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Assessment of Aerothermodynamic Analysis Methods With Regard to the Planned SHEFEX Flight Experiment

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1 OVERVIEW

Appraisal of aerothermodynamic analysis results is not always easy, because reliable wind tunnel results are often available for the low speed regime only. Therefore, in many cases theoretical analysis may be the only method available in some hypersonic flight regimes.

Depending on the amount of experience with similar configurations/hypersonic flight states, or the lack of thereof, a careful selection of appropriate safety factors for the calculated heat loads (and other parameters) is necessary. Obviously, the less sophisticated the analysis method, the more a safety margin has to be applied.

In order to improve the analysis tools, to reduce the safety margins required and to allow for a true optimization of hypersonic flight vehicles and re-entry systems further empirical knowledge is desirable.

Increasing the existing experimental aerothermodynamic database from freeflight measurements on actual flight systems remains therefore an important task.

The SHarp Edge Flight EXperiment SHEFEX initiated by the German aerospace research center DLR will provide such an opportunity. The launch of a two stage suborbital rocket with the experimental vehicle mounted on top is planned in the second half of 2005. The system will reach an apogee of 327 km. The SHEFEX system will then perform a reentry to deliver aerothermodynamic data up to flight Mach numbers between 7 and 8 at altitudes between 90 and 20 km.

The paper describes preliminary aerothermodynamic analyses performed at EADS-ST in preparation of the planned SHEFEX post flight assessment.

Simplified analysis tools (surface inclination methods combined to boundary layer analysis) as well as CFD-calculations based on structured and unstructured grids using various turbulence models are considered.

First conclusions can be drawn from results using different analysis tools regarding aerothermodynamic parameters such as calculated heat flux densities, surface temperatures and pressure distributions.

2 INTRODUCTION

2.1 General

Although many spacecraft are expendable on completion of their mission, a significant number of applications require recovery of either the complete vehicle, or some portion thereof, either from the considerations of reuse, or of the survival and/or recovery of scientific and industrial payloads and/or operating personnel. This approach based largely on expendable vehicles was performed in the past but is not applicable for the future anymore since the commercial market situation drives competition and the cost factor becomes a major design driver.

Especially when talking about future European launch systems. Will it be again a expendable or will it be a reusable system? A major issue in finding pro's and con's for expendable vs. reusable is - in terms of costs and TRL - the availability of an appropriate thermal protection system (TPS) design. For example the American shuttle has approx. 25.000 tiles on the windward side. One can imagine that manufacturing and maintenance costs are a major part in the overall life cycle costs. In addition TPS mass represents indeed a significant part of the overall mass (e. g. 12% of the shuttle empty mass ≈ 7 t) and is of vital importance in assessing the performance of the complete spacecraft system.

For this purpose DLR has conducted in 2001 a technology development program to evolve a fibre-ceramic based TPS design on a facetted aerodynamic shape called SHEFEX (SHarp Edge Flight Experiment) with the goals of: improving operations features, increasing adaptability, reducing weight and last but not least costs reduction.

Complex curved aerodynamic surfaces and very small manufacture tolerance requirements are essential cost factors for development and manufacturing of vehicle TPS:

- curved fibre-ceramic structures demand costly toolings like dies, moulds and support structures
- each single/individual part demands appropriate toolings and optimised manufacturing processes
- because of the low aerodynamic quality of the outer surfaces the heat flux density is very high and require costly TPS
- an aerodynamic surface build by facetted panels permits a reduction of variety of type which in turn drastically lower manufacturing costs
- from system point view significant savings are achieved concerning maintenance.

Assessments of applying a facetted approach for a re-entry vehicle front section (see Fig. 2.1) show very promising results:

- constructive and manufacture cost savings of at least 70%
- cost savings on system level of at least 40%, e. g. ability to maintain during operation, spare parts procurement
- TPS mass savings of at least 25% will increase vice versa the payload capability.

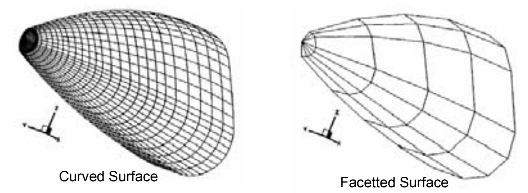

Fig. 2.1: Re-Entry Vehicle Front Section

Potentially this approach can be applied to all classes of re-entry vehicle or spacecraft involving atmosphere encounter. One essential step of using facetted fibre-ceramic TPS is the verification of its applicability. Beside others, one important mean to prove this is the flight experiment. Mounted on top of a two stage sounding rocket (see Fig. 2.2), the launch of SHEFEX is scheduled for October 2005.

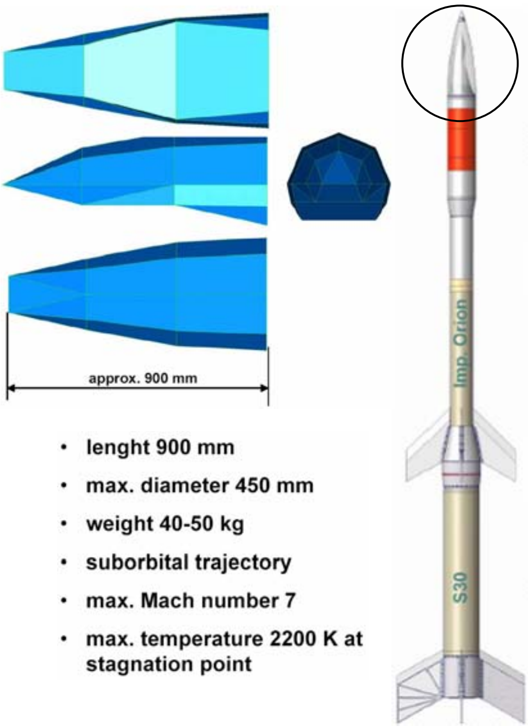

Fig. 2.2: SHEFEX Two Stage Suborbital Rocket [1]

Apart from this technical readiness level process of facetted TPS in addition SHEFEX offers very advantageous features:

- verification and validation of aerothermodynamic, structure and flow/structure coupled analyses methods
- flight database extension concerning shock/boundary layer effects in hypersonic flow
- wall catalyticity
- examination of reusability

2.2 Contributions of EADS ST regarding SHEFEX

For the design and improvement of TPS materials precise knowledge is mandatory of the mechanical and thermal loads the vehicle is exposed to during atmospheric entry. Using appropriate simulation models aerodynamic and aerothermodynamic flight loads are predicted. Applicability and meaningfulness of the used models and design approaches is directly linked to their verification and validation level. In this sense a high degree of confidence can be achieved by flight experiment, e. g. SHEFEX.

In the frame of the company co-funded contract with the German Aerospace Center DLR the participation of EADS ST consists of

- aerodynamic and aerothermodynamic analyses
- design, manufacturing and test of TPS materials

applicable for re-entry vehicles. In particular this means

- verification and validation of prediction models for mechanical and thermal loads
- to contribute with four TPS panels (C/SiC, SPFI, 2 x metallic) for in-flight testing.

The remaining portions of this paper focus on the aerodynamic and aerothermodynamic analyses as conceived by the Competence Center Bremen of EADS ST.

2.3 Mission and System Data

Based on a Brazilian S30 solid rocket motor as a first stage and an Orion motor supplied by DLR Mobile Rocket Base (Moraba) as second stage SHEFEX will be finally integrated and launched in autumn 2005 at the launch site Andøya Rocket Range in Norway (see Fig. 2.3).

Fig. 2.3: Launch Site Andøya Rocket Range, Norway

Lift off mass of the vehicle will be approx. 1896 Kg. The different flight phases are summarized in Table 2-1.

time [s]	altitude [km]	event
0	sea level	ignition of S30 motor
28	≈ 17	burnout/separation of S30, cruising phase
32	≈ 21	ignition Orion motor
58	≈ 64	burnout Orion motor, cruising phase
80	≈ 106	separation fairing
279	≈ 280	apogee, start descent
486	≈ 90	start experiment phase
521	≈ 20	end experiment phase, separation Orion motor
530	≈ 4	start recovery sequence

Table 2-1: Flight Sequences

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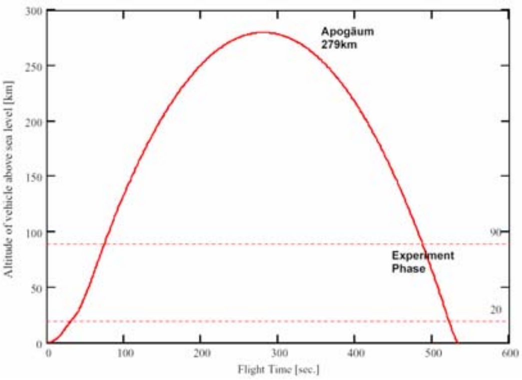

Fig. 2.4: Nominal Trajectory [1]

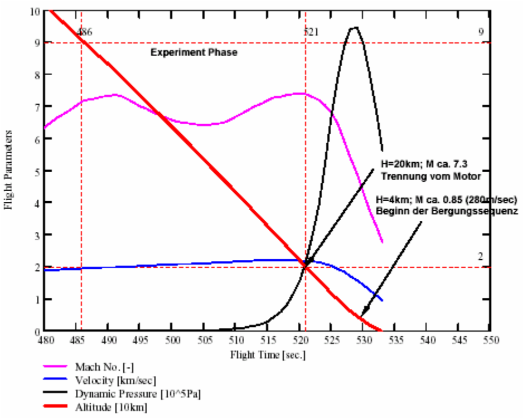

Fig. 2.5: Entry Flight Profile [1]

During the experiment phase SHEFEX experiences a Mach number of Ma≈7.4 (v≈2 km/s). The nominal trajectory and flight profile is shown in Fig. 2.4 and Fig. 2.5

3 ANALYSIS TOOLS AND VALIDATION CONCEPT

3.1 SHEFEX Specific Considerations

As shown in the previous chapter, the SHEFEX Trajectory is limited to Mach numbers between 7 and 8. Nevertheless the altitude Mach number combinations in the hypersonic flight region above Mach 5 are quiet representative for typical re-entry vehicles.

While the heat flux densities to be expected on the flat panels of SHEFEX are comparatively benign due to the limited flight Mach numbers, the small radii of curvature on the “sharp edges” of the nose structure will cause rather high peak heat loads there.

Heat flux densities, surface pressures and surface temperatures vs. flight velocity and flight altitude represent parameters of major interest concerning Aerothermodynamic assessment purposes.

3.2 Validation Approaches

Three basic approaches are widely used for the validation of theoretical aerothermo-dynamic analysis tools:

- comparison to other, already well validated analysis tools
- use of various ground-based test facilities such as plasma facilities and hypersonic wind tunnels. These allow code validation under well controlled flow conditions – not necessarily exactly the same as fully realistic flight conditions. However, useful “anchor points” for theoretical analysis models are definitely provided.
- free-flight measurements on actual reentry systems.

Among these validation approaches, free-flight testing (as provided by SHEFEX!) remains highly important for hypersonic analysis code validation, since it is nearly impossible to provide all important parameters by ground testing simultaneously and precisely as found in actual flight (flight Mach no. and exactly matching Reynolds no. conditions, actual air composition at altitude, use of TPS materials as on flight vehicle → surface roughness and catalycity issues)

3.3 Analysis Tools

The following aerothermodynamic analysis approaches are to be used at EADS ST Bremen for the SHEFEX post flight assessment:

- CFD(Computational Fluid Dynamics) – methods. For hypersonic flow conditions, appropriate physical models have to be incorporated addressing turbulence, transition criteria between laminar and turbulent flow, the thermochemical properties of air, surface radiation as well as surface catalycity.
- semi-analytical methods using local surface inclination methods in conjunction with boundary layer analysis (also necessitating the inclusion of physical modeling of turbulence and thermo-chemistry issues).

The latter, semi-analytical approach is considered important in the context of achieving quick turn around times, because it is computationally significantly more efficient than full blown CFD analysis and requires also considerably less engineering effort to set up calculations. However, applicability is basically restricted to the surfaces at the windward side of hypersonic vehicles.

In particular, the following aerothermo-dynamic analysis tools are to be used at EADS ST Bremen for the SHEFEX post flight assessment:

1) The computationally efficient semi-analytical **HYPER-N Code** currently under (continuing) development:

In the past, a NASA code based on methods described in [3] has been used at EADS ST Bremen to fulfill demands for quick first order analysis. However, this analysis code is based on the assumption of blunt body shapes. Also, the description of the vehicle sufaces is based in part on spline functions. Both code features disable the applicability to facetted, sharp-edged vehicles, thereby enforcing the use of the more expensive CFD tools.

Therefore, the need to supply a computationally efficient analysis method that is applicable to sharp edged vehicles (like SHEFEX), which cannot be described well via spline functions has been identified and led to the development of HYPER-N.

The main features of the current HYPER-N version are as follows:

Choice of different local surface inclination methods:

- determination of surface pressure distribution via pure or modified Newton method
- for low supersonic Mach numbers and slender flight vehicles alternative calculation of surface pressure distribution via slender body theory.

Determination of surface heat flux densities via semi-empirical boundary layer formulae as described in [6], or by numerical solution of the boundary layer eqations:

- imposed (constant) wall temperatures
- radiation equilibrium condition using prescribed emissivity coefficients

The air flow is treated:

- as perfect gas or
- using thermochemical equilibrium data (based on Hilsenrath [5])

The SHEFEX flight test data will represent an excellent way for further Validation of HYPER-N

2) Two- and Three-Dimensional CFD-Codes, e.g.:

- the two-dimensional Navier-Stokes Code CFDUNS [9] for unstructured grids, employing a low Reynolds No. k-ε model. CFDUNS works for plane and axisymmetric cases. It is based on a finite volume formulation employing a 2nd order upwind Roe scheme for the computation of the convective fluxes [7]. (Allows analysis of cross sections in SHEFEX plane of symmetry).

- the well proven three-dimensional Navier-Stokes Solver Tau-Code [10] developed by the German Aerospace Center DLR for unstructured and structured grids, offering a choice of different one- and two-equation turbulence models (Spalart-Allmaras-model, various versions of the k-ω-model). The Tau-Code has already been used extensively by DLR for SHEFEX related analysis. For further calculations at EADS ST the impact of various turbulence models supplied by the Tau-Code on the results will be one area of investigation within the SHEFEX post flight analysis.

4 RESULTS

Pending the availability of flight test data, first calculations have already been performed at EADS ST, using nominal SHEFEX trajectory data as basis for the free stream conditions to be analyzed.

Fig. 4.1 Mock Up of Re-Entry Vehicle Front Section

The results presented here approximate the flight condition representing the maximum heat flux densities within the SHEFEX nominal trajectory (~Mach 7.5 at altitude ~40 km).

4.1 Hyper-N Results

Fig. 4.2 shows the surface discretisation comprising of 2000 panels used for first calculations using the simplified surface inclination/boundary layer code HYPER-N.

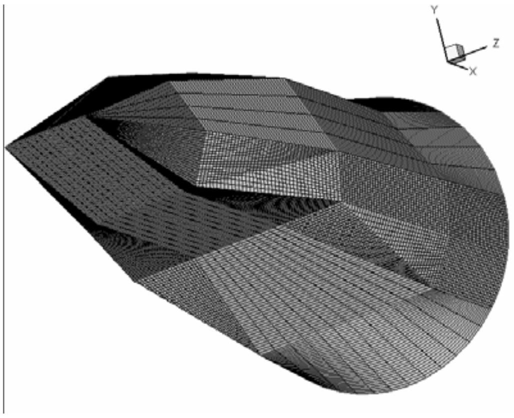

Fig. 4.2 HYPER-N Surface Discretization of Re-Entry Vehicle Front Section

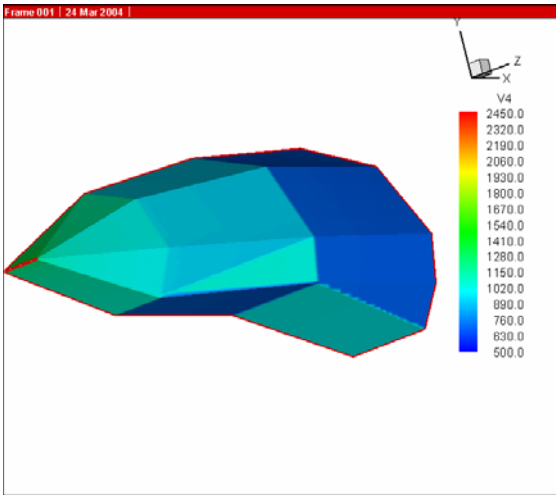

Fig. 4.3: HYPER-N Result: SHEFEX Radiation Equilibrium Temperatures at M=7.5, Altitude 42.6 km

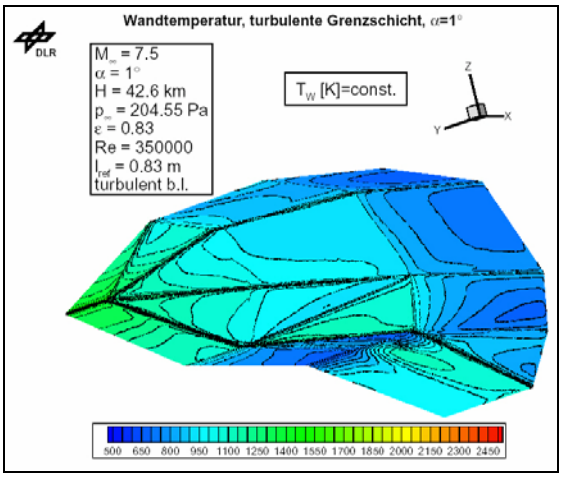

Fig. 4.4: DLR Tau-Code Result: SHEFEX Radiation Equilibrium Temperatures at M=7.5, Altitude 42.6 km (Courtesy T.Eggers, DLR)

Fig. 4.3 - Fig. 4.7 provide a first comparison of the three-dimensional surface inclination Code HYPER-N to DLR's full Navier-Stokes Tau-Code analyses [1].

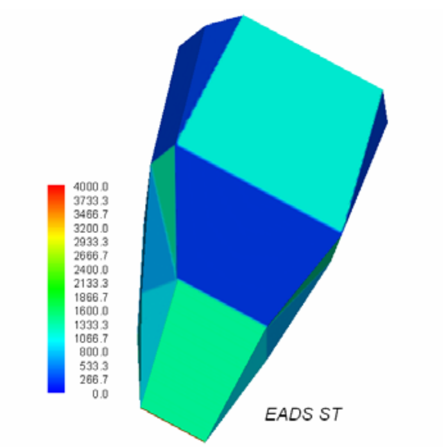

Fig. 4.5: HYPER-N Result: SHEFEX Pressure Distribution at M=7.5, Altitude 42.6 km, Lower Side

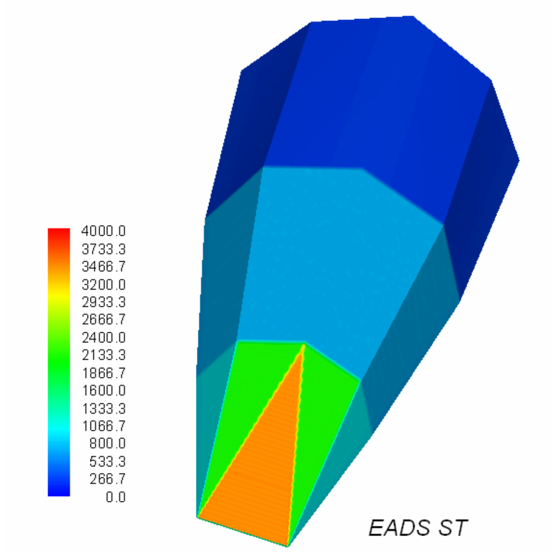

Fig. 4.6: HYPER-N Result: SHEFEX Pressure Distribution at M=7.5, Altitude 42.6 km, Upper Side

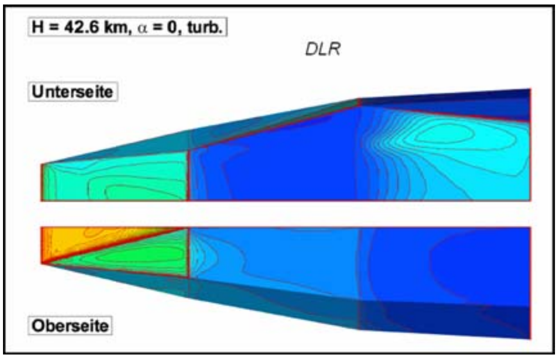

Fig. 4.7: DLR Tau-Code Result: SHEFEX Pressure Distribution at M=7.5, Altitude 42.6 km, Lower and Upper Side (Courtesy T.Eggers, DLR)

Both results were generated for flight condition Mach 7.5 at Altitude 42.6 km and used the assumption of fully turbulent flow and radiation equilibrium conditions at the walls. Walls were considered fully catalytic for the computations.

Fig. 4.3 - Fig. 4.4 contains a color coded representation of the surface temperatures calculated by both methods, whereas Fig. 4.5 - Fig. 4.7 shows the surface pressure distribution.

In line with the use of surface inclination methods for the calculation of the surface pressures, the HYPER-N result exhibits absolutely constant pressure levels on the individual panels. DLR's Navier-Stokes results (Tau-Code) predict a comparable relation of the pressure levels at the panels; however some pressure variation around these levels is predicted for each panel (as to be expected from analysis methods without the idealized assumptions of surface inclination methods).

Nevertheless, it is evident that both results correlate quite well considering the limitations inherent to the simplified modeling approach of HYPER-N.

This is true for the predicted pressure distribution as well as the wall temperatures .

More validation calculations concerning HYPER-N will follow after the SHEFEX flight test.

4.2 CFD Results

First Navier-Stokes calculations were performed at EADS ST based on the two-dimensional CFD-Code CFDUNS.

Albeit the SHEFEX nose represents a three-dimensional geometry, two-dimensional analysis also can yield useful results (in a computationally more efficient manner than three-dimensional CFD analysis) when the plane of symmetry is considered.

A corresponding result using the CFDUNS Solver of EADS ST is shown in Fig. 4.8 and Fig. 4.9.

Again a flight condition of Mach 7.5 at altitude 42.6 km was considered.

Fig. 4.8 contains the calculated Mach no. distribution at the cross section through the symmetry plane of the SHEFEX nose.

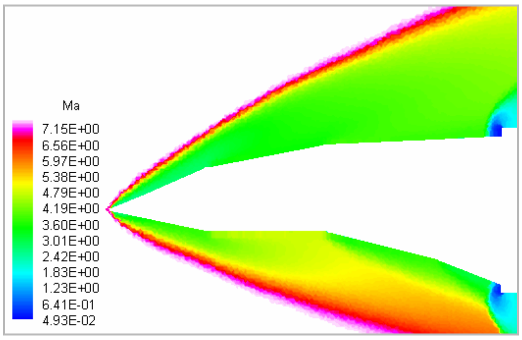

Fig. 4.8: Mach No. Distribution around the SHEFEX Nose (2D-Calculation, Plane of Symmetry)

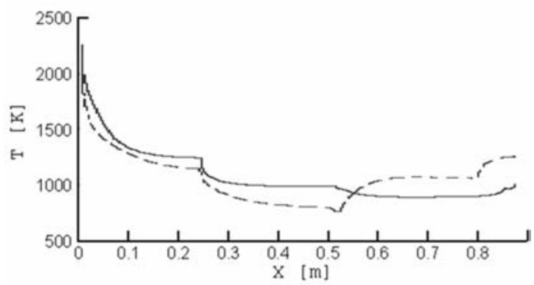

Fig. 4.9: Calculated Radiation Equilibrium Temperatures along Upper (Solid Line) and Lower (Dashed Line) Wall Contour of SHEFEX Nose (2D-Calculation, Plane of Symmetry)

Fig. 4.9 shows the radiation equilibrium temperatures (emissivity ε=0.8) along the upper and lower wall contour of SHEFEX nose as determined by the same CFDUNS calculation.

It is clearly evident from this result that rather high temperature peaks (well in excess of 2000K) are produced in the area of the SHEFEX nose tip even at the relatively low hypersonic Mach number of 7.5.

More detailed two- and three-dimensional CFD calculations, based on the conditions of the actual SHEFEX flight are reserved for the post flight analysis effort at EADS ST and will be documented in a future paper.

5 FUTURE PROSPECTS

As soon as the actual SHEFEX flight test data are available, a post flight assessment based on the actual trajectory will be performed, using the aforementioned array of aerothermodynamic analysis methods, encompassing laminar and turbulent flight regions within the hypersonic part of the trajectory.

Such calculations will be of use not only for the planned validation purposes of the analysis methods, but can also be very helpful in providing additional detail information concerning the interpretation of the experimental flight data.

Regarding possible follow-on flights the realization of higher flight Mach numbers significantly beyond 8 would certainly be of interest concerning further code validation work.

As far as feasible, an inclusion of features representative of body flap systems and related gap flows also could provide useful data.

6 REFERENCES

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