PROPOSAL FOR “IN FLIGHT RESEARCH ON RADIATION / ABLATION COUPLING” FILLING A 40 YEAR GAP AFTER FIRE II

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ABSTRACT

The paper, meant as a discussion paper, describes a proposal for gathering radiation/ablation flight data using state of the art flight measurement techniques on blunt cone ballistic shapes launched by the low cost VOLNA launcher. Thanks to an additional booster unit, integrated into the VOLNA 3rd stage launcher, earth re-entry speed up to 11 km/sec can be realized thereby representing lunar - and approaching Mars return speeds.

The purpose of this “in flight research programme” is to acquire new flight data, revisiting herewith the Fire II flight data obtained more than 40 years ago, on radiation for validation of the physical models incorporated in the numerical tools used for design of the thermal protection systems.

These design tool validation activities deal with:

- validation of the physical models incorporated into the CFD tools,
- experimental testing activities such as plasma wind tunnel testing simulating heat loads for TPS qualification,
- flight extrapolation and scaling, including the analysis of the uncertainties associated with the flight measurements integration and qualification.

A TPS qualification methodology is proposed combining 2 flights: one flight at 11 km/sec simulating the proper convective and radiative contributions to the TPS heat flux and one flight at enthalpy levels allowing a crossing with the plasma wind tunnel performance envelops thereby linking, using CFD, wind tunnel and flight for improved analysis of the uncertainties associated with flight extrapolation and scaling.

1. BACKGROUND

Huge margins are taken for the design of the TPS for science exploration vehicles due to the large uncertainties associated with radiation, radiation / ablation coupling and the occurrence of transition from a laminar to turbulence boundary layer.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Entry Date</th>
<th>Geometry</th>
<th>Destination</th>
<th>V (km/sec)</th>
<th>Y (deg)</th>
<th>Utility</th>
<th>Recent Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire II</td>
<td>Nov. 7, 1965</td>
<td>Truncated Sphere</td>
<td>Earth</td>
<td>7.4</td>
<td>12</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>AS-201</td>
<td>Mar. 27, 1966</td>
<td>Truncated Sphere</td>
<td>Earth</td>
<td>7.7</td>
<td>20</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>AS-202</td>
<td>Aug. 25, 1966</td>
<td>Truncated Sphere</td>
<td>Earth</td>
<td>8.1</td>
<td>18</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>Apollo 4</td>
<td>Nov. 9, 1967</td>
<td>Truncated Sphere</td>
<td>Earth</td>
<td>10.7</td>
<td>15</td>
<td>High</td>
<td>No</td>
</tr>
<tr>
<td>Apollo 6</td>
<td>Apr. 24, 1968</td>
<td>Truncated Sphere</td>
<td>Earth</td>
<td>9.6</td>
<td>25</td>
<td>High</td>
<td>No</td>
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<td>Rendezvous</td>
<td>Apr. 23, 1968</td>
<td>Vacuum Cone</td>
<td>Earth</td>
<td>6.5</td>
<td>0</td>
<td>High</td>
<td>No</td>
</tr>
<tr>
<td>Vostok 2</td>
<td>Jul 19, 1967</td>
<td>Sphere</td>
<td>Mars</td>
<td>4.5</td>
<td>11</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>Vostok 3</td>
<td>Oct 8, 1967</td>
<td>Sphere</td>
<td>Mars</td>
<td>4.5</td>
<td>11</td>
<td>High</td>
<td>No</td>
</tr>
<tr>
<td>Ginzburg</td>
<td>Dec 7, 1997</td>
<td>45° Sphere Cone</td>
<td>Jupiter</td>
<td>47.4</td>
<td>0</td>
<td>Low</td>
<td>Yes</td>
</tr>
<tr>
<td>Polaris</td>
<td>Jul 9, 1997</td>
<td>70° Spherical Cone</td>
<td>Mars</td>
<td>7.5</td>
<td>0</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>MIREA</td>
<td>Oct 15, 1997</td>
<td>45° Spherical Cone</td>
<td>Earth</td>
<td>7.5</td>
<td>31</td>
<td>Low</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Fig. 1: Summary of entry flights with usable aeroheating data

Fig. 1 shows a table from RD[1] highlighting the usable flight data obtained during the last 50 years. The last flight data date from the sixties: the Fire I and II flights; the AS 201, AS 202 precursor to Apollo flights and the Apollo 2 and 4 flights revealed radiation heat fluxes varying from 1 to 7 MW/m² and convective heat fluxes varying from 2 to 14 MW/m².

The differences are attributed due to errors in Flight Measurement Techniques from the sixties, errors due to sensor TPS integration issues, wrong calibrations, poor knowledge of the free stream, poor knowledge of the physics (non-equilibrium/non-Bolztmann, coupling, absorption, transition, ablation, spallation, catalysis...).

In addition to the need to better understand these errors there is also a need to consolidate a TPS qualification methodology.

Flight heat loads can be simulated but not duplicated in ground based facilities; the contributions to the heat flux; the combined convective and radiative components
to the heat flux can not be simulated in plasma facilities due to limited combined enthalpy and pressure levels.

In order to consolidate a TPS qualification methodology a combined 2 flight approach is proposed: one flight at 11 km/sec simulating the proper convective and radiative contributions to the TPS heat flux and one flight at enthalpy levels allowing a crossing with the plasma wind tunnel performance envelops. The latter will evidently be at lower enthalpy levels, approaching the 6 km/sec, where wind tunnel and flight model dimensions need to be defined so that both the 6km/sec flight and the wind tunnel produce the same heat flux.

2. OVERALL IN-FLIGHT TESTING APPROACH

1. FULL SCALE FLIGHT VEHICLES:
   - SHUTTLE, BOURANE, APOLLO, SHENZOU, ARIANE 5,
   - HUYGENS, GALILEO
   - HOPE, HERMES, OSP
   - HERCULES, SOCRATES

2. EXPERIMENTAL DEMONSTRATORS:
   - X23, X24, X33, AS201, AS202, APOLLO 4,6 ARD,
   - BOR4 for TPS; BOR5 for GNC
   - OREX, HYFLEX for TPS; ALFEX for GNC
   - MAIA, PHOENIX 1 and 2 for GNC
   - FLPP IXV (PRE-X) – USV

3. IN FLIGHT RESEARCH EXPERIMENTATION
   - SHARP B1, B2 FLIGHTS, HYSHOT, X43,
   - IRDT, PAET, RAMC,
   - FIRE I&II, MIRKA, EXPRESS, SHEFEX, SFYFE,
   - EXPERT

Fig. 2: In-Flight experimentation classification

Fig. 2 presents a general in-flight experimentation classification where in-flight testing can be grouped in 3 classes: full scale flight testing; experimental demonstrators and in-flight research experimentation. The present proposal focuses on class-3 in-flight experimentation; this class deals with in flight research experimentation and addresses critical issues for design on the phenomenological level for Aerothermodynamics and TPS gas surface interaction such as boundary layer transition, catalysis and oxidation, ablation, blackout, radiation, shock interaction, real gas chemistry radiation, scram combustion etc.

Class-2 deals with programme driven experimental demonstrations for class-1, which represents full scale flights. Class-2 deals with subsystem and system demonstrators required to qualify the class-1 full scale flight. Good examples for class-2 are the Bor 4, designed to match the local heat flux of the Bourane and the Bor 5, a 1/8 scaled Bourane configuration, for aero data base and guidance, navigation and control purposes.

Fire II was a ¼ scaled Apollo configuration, flown in 1965, on a shallow trajectory with an entry speed of 11.3 km/sec designed with 3 ejectable thermal protection systems to obtain in-flight uncontaminated shock layer radiation data. This mission has been very useful for the design of the subsequent AS 201, AS 202 and Apollo flights.

3. JUSTIFICATION FOR IN-FLIGHT RESEARCH

Below some key lessons learned from 2 planetary entry (Huygens, Galileo) and 2 earth re-entry flights (Fire II, Re-entry F) will be discussed and recommendations issued for design and instrumentation of a new in flight research programme.

3.1 Huygens Lessons Learned

Fig. 3 shows the coupled convective and radiative numerical approach which was used for the verification of the design heat flux of the Huygens capsule. TINA code was used for the convective part and Parade/Herta for the radiative part.

Some typical results RD[2] are addressed in Fig. 4 and confirmed the importance of radiative/convective coupling. The total heat flux is reduced by 40 % mainly due to the reduction of the radiative contribution resulting from the modified emission and absorption characteristics of the shock layer due to coupling.

Fig. 4: Heat fluxes without absorption assumption
The question is how well are these codes validated for flight conditions. Prior to Titan entry (15 January 2006) a series of new experiments in shock tubes and plasmatrons were performed to verify whether assumptions made during the design of the Huygens heat shield were conservative enough. The main conclusion of these recent experiments were that radiation coupling is still not well enough understood and, in particular, that collisional radiative non-equilibrium data are still missing in part due to lack of well calibrated shock tubes and associated non intrusive instrumentation at flight conditions. In addition, the methodology how to use plasmatrons for gas surface interactions, plasma facilities for TPS testing and shock tubes for shock layer chemistry in a design process for TPS qualification need to be improved. In particular, the assessment of the remaining uncertainties drives the design of the TPS. As a summary: the Huygens task force lessons learned confirmed the need to fundamentally rebuild a new ground based facility and flight data base on radiation coupling for future planetary missions.

3.2 Galileo Lessons Learned

Ablation recession data measured during the Galileo entry phase (Fig. 5 and Fig. 6) indicated that:

- Stagnation point recession was less than predicted
- Ablation at frustrum and shoulder was much higher than predicted

Recent mathematical models have not been capable to fully explain the observed behavior. Possible reasons for this are enhanced turbulence from mass injection, particle spallation (not modeled) and/or the not well understood complex interaction between ablation and shock layer radiation.

In conclusion, it can be said that for Galileo the ablation and recession rates in regions away from the stagnation area are not understood and totally underestimated. Transition to turbulent flow thereby enhancing ablation interaction could be the reason and need to be addressed in future in-flight research programmes.

3.3 Fire II Lessons Learned

The Fire II had a ¼-scaled Apollo-like geometry with a multi-layered TPS configuration and a re-entry speed of 11.3 km/s. Three ablative heat shields sandwiched between beryllium calorimeters (as seen on Fig. 7) were designed to be ejected after the onset of melting providing three separate data-gathering periods.

Fig. 6: Galileo TPS thickness

In Fig. 6, it can be seen that for Galileo the ablation and recession rates in regions away from the stagnation area are not understood and totally underestimated. Transition to turbulent flow thereby enhancing ablation interaction could be the reason and need to be addressed in future in-flight research programmes.

Fig. 7: FIRE II TPS design

Fig. 8 shows the implementation of the instrumentation on Fire II. Radiometers, pressure sensors as well as
calorimeters were mounted on front and conical part of the multi layer TPS.

Fig. 8: Schematic diagram of FIRE II instrument placement

Typical results are shown in Fig. 9. It shows that heat fluxes on the conical afterbody are 1 to 2 % of the stagnation point. The Fire II data base is the only available flight data ever produced on uncontaminated shock layer radiation.

Fig. 9: FIRE II In-Flight data

Fig. 10, from Jim Moss RD[3], summarises the available numerical computations performed on Fire II and Apollo 4. For Fire II the point taken on the trajectory at 1642.7 seconds corresponds to an altitude of 54km and a speed of 10.6 km/sec. Of concern are the large differences found for the convective heating: from 6 to 14 MW/m² as well as for the radiative heating: from 3 to 6 MW/m² pointing to a serious need in understanding thermo-chemical chemistry and non-equilibrium radiation coupling.

<table>
<thead>
<tr>
<th>Vehicle/Source</th>
<th>max q_c</th>
<th>max q_r</th>
<th>max q_t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire II @ 1642.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Gupta(^2)</td>
<td>6.8 (7.0)</td>
<td>3.2</td>
<td>10.0 total</td>
</tr>
<tr>
<td>• Sutton (Inviscid)(^3)</td>
<td>6.8 (BL correlation)</td>
<td>3.8</td>
<td>10.6 total</td>
</tr>
<tr>
<td>• Park(^4)</td>
<td>6.6</td>
<td>6.5</td>
<td>13.1 total</td>
</tr>
<tr>
<td>• Park(^5) Latest Result</td>
<td>14.3</td>
<td>3.8</td>
<td>18.1 total</td>
</tr>
<tr>
<td>• Flight data</td>
<td></td>
<td></td>
<td>10.7 total</td>
</tr>
<tr>
<td>• Fay &amp; Riddell</td>
<td>7.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Apollo 4</th>
<th></th>
<th></th>
<th>with ablation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Park(^6)</td>
<td>2.3</td>
<td>5.0</td>
<td>7.3</td>
</tr>
<tr>
<td>• Park(^7) Latest results</td>
<td>3.6</td>
<td>1.7</td>
<td>5.3</td>
</tr>
<tr>
<td>• D. B. Lee(^8)</td>
<td></td>
<td></td>
<td>1.1 Visible &amp; IR</td>
</tr>
<tr>
<td>• Fay &amp; Riddell</td>
<td>2.3</td>
<td></td>
<td>3.3(^9)</td>
</tr>
</tbody>
</table>

Fig. 10: Heating Prediction and Measurements (MW/m²)

New comparisons between in-flight and computed are part of the Test-Case which will be presented during the 2nd International Radiation Workshop RD[4].

It is time now, 40 years later after Fire II, to get new radiation flight data using advanced non-intrusive techniques in such a way that the physical models associated with shock layer radiation and coupling can be improved.

3.4  Reentry F lessons learned

Reentry F was a sharp-cone vehicle designed for the laminar/turbulence transition in-flight study. Opportunity has been taken to implement some instrumentation for base flow study.

As pointed out by Wright RD[1], simulations of axisymmetric bodies at high Mach number and zero angle of incidence frequently show a disk shock in the base. This disk shock creates large increase in predicted base pressure and heating as can be seen from the simulations performed by Wright on Reentry F (Fig. 11) as well as on a planetary 70 degree conical Mars probe (Fig. 12). This disk shock disappears with small incidence angle. Reentry F flight data were not able to confirm the existence of this disk shock and sting mounted ground based facility experiments cannot provide insight into this problem, leading to large uncertainties in the design of the back cover thermal protection systems.

Lessons learned from Reentry F is the need to understand better the base flow heating and in particular the confirmation of the existence of a disk shock at zero incidence.
5. PROPOSED NEW IN-FLIGHT RESEARCH STRATEGIES

A TPS qualification methodology is proposed in Fig. 13 combining 2 flights: one flight at 11 km/sec simulating the proper convective and radiative contributions to the TPS heat flux and one flight at 6 km/s at enthalpy levels allowing a crossing with the plasma wind tunnel performance envelops thereby linking, using CFD, wind tunnel and flight for improved analysis of the uncertainties associated with flight extrapolation and scaling.

The 11 km/sec flight will address ablation and radiation coupling including all relevant physics of transition to turbulence, ablation radiation interaction and base flow heating.

The 6 km/sec flight is proposed to be designed to link with ground based plasma facility testing. Multiple capsules can be flown on the Volna using an appropriate dispenser, all with same geometry but different ballistic coefficients to fly different ballistic trajectories covering different heat flux levels.

The 6 km/sec flight provides therefore the “anchor point” with the European plasma facilities (SCIROCCO, L3K, IRS, Simoun).

Same heat flux levels and corresponding heat loads can be obtained both on the 11 and the 6 km/sec flight; however both with completely different radiative and convective contributions to the same total heat flux.

The link with ground based plasma facility activities obviously is with the 6 km/sec flight where reservoir conditions and model dimensions can be defined so as to match the flight heat fluxes.

### 11 km/s
- **Boosted Flight**
- **Focused on radiation coupling**
- **Base heating**

### 6 km/s
- **Flight**
  - Single capsule
  - Multiple capsules
- **Windtunnel**
  - Rebuilding
  - Data basing and Design

The dual flight approach was verified with the Japanese Muses C re-entry capsule as shown in Fig. 14 (dotted lines). The figure demonstrates the capability of the Volna (solid lines) to simulate on a suborbital 6.2 km/sec flight the stagnation heat flux as well as the integrated heat load which the Muses capsule will be...
subjected to when re-entering earth with a speed of 15 km/sec.

- **MUSE flight:**
  - 13 km/s ≈ 15MW/m²

- **VOLNA flight:**
  - 6.2 km/s ≈ 15MW/m²
  - FPA = -20

- Both same heat load

Fig. 14: Japanese MUSES / VOLNA-launched RV

6. **BRIEF DESCRIPTION OF PROPOSED MISSION SCENARIO’S**

Fig. 15 shows a picture of the Volna with the Volan model flown for microgravity experimentation.

Fig. 15: Volan in Volna launcher

Fig. 16 shows a sketch how potentially a 3-cone dispenser can be mounted onto the Volna 3rd stage and demonstrates that with one flight different trajectories can be flown for the study of ablative TPS performance varying from 4 to 11 MW/m²; each with the same geometry but different ballistic coefficients. The purpose is that the capsules be recuperated using small parachutes enabling post-flight inspection of the materials and integrated sensors.

Being able to get comparative flight data on one and the same TPS at different heat fluxes and in addition being able to post-flight inspect the material and its instrumentation will greatly advance ablative TPS characterization as well as improve methodologies as to use ground based facilities for design.

Fig. 16: Ablation In-Flight research

Fig. 17, 18 show the results of a feasibility study performed at MDB demonstrating the capability of the Volna launcher to carry an additional boosted stage providing the additional delta-V to obtain the 11 km/sec re-entry speeds for radiation/ablation in flight research.

Fig. 17: SRM based booster

Fig. 18: Flight Phases

Fig. 19 shows a possible mission scenario using a solid booster. Its specific impulse of 275 seconds during 60 seconds provides the required delta-V to reach the final speed up to 10.8 km/sec at 100 km altitude. The subsequent entry angle is 22.7 degrees.
7. CONCLUSION

The paper, meant as a discussion paper, described a proposal for gathering radiation / ablation flight data using two VOLNA flights.

The objective was to gather data for “design tool” validation encompassing:

- validation of the physical models incorporated into the numerical tools,
- experimental testing activities such as plasma wind tunnel testing simulating heat loads for TPS qualification and
- flight extrapolation and scaling including the analysis of the associated uncertainties.

A TPS qualification methodology was proposed combining two flights: one flight at 11 km/sec simulating the proper convective and radiative contributions to the TPS heat flux and one at flight enthalpy levels allowing a crossing with the plasma wind tunnel performance envelope thereby linking wind tunnel and flight using numerical CFD tools for flight extrapolation and scaling.

8. REFERENCE


