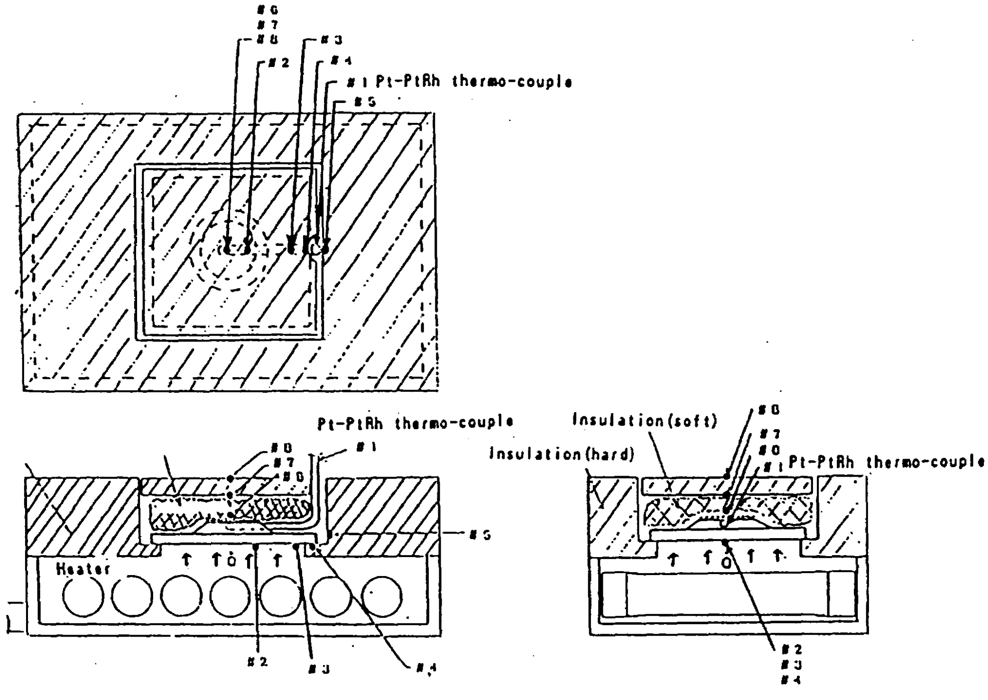


Fig.3 Outline of heat test

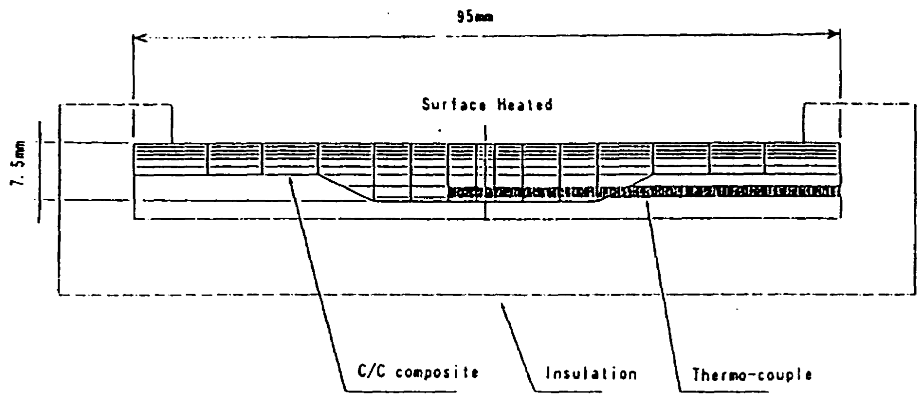


Fig.4 Analysis model for heat test

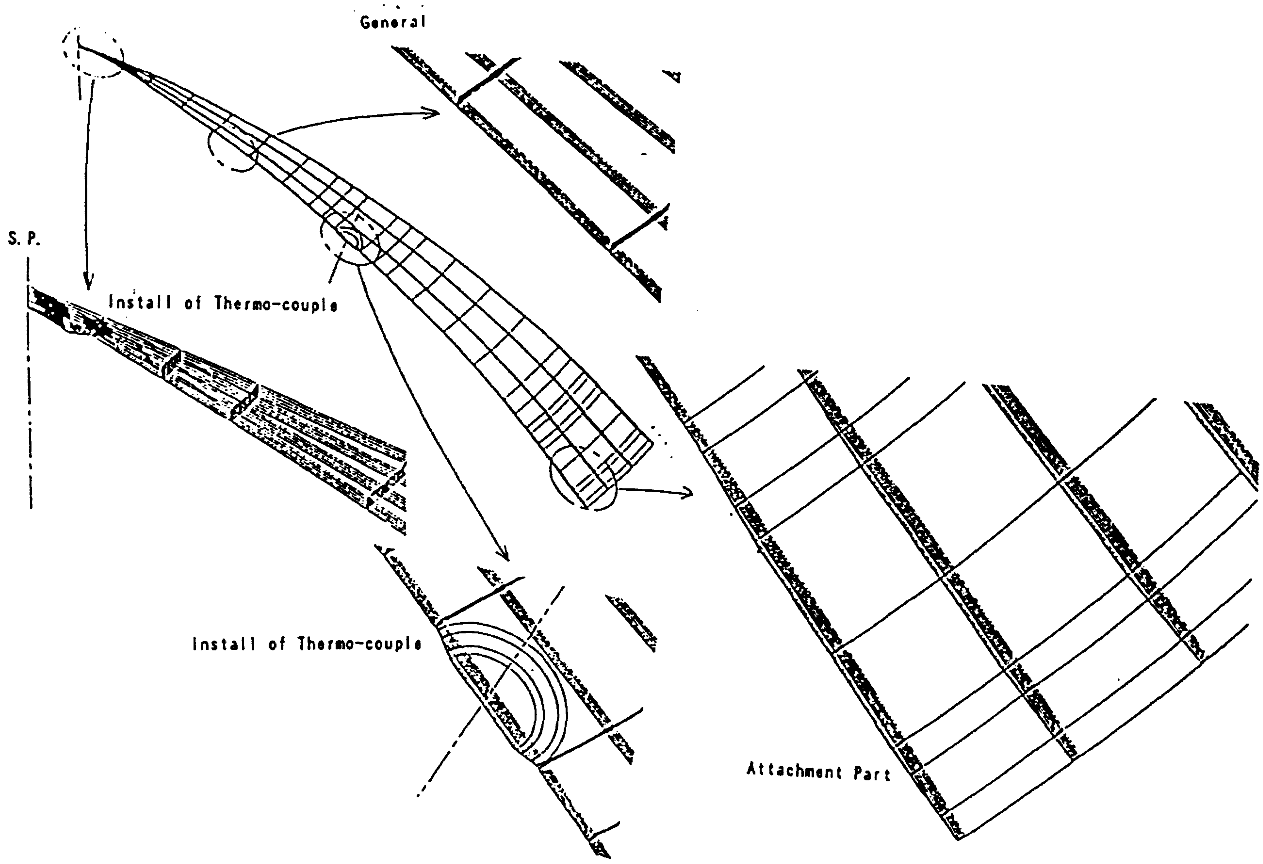


Fig.5 ANALYSIS MODEL OF C/C NOSE CAP

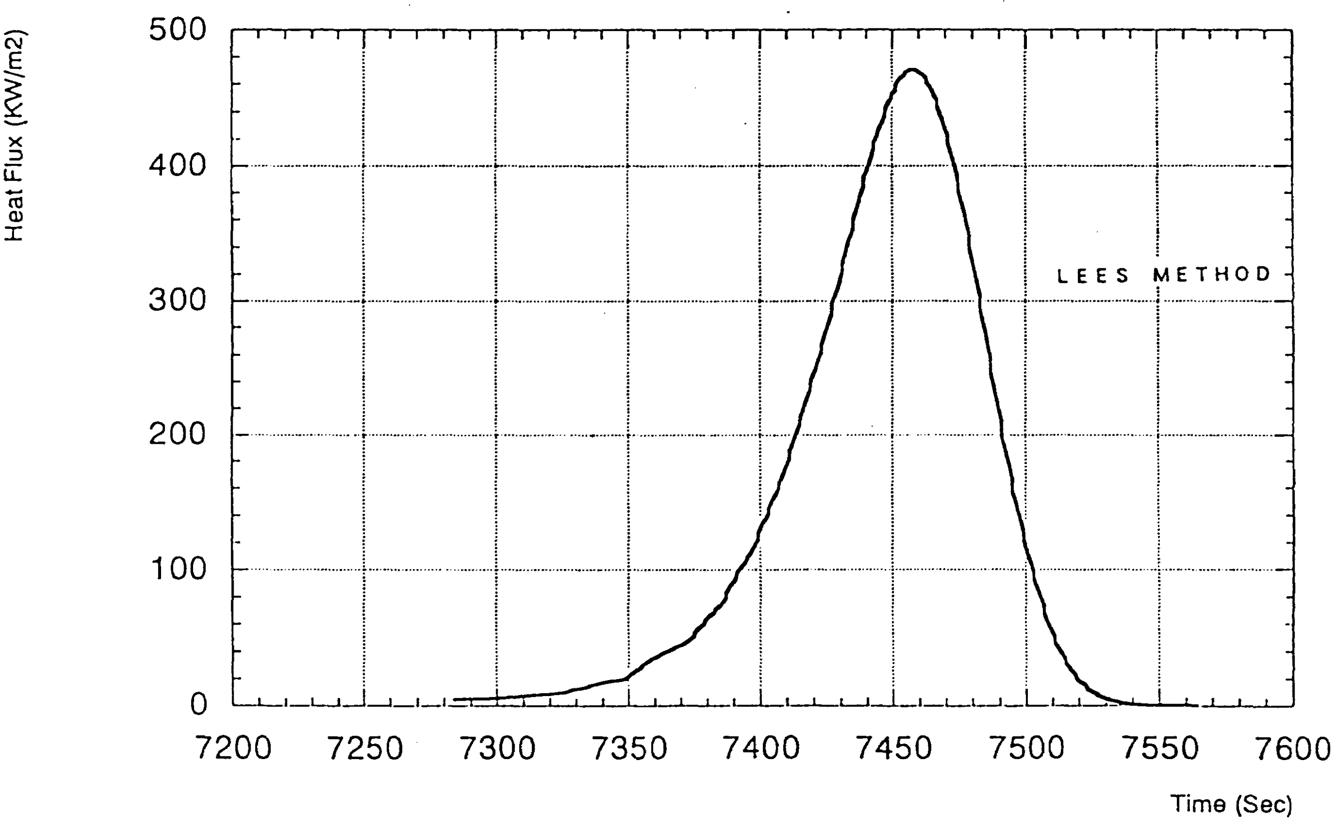


Fig.6 Heating rate estimated by Fay&Riddell

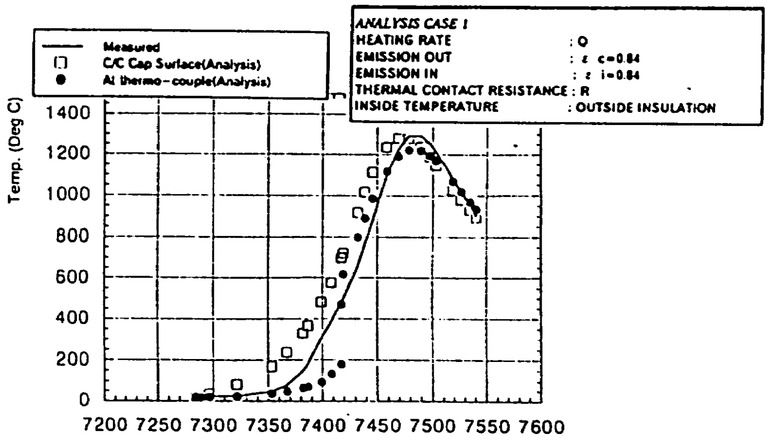


Fig.7 Nominal Case

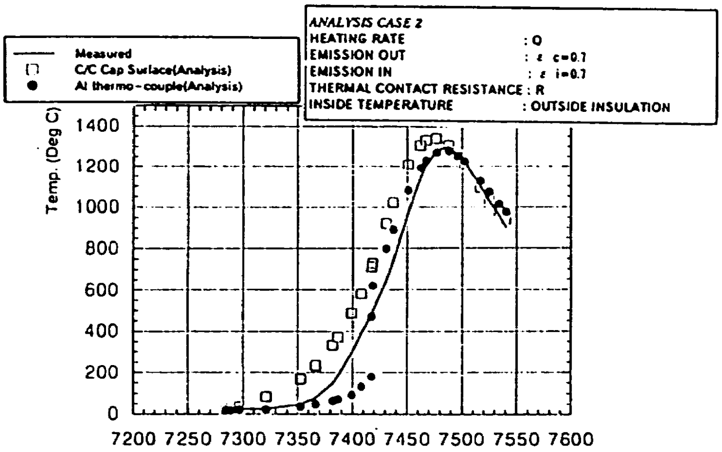


Fig.8 Effect of Emission

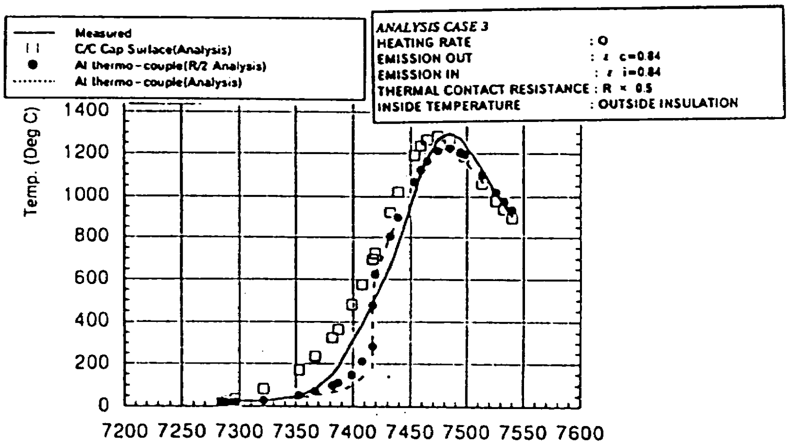


Fig.9 Effect of Thermal Contact Resistance #1

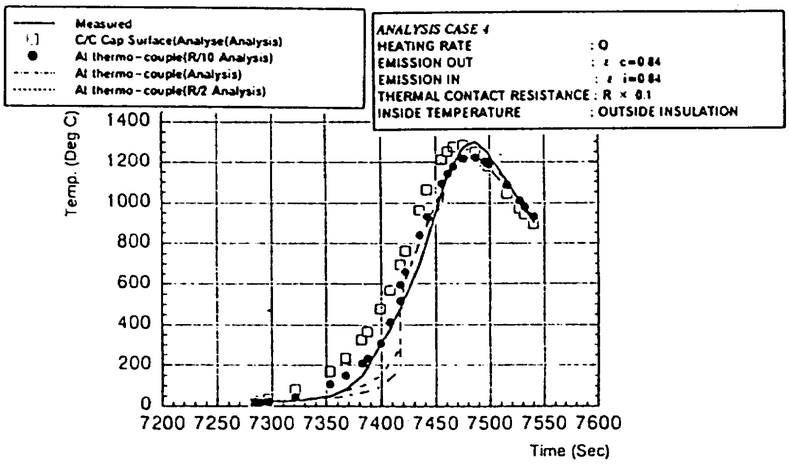


Fig.10 Effect of Thermal Contact Resistance #2

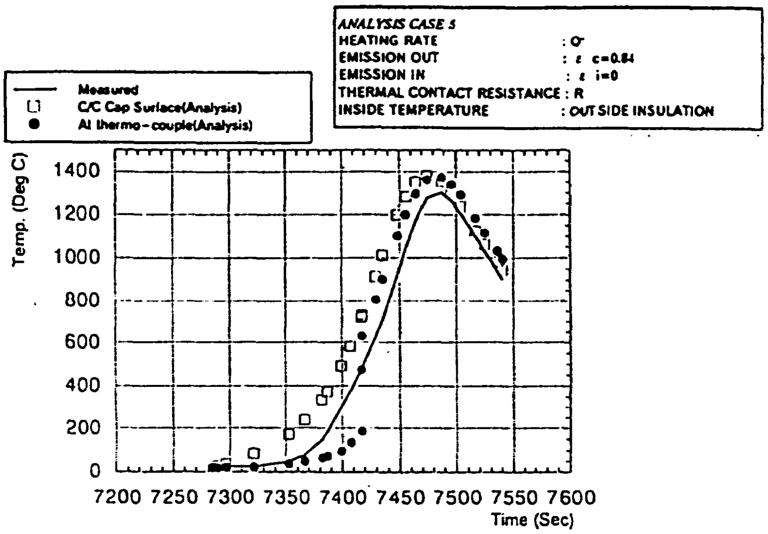


Fig.11 Effect of Emission inside C/C Nose Cap

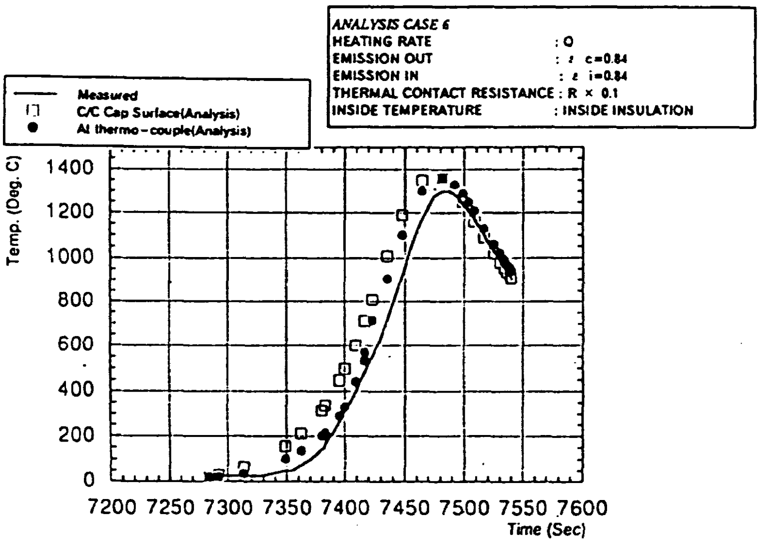


Fig.12 Analysis using Temp. data inside Insulation

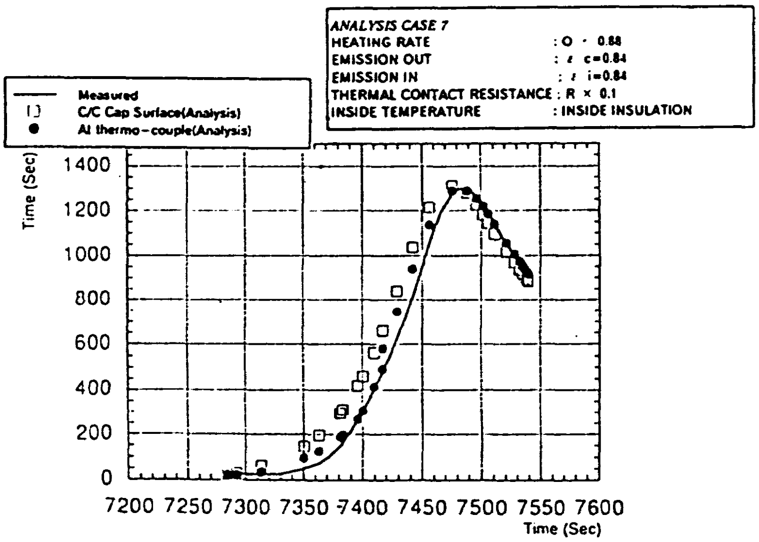


Fig.13 Analysis taking heating rate 12% OFF

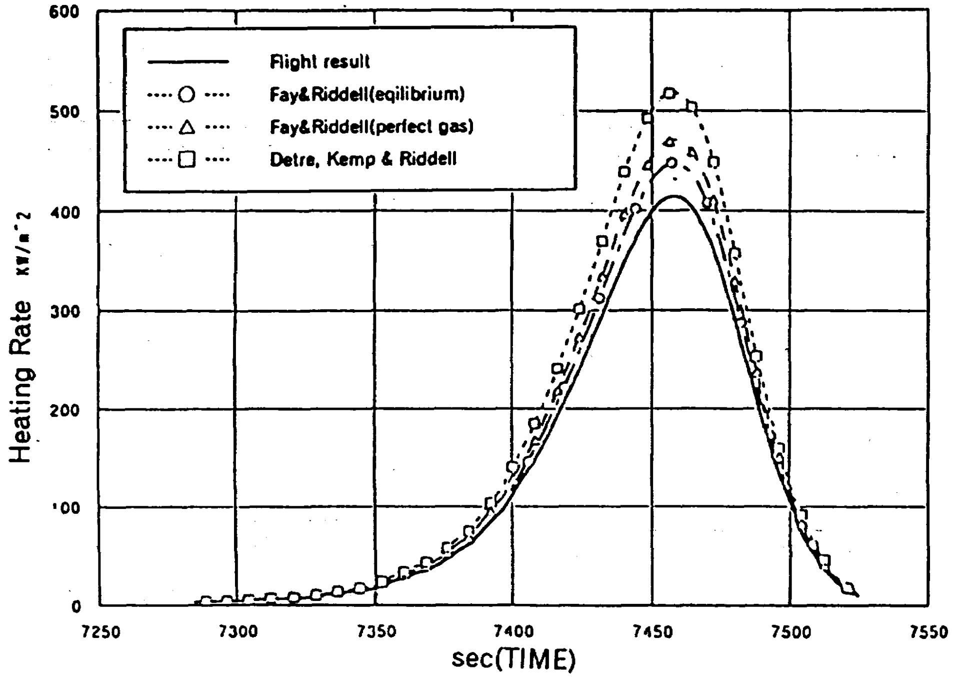


Fig.14 · Comparison between Flight data and Estimation Method

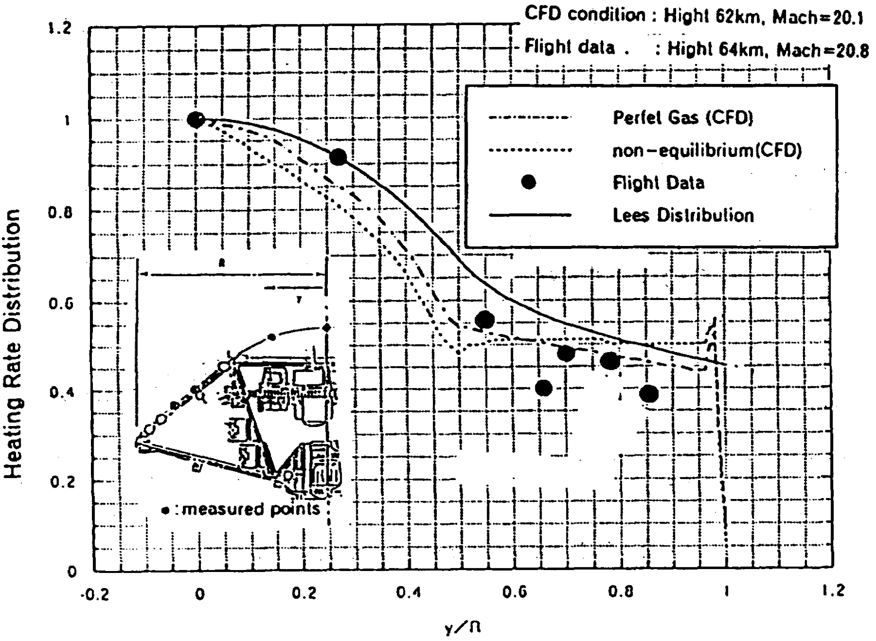
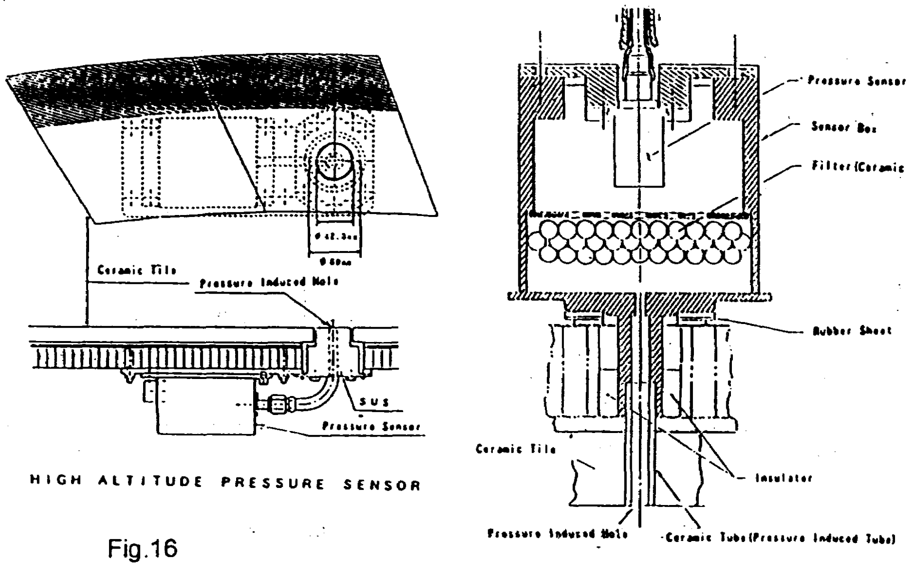


Fig.15 Comparison of heating rate distribution



HIGH ALTITUDE PRESSURE SENSOR

Fig.16

MIDDLE ALTITUDE PRESSURE SENSOR

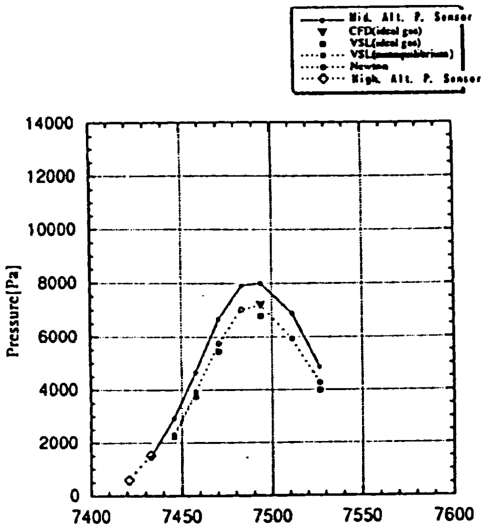


Fig.17 The result of Pressure data

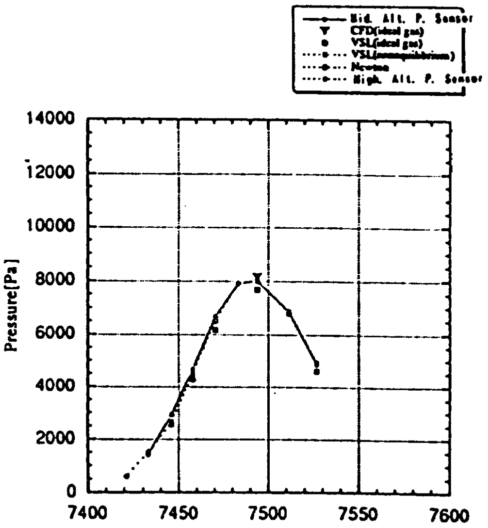


Fig.18 The result of Pressure data (1km shift)

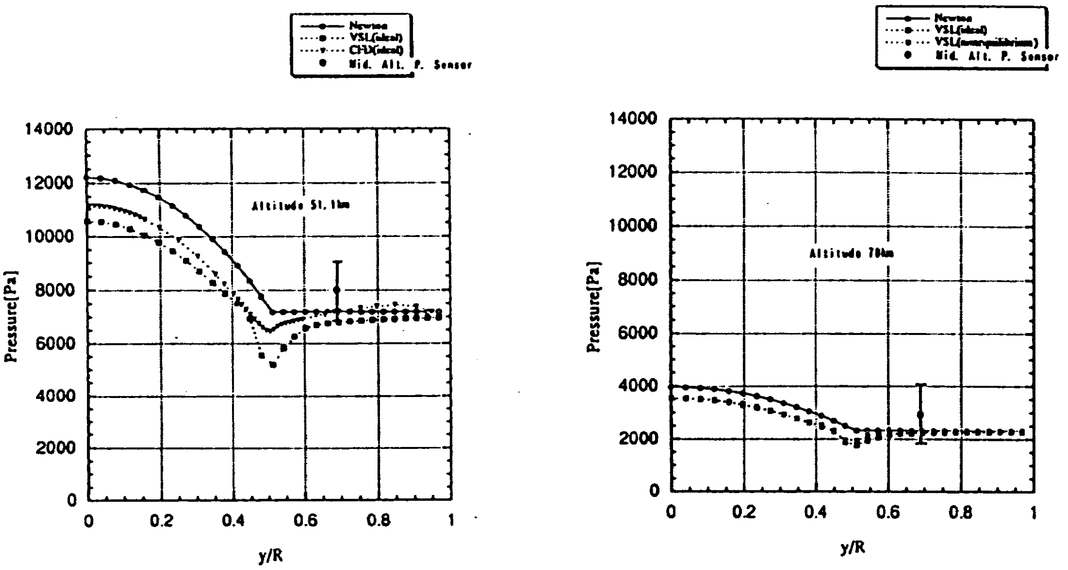


Fig.19 Surface Pressure distribution

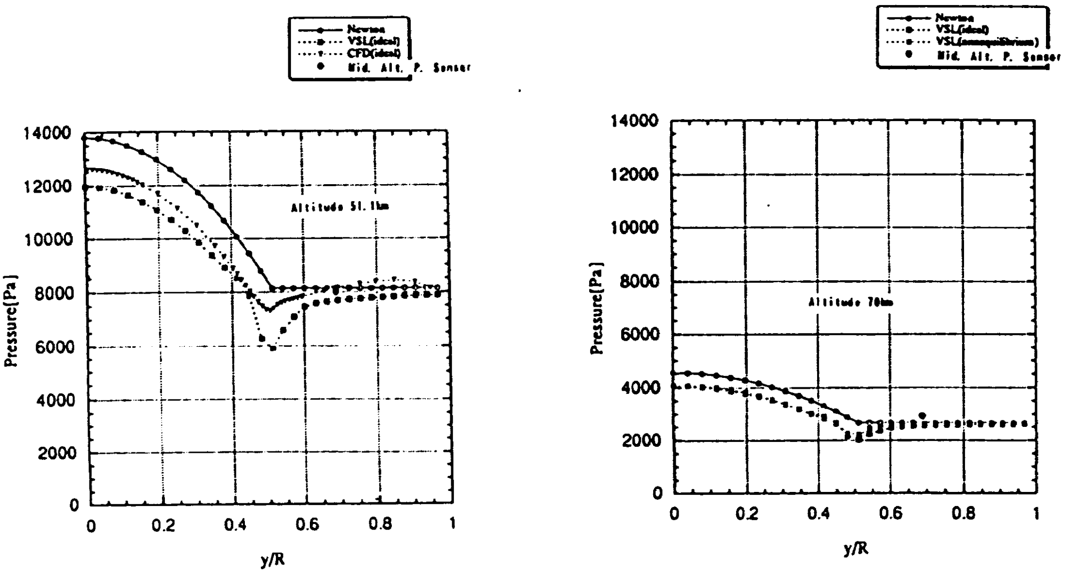


Fig.20 Surface Pressure distribution (1km shift)