ABSTRACT
FIRE II re-entry rebuilding has been proposed as a Test case for the Radiation workshop.
This paper includes the description of the FIRE II vehicle and its mission, particularly focusing on the locations of experimental sensors and on the data. The booklets of this test case will be then presented. In a second part, the flow-field computation and the post-treatment for the radiation computation performed with the ESA/ESTEC tools will be presented. Numerical results and experimental measurement will be compared and analysed in terms of spectral emission and radiative heat flux.

1. INTRODUCTION
The numerical rebuilding of Fire II radiation flight measurements has been proposed as a Test case for the 2nd Radiation Workshop, based on an earlier investigation [1]. Few flight measurements have been performed. FIRE II re-entry flight took place in May 22, 1965 with the assessment of the radiative heating environment during the re-entry as primary objective.

2. DESCRIPTION OF THE FIRE II VEHICULE
2.1. FIRE II geometry
The FIRE II geometry was an Apollo-type as presented in Figure 1 with a re-entry velocity of 11.4 km/s [5]. The fore body (Figure 2) consisted in a three layers configuration formed by phenolic-asbestos heat-shield sandwiched between beryllium calorimeters. The first two calorimeters and their associated heat-shield were designed to be ejected.

2.2. FIRE II instrumentation
Direct measurements of the gas radiance from the hot plasma surrounding the re-entry package are obtained with onboard radiometers.

The total radiometers are placed at three locations in the re-entry package as shown in Figure 1 and Figure 2. (here, the word total indicates integrated broadband measurements without spectral selectivity; the wavelength range covered by each of these instruments
is from 0.2 μm to 4 μm). One total radiometer is positioned to view the radiation to the after-body; a second is positioned to view the radiation at a location on the spherical front face that is offset from 16 to 20 degrees from the geometrical stagnation point (the angle varies slightly with the particular calorimeter exposed); the third instrument is positioned to monitor the intensity of the gas at the stagnation point.

The low wavelength cut-off for the total radiometer experiments is dictated by the fused quartz windows through which the radiometers view the plasma radiation.

3. TEST CASE CONDITIONS

Three points during Fire II re-entry trajectory from non-equilibrium to equilibrium regime were selected as follow:

- 1634 s: non-equilibrium effects (1st data period)
- 1642.66 s: close to thermal equilibrium (2nd data period)
- 1648 s: equilibrium phase (3rd data period)

The re-entry conditions for the three points above are given in Table 1.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Altitude (km)</th>
<th>Velocity (km/s)</th>
<th>Density (kg/m³)</th>
<th>T∞ (K)</th>
<th>Tw (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1634</td>
<td>76.42</td>
<td>11.36</td>
<td>3.72E-5</td>
<td>195</td>
<td>615</td>
</tr>
<tr>
<td>1642.66</td>
<td>53.86</td>
<td>10.56</td>
<td>7.17E-4</td>
<td>273</td>
<td>480</td>
</tr>
<tr>
<td>1648</td>
<td>42.14</td>
<td>8.30</td>
<td>3.00E-3</td>
<td>267</td>
<td>1560</td>
</tr>
</tbody>
</table>

The flow-fields have been computed with a Navier-Stokes non-equilibrium flow solver, iso-thermal (T_w) fully catalytic wall assumptions. The results of the computations are presented in chapter 4.

The assumption concerning the chemical model used for the determination of the forward and backward chemical reaction rates as well as the viscosity relation are presented in the booklets of the Test Case 6.

4. FLOW-FIELD COMPUTATIONS

The flow field computations have been performed with TINA developed by FGE [9] with the boundary conditions presented in Table 1. TINA code (Thermodynamic Implicit Non-equilibrium Algorithm) is a fully three dimensional, non-equilibrium chemistry, Navier-Stokes code.

4.1 Flow comparisons

Figure 3 and Figure 4 present respectively the Mach and temperature contours over FIRE II vehicle computed with TINA code for the three selected times proposed for the radiation analysis.

A decrease of the stand-off distance of the shock from 5 cm at t = 1634 s down to 4 cm at t=1648 s can be observed. At the frustum of the probe, geometry and level modifications of the bow shock can be observed due to the increase of the density and the decrease of the free-stream velocity.
From the flow-field computation, parameters such as temperature ($T_t$, $T_v$), density and molar fractions have been extracted along the stagnation line first for comparisons and finally for the radiation computations.

Only temperatures (Figure 5) and species concentrations (Figure 6 and Figure 7) evolutions for the three selected times are compared and presented here after. The times 1634 s, 1642.66 s and 1648 s have been drawn respectively with dash-dotted, dashed and solid lines.

Figure 5 presents translational (red line) and vibrational (blue line) temperatures along the stagnation line. High temperatures are reached at the shock position; more than 24 000 K at $t = 1634$ s whereas at $t = 1648$ s, the maximum temperature is around 13 000 K. At $t = 1634$ s, the thermal non-equilibrium region is relatively large (around 1 cm) whereas it is nearly zero for the two other points of the trajectory. Moreover, both translational and vibrational temperatures are constant at 11 000 K and 8 000 K for $t = 1642$ s and 1648 s respectively. These constant periods are characteristic of a chemical equilibrium regime.

On Figure 6 and Figure 7, concentration comparisons for the neutral and ionized species are presented respectively. First, the chemical equilibrium region can be observed for both $t = 1642$ s and 1648 s as it was concluded with the temperature evolution previously. For the three points of the trajectory, O$_2$ is rapidly and highly dissociated to form O and O+. Small amount O$_2^+$ is observed and may be neglected for the radiation computation.

N$_2$ is dissociated to form N and NO by recombination with O.

The highest species concentrations are for N$_2$, N, N$, O$, and O$. The other species concentrations are lower by at least a factor 100.
With the density, the molar fractions and the two temperatures (translational and vibrational), the radiation heat flux (spectral and total) has been computed with PARADE.

5. RADIATION ANALYSIS

The PARADE code [10] has been developed in collaboration between Fluid Gravity Engineering Ltd (UK) and Institute Raumfahrtsysteme of Stuttgart (D) under an ESA/ESTEC contract in 1996 for Air species first. Since then, it has been modified in order to take into account more species, in particular CN. The code is used to compute flow-field emission and absorption, between the shock layer and the surface of the probe.

The spectral emission and absorption are determined as function of transition level (from upper level to lower level) and emitting population of this level. The population can be derived from the Quasi-Steady-State (QSS) method or by a Boltzmann method in order to take into account the non-equilibrium or equilibrium regime respectively.

The radiative computations have been performed with the Boltzmann assumption for the determination of the population of the excited molecular states.

The species taken into account for FIRE II trajectory in Earth atmosphere are N2 (1+, 2+ and bh2), N2+ (1-), N, N+, O, O+, O2 and NO. O2+ and NO+ have been disregarded for the radiation computation for two reasons: first the spectroscopic data were not available in the present version of PARADE and secondly these molecules have not been yet implemented in PARADE.

The Parade outputs are then the radiative emission and absorption power function of the wavelength and position on each point of the mesh used for the flow-field computation. Here, only the stagnation line is used.

For each point presented in Table 1, the comparisons requested in the booklets of the test case 6 were as follow:

1. Spectral analysis: The wavelength range from 0.3\(\mu\)m to 0.6\(\mu\)m; space integration over the shock layer to provide the spectral radiation evolution at the stagnation point.
2. Integrated spectral analysis: radiation heat flux at the surface of the probe on the wavelength range from 0.3\(\mu\)m to 0.6\(\mu\)m (Spectral and space integrations).
3. Total analysis: wavelength range from 0.2\(\mu\)m to 4\(\mu\)m; spectral and space integration in order to have the radiative heat flux at the stagnation point.

The above results are obtained by post-treatment of PARADE outputs as follow

1. the spectral intensity has been obtained by spatial integration of the emission intensity over the shock layer along the stagnation line.
2. the integrated spectral intensity has been obtained by spectral integration of the previous results.
3. the total radiation heat flux by resolution of the transfer equation which allows to take into account the self-absorption phenomenon of the species.

5.1. Spectral comparison

The spectral computation has been performed for the three selected points previously presented. No self-absorption by molecules was taken into account for the analysis and 1 000 points have been used over the wavelength range (0.3 – 0.6\(\mu\)m).

On Figure 8 (t = 1634 s), the computation by TINA/PARADE predicts much higher radiation than the measurement values. This over-prediction is probably due first to the assumption used for the population level determination (Boltzmann) not valid in the free-molecular regime, second by an over-estimation of the vibrational temperature.

Between 0.4 and 0.5 \(\mu\)m, some measured lines are higher than the prediction. It seems that some species or lines are missing in our chemical model or spectroscopic data. Further investigation has to be initiated in order to identify the corresponding species in order to adjust the chemical kinetic model.

For t = 1642 s (Figure 9), a good agreement is obtained between 0.3 and 0.4 \(\mu\)m whereas an under-prediction is observed for the higher part of the wavelength.

For t = 1648 s (Figure 10), a relatively good agreement is obtained between 0.3 and 0.5 \(\mu\)m whereas an under-prediction is observed for the higher part of the wavelength.
The methodology presented in the paper to perform the comparison between the flight data and the simulation seems to be more adapted for the equilibrium regime. Good agreement has been found for t=1642.66s and t=1648s respectively near and at equilibrium regime whereas significant discrepancy has been found for the non-equilibrium one (t=1634s).

5.2. Radiation heat flux

Two radiation heat fluxes have been computed with the following assumptions:

§ Spectrum from 0.3 μm to 0.6 μm, absorption not taken into account, 1 000 points over the wavelength range;

§ Spectrum from 0.2 μm to 4 μm, absorption taken into account, 1.8 $10^6$ points over the wavelength range.

Figure 11 presents the comparison between experimental measurements and radiation heat fluxes obtained with TINA/PARADE process. The red points correspond to the spectrum from 0.3 μm to 0.6 μm whereas the yellow points represent the spectrum from 0.2 μm to 4 μm. Relatively good agreement is found between the experiments and the computations for the last two points of the trajectory (t = 1642 s and 1648 s) whereas an over-estimation can be seen for t = 1634 s. This discrepancy can be due to the assumption used for the computation of the population of levels (Boltzmann) whereas non-equilibrium radiation approach might be more appropriate such as a QSS model (Quasi Steady State) or a collisional-radiative model.

6. CONCLUSION

In this paper, the test-case 6 concerning the emission measurements during FIRE II re-entry has been presented. Three trajectory points on different periods have been selected for numerical comparisons. The three periods correspond to the non-equilibrium, near-equilibrium and equilibrium regimes.

In a first part, the flow-field simulations performed with TINA code have been presented. Then after extraction of parameters such as temperatures (translational and vibrational), density and molar fractions along the stagnation line, spectral and total radiation computation have been computed and compared with the flight data. Good agreement has been found for the second and third point (near and at equilibrium regime) for both spectral emission and total radiation heat flux whereas an over-prediction is obtained for the first point in non-equilibrium regime. The discrepancy can be due to the Boltzmann assumption used whereas a QSS or collisional-radiative model might be more appropriate.

Some investigations have to be realised in order to obtain a better fitting of the flight data for a wavelength
range from 0.4 to 0.6\(\mu\)m where some under-predictions have been found.

7. ACKNOWLEDGEMENT

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8. REFERENCES


Figure 11: Radiative Heat fluxes comparison