Intermediate Experimental Vehicle, ESA programme

Aerodynamics – Aerothermodynamics and In Flight Experiments
A system loop for validating the design tools and for mastering the aerothermodynamics phenomena

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Abstract

With the aim of placing Europe among the world's space players in the strategic area of atmospheric re-entry, several studies on experimental vehicle concepts and improvements of critical re-entry technologies have paved the way for the flight of an experimental spacecraft.

The Intermediate eXperimental Vehicle (IXV), under ESA's Future Launchers Preparatory Programme (FLPP), is the significant and fundamental step forward from the successful Atmospheric Re-entry Demonstrator flight in 1998, establishing Europe's role in this field.

The IXV project objectives are the design, development, manufacture on ground and flight verification of an autonomous European lifting and aerodynamically aero-controlled re-entry system, which is highly flexible and manoeuvrable. Among the critical technologies of interest, special attention has been paid to:

- Advanced instrumentation for aerodynamics and aerothermodynamics
- Thermal protection and hot-structure solutions
- Guidance, navigation and flight control through a combination of thrusters and aerodynamic flaps

The paper depicts the main components of the system loop involving AeroDynamic (AED) – AeroThermoDynamic (ATD) and In Flight Experiments (IFE) aiming a better mastering and validation of aerothermodynamics phenomena with improvement of design tools including CFD, WTT.

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1. Introduction

The IXV is designed to fulfill a set of high level requirements and objectives that have been iteratively discussed and jointly defined by the Agency and Industry.

The main technical and programmatic constraints that define the project are:

- Perform the atmospheric re-entry with a lifting configuration controlled by combined thrusters and aerodynamic surfaces.
- Perform verification and experimentation of a well defined set of critical re-entry technologies and disciplines (e.g. aerodynamics, aerothermodynamics, thermal protections, hot structures, guidance, navigation and control, …).
- Concentrate the verification and experimentation in the hypersonic and high supersonic flight domains.
- Perform landing and recovery of the vehicle at sea and in an "intact" state to allow post flight inspection and analysis.

The vehicle configuration defined along the project phases and has been presented successfully at the SCDR (System Critical Design Review (SCDR) is shown in Figure 1.

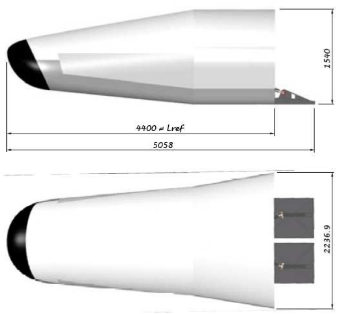

Figure 1: Intermediar eXperimental Vehicle, general layout (courtesy of ESA)

It is a lifting platform characterized by a L/D of ~0.7 in hypersonic regime, two body flaps used for aerodynamic control. The vehicle is equipped with a descent and recovery system including a set of parachute, floatation and localisation devices.

The resulting nominal ETE trajectory is shown in Figure 2, where the maximum altitude is set at ~475 km in the ballistic arc. It provides a velocity at the entry gate equal to 7450 m/s and a flight path angle of -1.6°, fully representative of a re-entry from low-earth-orbit (LEO) missions.

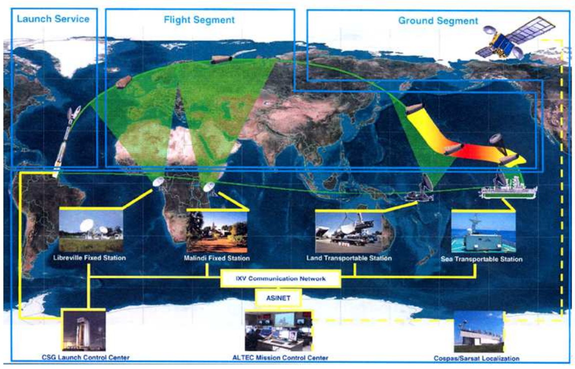

Figure 2: Intermediate eXperimental Vehicle, mission general overview (courtesy of ESA)

Under ESA control, Thales Alenia Space Italy is leading the industrial organization gathered by more than 30 European partners.

One important component of the system loop involved AED (Aerodynamic), ATD (AeroThermoDynamic) and IFE (In Flight Experiment).

The development of a robust Aerodynamic and aerothermodynamic data bases is carried out for securing the aeroshape definition and providing reliable nominal and sizing data for TPS (Thermal Protection System) and vehicle dimensioning purposes. Currently, only ground prediction tools are used for assessing the general aerothermodynamic characteristics of the IXV vehicle in flight. Moreover above Mach number 10, ground prediction tools like wind tunnel facilities are not able to reproduce all parameters involved at flight condition. Having any flight data for validation, the extrapolation ground to flight strategy is only based on CFD.

For designing a hypersonic spacecraft, a close loop between AEDB , ATDB & mission analysis is mandatory for consolidating the aeroshape. At each iteration, the AEDB and ATDB are providing data for mission analysis, FQA / GNC and TPS activities as well. Potential critical points are solved by analyzing in depth the date predicted at different level of the system loop.

Among the different objectives of the mission, the IXV vehicle is a flying test bed able to retrieve flight data for validating the various prediction tools used for the design.

As shown in Figure 3, the AEDB provides the aerodynamic data to be used by the mission analysis which gives as output the Mach number, altitude, angle of attack sideslip aileron and flap setting for each re-entry trajectory point. Then using the ATDB, for any flight trajectory point, a pressure and thermal mapping is computed to be used for in flight sensors location. Finally considering one of the flow field phenomena to be occurred in flight, the shock wave boundary layer interaction phenomena (SWBLI), the Figure 3 displays the evolution of the boundary layer separation zone evolution for various flap setting at Mach number 17.75 enabling to define the more promising IR camera and thermocouples location as well.

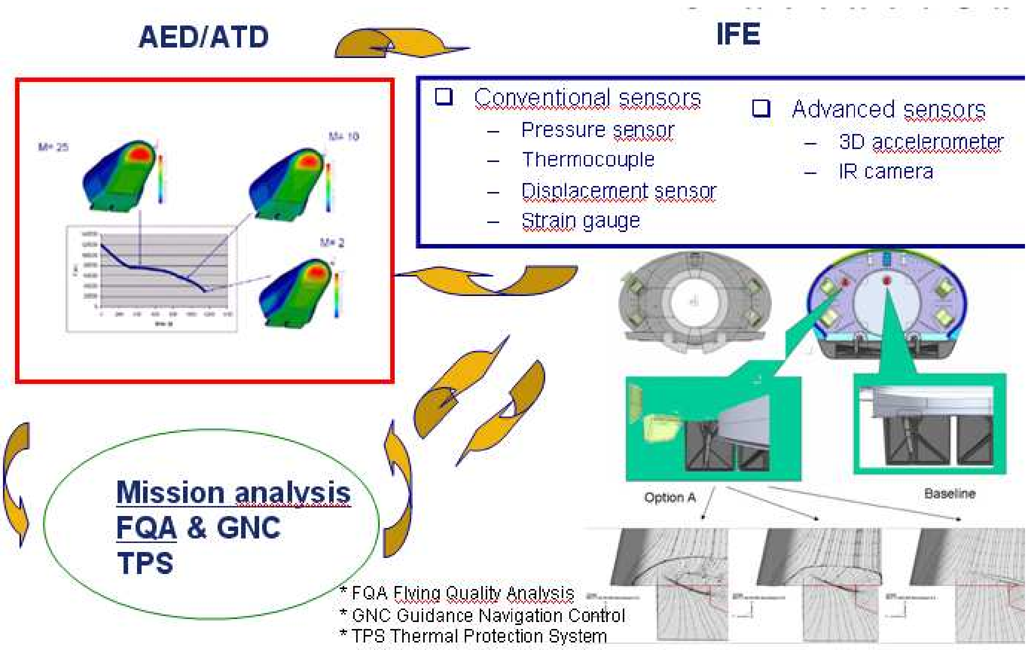

Figure 3: AED / ATD / IFE System loop

Within the IXV programme, the AED/ATD and IFE activities are under Dassault Aviation responsibility and involving RTECH, CFSE, UNIROMA, NLR, VKI (for CFD activities), STARCS, ONERA, VKI (for WTT activities) and RUAG, ONERA, CIRA, ETHZ, VKI (for In flight Experiments) as shown in the Figure 4.

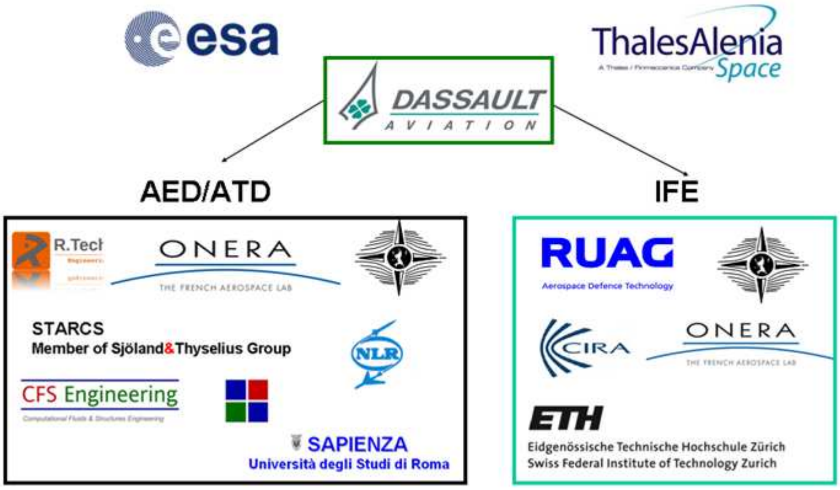

Figure 4: AED, ATD and IFE industrial organisation

3. Aerodynamic

Design and data basing studies require the prediction of forces on the « clean » aircraft (i.e. with no control surface deflections), of the derivatives of these forces with the attitude and motions parameters (primarily angle of attack and angle of sideslip), and with control surface deflection.

The AErodynamic DataBase (AEDB) (see Figure 5) covers a wide range of Mach number from supersonic to hypersonic up to rarefied regime for which global and partial aerodynamic forces and moments are made available. The ADB is built up in one block including two types of data as follows:

. Supersonic: mainly based on WTT results with CFD (Navier-Stokes) for specific effects such as Reynolds number effect and model set up interaction

. Hypersonic: based on CFD (Navier-Stokes) for continuum flow field regime and DSMC for rarefied flow field regime, with wind tunnel crosschecks.

The aerodynamic forces and moments are usually grouped as longitudinal or lateral directional coefficients. The longitudinal terms are normal force, axial force, and pitching moment, while the lateral directional terms are rolling moment, yawing moment, and side force. Further, it is common in many instances to use coefficients in a derivative form based on either a control surface deflection angle, the side slip angle, or angle of attack.

The formulation of the Aerodynamic DataBase has been chosen to be easily usable for aerodynamic analysis purpose and for a direct integration into the FES (Flight Engineering System).

Finally, uncertainty on each aerodynamic coefficient is taken into account.

The uncertainties are defined with respect to the associated origin and quality of the data implemented into the database (CFD, WTT, level of validation, available comparisons, ...)

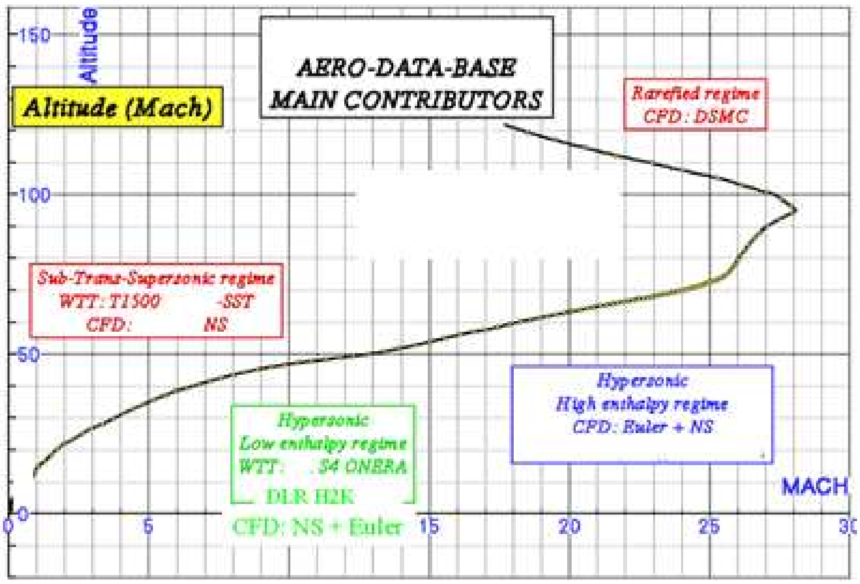

Figure 5: AErodynamic Data Base AEDB, main components

3.1 Aerodynamic uncertainties

For both supersonic and hypersonic domain the same strategy was used for updating the aerodynamic uncertainties.

The building up of these uncertainties is based on a Dassault Aviation in-house tool developed for aircraft.

For both supersonic and hypersonic AEDB, the list of aerodynamic parameters with uncertainties is:

- CA (axial coefficient) : UCA
- CN (normal coefficient) : UCN
- CM (pitching moment coefficient) : UCM
- CMDE (pitching moment elevator derivative coefficient) : UCMDE
- CYB (side force beta derivative coefficient) : UCYB
- CLLB (rolling moment beta derivative coefficient) : UCLLB
- CLNB (yawing moment beta derivative coefficient) : UCLNB
- CYDA (side force aileron derivative coefficient) : UCYDA
- CLLDA (rolling moment aileron derivative coefficient) : UCLLDA
- CLNDA (yawing moment aileron derivative coefficient) : UCLNDA
- CLL (rolling moment coefficient) : UCLL0
- CLN (yawing moment coefficient) : UCLN0

All these uncertainty coefficients are given as functions of the Mach number. They are generally given in absolute value, except for UCMDE, UCLLDA and UCLNDA which are respectively given in relative value of CMDE, CLLDA and UCLLDA. They are all given in body axes. All derivative coefficients (wrt beta or control deflections de and da) are given per radian.

So far, no uncertainty has been defined for the dynamic derivatives. These coefficients are of minor importance, especially in supersonic / hypersonic regimes, and for a vehicle controlled by a FCS.

The uncertainties may be considered as a combination of "tolerances" (dispersion from the estimation means : computation codes, wind tunnels) and of "variations" (flight transposition error). So, the breakdown of contributors to these uncertainties may be as follow:

"Tolerances":

CFD

- Meshing inaccuracy
- Solving method(Euler, Navier Stokes, …)
- Computation code

- Inaccuracy due to convergence
- Models (turbulence, real gas, chemistry …)

WTT

- Model inaccuracy
- Flow similitude (Reynolds …)
- Mounting effect (sting …)

All these contributions induce CFD to CFD dispersions as well as WTT to WTT and WTT to CFD dispersions. It is out of question to quantify separately each contribution. The way of estimating the tolerances is based on the assessment of deviations between CFD or WTT results, WTT repeatability tests, etc … In other words, the tolerance assessments are obtained from the analysis of the available data resulting from the various prediction means.

"Variations"

- Representativeness of the prediction means (models, flow characteristics …)
- Realization of the vehicle (consistency with the theoretical shape, aeroelastic distortion …)

The variation cannot result from the observation of result dispersions. We have here to assess what could be the deviation from the flight. It can only result either from experience, or from some rationale about physical phenomena well known to be difficult to predict, such as real gas effect in hypersonics.

3.2 Flying Quality Analysis, AEDB evolution check out

The AEDB evolution is assessed by means of a preliminary trim conditions analysis in hypersonic-supersonic regimes at the AEDB reference point centring condition and without uncertainties.

For both longitudinal and lateral behaviour analysis, the CoG considered is located at h reference point of the AED (e.g. 58% in X and -2.5 % in Z with the origin at nose).

The sizing re-entry trajectory is used as input for FQA (Flying Quality Analysis) at which thr trim analysis is done.

Assuming only nominal aerodynamic and a given AoA of 45°, the flap setting evolution is drawn on the Figure 6 versus Mach number for the previous and the last AEDB.

Due the aeroshape evolution (ie: real flap geometry), the nominal flap setting increases slightly in supersonic (above Mach 4) and in hypersonic. A, increase of around 1 degree of flap setting is noticed. The effect of choosing a null elevator efficiency below de = -10 deg of elevator deflector can induce longitudinal trim impossibility in some centring conditions or AoA range.

The static margin evolution, given for AoA) 45° and trim conditions, shown in Figure 6, is acceptable regarding the aeroshape design requirements and close to the previous one.

For the lateral stability Cnβdyn coefficient (see Figure 7), the value observed from the last evolution of the AEDB are quite constant and well below the value prescribed; assuming trim flap setting with nominal aerodynamic and given inertia ratio.

Obviously, such current status must be consolidated by a more detailed analysis of flying qualities integrating MCI, and aerodynamic uncertainties.

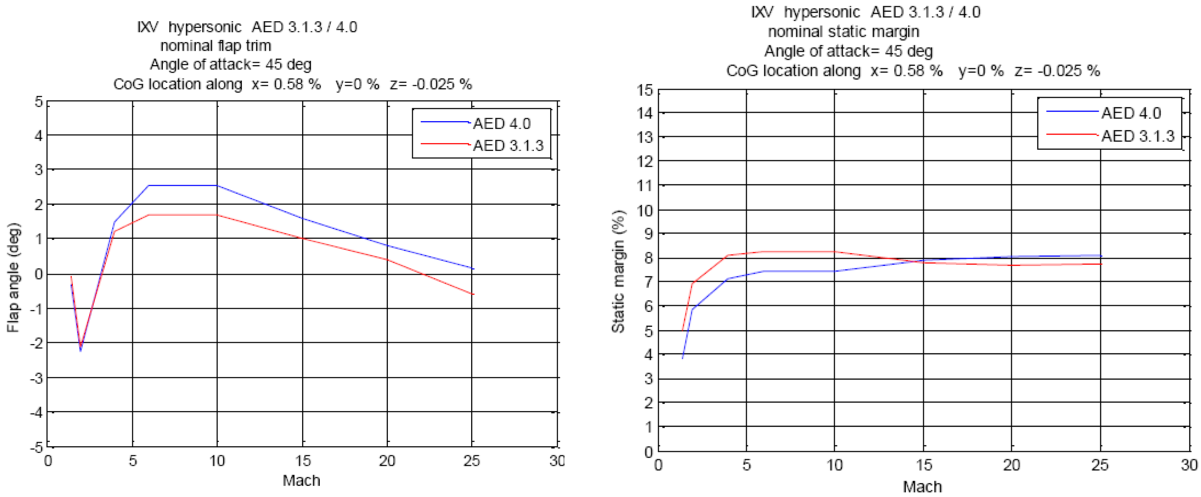

Figure 6: AErodynamic DataBase check out, IXV longitudinal behaviour

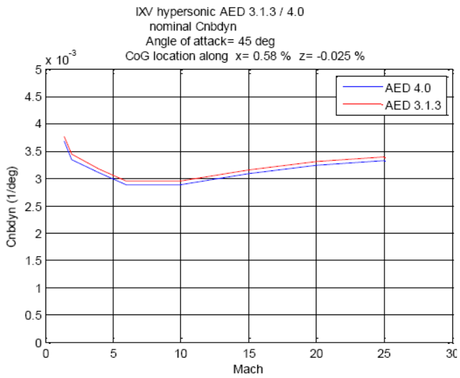

Figure 7: AErodynamic DataBase check out, IXV Lateral stability behaviour

4. Aerothermodynamic

In order to provide time history heat fluxes during a re-entry to be used as input at mission analysis and aeroshape design level as well, a Aero thermodynamic Database and an interpolation software have been produced.

The ATDB is based on 45 masks stored on a same grid and built from selected 3D Navier-Stokes computations and on 5 sizing skin data obtained by the new methodology for uncertainties assessment. Its construction consists of projecting skin results of these computations on a same grid. A nominal database of 5 solutions is also available and this reference case provides results with a partial catalycity assumption.
The effects that are taken into consideration by ATDB tool are deflection angle, angle of attack, sideslip and spillage. The migration to aeroshape 2.3 is also ensured.

During a re-entry phase of the vehicle, it is necessary to know the time where the laminar turbulent transition occurs on the flap and on the body of the vehicle. For this aim, an analysis of laminar - turbulent transition criteria were performed.
It appears that for a given upstream Reynolds number, it is possible to know if the flow remains laminar or becomes turbulent.

The ATDB software allows to compute heat fluxes, wall pressure and skin friction for given re-entry trajectories for the whole body as well as for a given number of checking points on the body
In order to generate an aero-thermo database for interpolation, the strategy which consists of projecting different European partners CFD results on a same grid, has been applied by Dassault Aviation.

The anchor points of the database were selected assuming fully catalytic wall assumption with AOA=45°, sideslip angle=0° and a reference flap deflection angle of 10°. The assessment of these reference data was performed using a statistical method for uncertainties based on CFD computations and WTT results. The reference database can be a sizing database (assuming fully catalytic wall assumption) or a nominal database (partial catalytic assumption).

Other effects due to deflection angle, angle of attack, sideslip angle or aileron effect are treated using masks. The mask is the ratio between a given CFD and the CFD in the reference configuration (AOA=45°, AoS=0°, de=10°, da=0°, fully catalytic). When it is possible, the considered Mach numbers are Mach=10, Mach=15, Mach=20 and Mach=25 with a laminar or/end turbulent flow. The database includes CFD:

- with flap deflection angles of 0°, 5° and 15° (at AoA=45°)
- at 40° and 50° angle of attack and at flap deflection angles of 10° and 0°.
- with sideslip angles of 5° and 8°
- with a spillage angle=5° (AoA=45°, de=10°)

4.1 Transition criteria

Two criteria for the laminar / turbulent boundary layer prediction transition were proposed (see Figure 8).

The first one (ie: CRIT1) is devoted to predict the transition on the windward side at X=700mm (nose junction with the first raw of tiles)):

The second criterion (CRIT2) is applied at X/L=60% (or X=2640mm) to determine the onset of laminar turbulent transition in the flap separation along the trajectory. Such transition criterion depends of the flap deflection angle, and respectively of the free-stream Mach number and the Reynolds number based on the vehicle length.

The second transition criterion (CRIT2) can be treated independently of the two flaps. One flap can be turbulent and the other laminar.

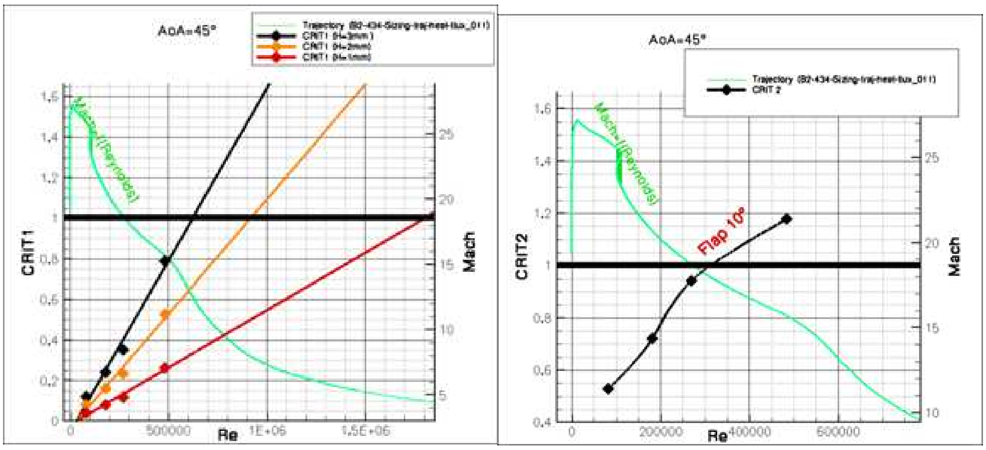

Figure 8: AeroThermodynamic Transition criteria, CRIT1 (nose) & CRIT2 (flap)

4.2 Uncertainties and margins

4.2.1 Uncertainties

The analysis of thermal phenomena on the IXV vehicle is mainly led by CFD computations. WTT and ideally flight data are essential to measure the reliability of computational results by simple comparison.

Despite the enormous power of computation models, they are not perfect because all of them are only abstractions of the realities. Due to the lack of knowledge and the use of assumptions by model builder, uncertainty is inevitable for models at every stage of life cycle. Moreover certain physical phenomenon are very far from today simulation capabilities, at least in an industrial program frame, as transitional flow or Göertler vortices. For these phenomenons, appropriate evaluation by dedicated experiment (eventually found in bibliography) can be done to predict a dimensioning value covering the risks induced by the phenomenon considered.

Another problem is difficult to take into account in CFD: the real detailed shape of the vehicle with steps and gaps, cavities, hinge geometry and so on… Due to the cost of CFD with high level of modelization and high mesh refinement to cope with a given accuracy, when a huge amount of calculation is needed to cover an entire vehicle mission, and finally as the final shape of the vehicle is known late in a program, data bases are built for a simplified “smooth” geometry and to cope with the sizing needs for final manufacture, these data bases have to be modified to account for uncertainties, necessary margins to cover the different risks induced by specific features (roughness transition, overheating on geometrical singularities …).

In the ATD margin policy, all these problems are considered and have a specific solution in the ATDB construction. Let us divide things in three main categories:

- Uncertainties in the simulation (models accuracy)
- Margins on phenomenon indescribable by simulation (particular flows)
- Margins on specific problems hard to take into account in global simulation (fine geometry)

The first item is addressed by a statistical method which will be exhaustively described in the paragraph 4. Briefly, first a dispersion of numerical results is considered (softwares, chemical and transport models …) to build a probability law and deduce the most likely / worse solutions for existing numerical tools, second relevant CFD solutions are compared to WTT data to quantify a systematic error and/or another dispersion term to upgrade the “sizing” solution retained.

For this second item, different CFD contributors have made WTT rebuilding (CFSe in phase C2, DLR & CIRA in phase B2/C1). Code-to-code uncertainty effect is present between these contributors and this with too few common data to build a CFD “most likely” in WTT rebuilding. So, only one contributor is retained in this analysis, the one giving the more dimensioning WTT-CFD discrepancy (provided there is no particular doubt on CFD accuracy of the so chosen candidate).

4.2.2 Margins

Some margins have been added to nominal and sizing quantities in order to take into account risks. We can distinguish three kinds of margin:

- Transitional overshoot: remember that the flap transition is controlled by the transition criterion CRIT2 (one for each flap). If CRIT2>1 for a flap, then we add a margin of 30% for this flap, on the interpolation given by the turbulent base. This percentage has been deduced from the wind-tunnel campaign ONERA S3.

- Steps and gaps: this margin only concerns the body and not the flaps. A percentage of 15% is used when the flow is laminar and a percentage of 20% is used when the flow is turbulent. Theses values have been deduced from the wind-tunnel campaign ONERA S3.

- Göertler effect margin: using Taylor Göertler generic instability maps, and analyzing the local properties (boundary layer thickness, separation bubble characteristics, local velocities, pressure or density) on the IXV flap, we observed that Taylor Göertler instabilities could appear within the flap and thus generating local overheating, to be taken into account by margin. This margin only concerns flaps when the flow is laminar. Moreover, the margin level directly depends on the deflection angle. An angle of 0° is associated with a margin of 0% and an angle of 15° is associated with a margin of 30%.

4.3 AeroThermodynamic Data Base, ATDB

From a re-entry trajectory either sizing maximizing heat flux at nose , maximizing the heat load or nominal including AoA, sideslip flap and aileron setting variation, the ATDB as shown in the Figure 9 provides as an output : many files as trajectory points desired describing physical parameters like TW, Q, etc… and one file describing the time history of several physical parameters including heat fluxes (Q) and wall static pressure given for geometrical checkpoints throughout the IXV (see Figure 9).

The geometrical checkpoints can be defined on both sides of the IXV vehicle. Each flap is treated independently. The right flap and the left flap have their own deflection angle, transition criterion and margin (especially the Göertler coefficient).

The wall output files are stored in Tecplot software ASCII.

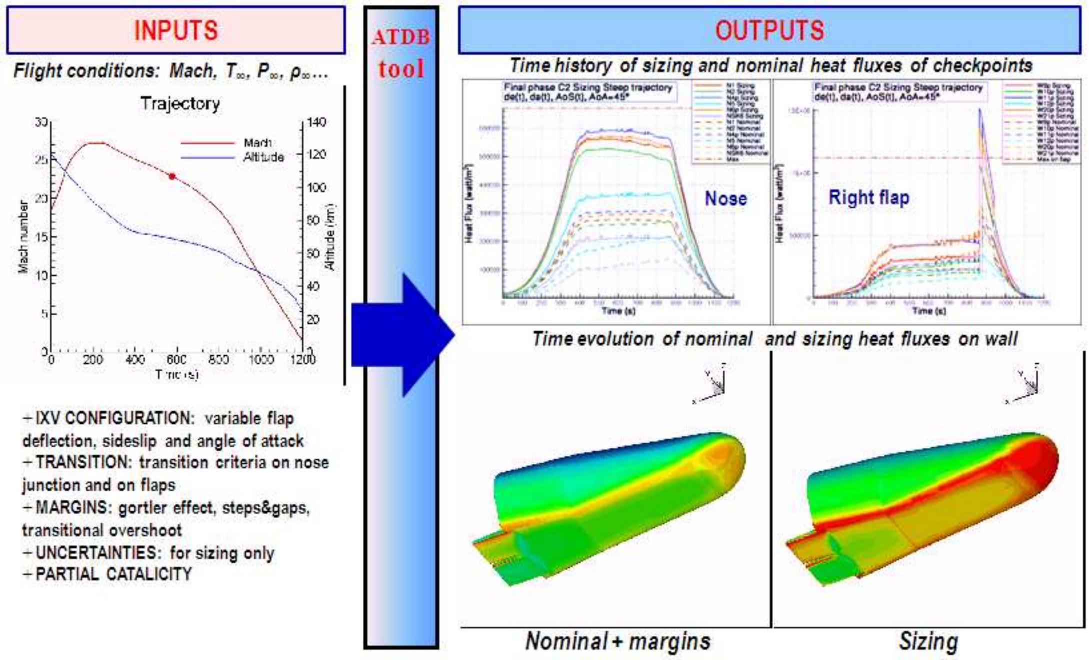

Figure 9: AeroThermodynamic Data Base, ATDB

5. In Flight Experiment

The technological objectives of the IXV mission are met by flying a set of experiments that have been chosen among a wide range of proposals. The main areas of investigation are:

- TPS, for verification and characterization of thermal protection technologies in representative operational environment (i.e. re-entry from LEO).
- AED-ATD, for understanding and validation of aerodynamics and aerothermodynamics phenomena with improvement of design tools, including CFD and WTT.
- GNC, for verification of guidance navigation and control techniques in representative operational environment (i.e. re-entry from LEO).

Figure 10 summarizes the TPS and AED/ATD experiments currently selected to be embarked in the IXV mission. Since each experiment required a specific set of measurements, several synergies and commonalities were exploited to identify a global set of sensors covering all experimentation requirements.

Although large part of the experimentation is based on the utilization of “conventional” sensors, specific areas necessitated dedicated equipment, so-called “advanced”, to acquire specific data. The selection of these “advanced” experiments was performed on the basis of their technological maturity and compatibility with the overall system.

Experiment	Category	Phenomena	Area
SWBLI	AED/ATD	Real-gas effects. Shock-wave-boundary-layer interaction. Flap surface efficiency/ATD.	Flap/Hinge
Continuum Flow - 1	AED/ATD	Rarified and continous	Windward/Flap/Chin/Si
High Altitude AD - 2	AED/ATD	Rarified and continous	Inside vehicle
Base Flowfield - 3	AED/ATD	Real-gas effects. Base AED and ATD.	Base
General Heating - 5	AED/ATD	Real gas effects. Turbulent heating.	whole vehice surface
Wall catalysis - 6/58	AED/ATD	Real gas effects. Material catalytic behaviour.	Windward
Flap Interaction - 7	AED/ATD	Real gas effects. Shock-wave-boundary-layer interaction. Shock-Shock interaction. Transitional separation.	Flap
Jet flowfield interaction - 8	AED/ATD	RCS efficiency.	Base
L-t-T transition - 9	AED/ATD	Laminar-to-turbulent transition.	Windward/Chin
3Axis Accelerometers	AED/ATD	AED.	Inside vehicle
IR CameraTemp Mapping	AED/ATD	Real gas effects. Shock-wave-boundary-layer interaction. Shock-shock interaction. Transitional separation.	Flap
Nose Cap	TPS	Material Verification.	Nose
Ablative TPS	TPS	Material Verification.	Leeward/Base
Hinge line seal	TPS	Material Verification.	Hinge
Large Shingle	TPS	Material Verification.	Windward
Shingles junction	TPS	Material Verification.	Windward
C/SiC Shingles	TPS	Material Verification.	Windward
C/SiC Leading Edges	TPS	Material Verification.	Leading Edge
Body Flap	TPS	Material Verification.	Flap
CMC FADS	AED/ATD	Rarified and continous	Nose
Gap and cavity heating - 10	AED/ATD	Cavity heating	Windaward/Flap

Figure 10: ESA Mission & System Requirements Document, In Flight Experiments

In-Flight-Experimentation (IFE or Experimentation) defines the subsystem responsible for the selection, design, development, and manufacturing of the experiments for the scientific data acquisition during the IXV mission. The IFE subsystem is requested also to provide support for the integration of the experiments in the vehicle and to provide support for the operational phase during the flight and post flight.

A detailed design ensuring the successful integration of the IFE with the various engineering disciplines has been performed.

Also, a IFE plan clean up was carried out enabling to achieve a number of sensors about 283 being compatible with the scale of the IXV vehicle and avoiding any deviation from the IFE general objectives (see Figure 11).

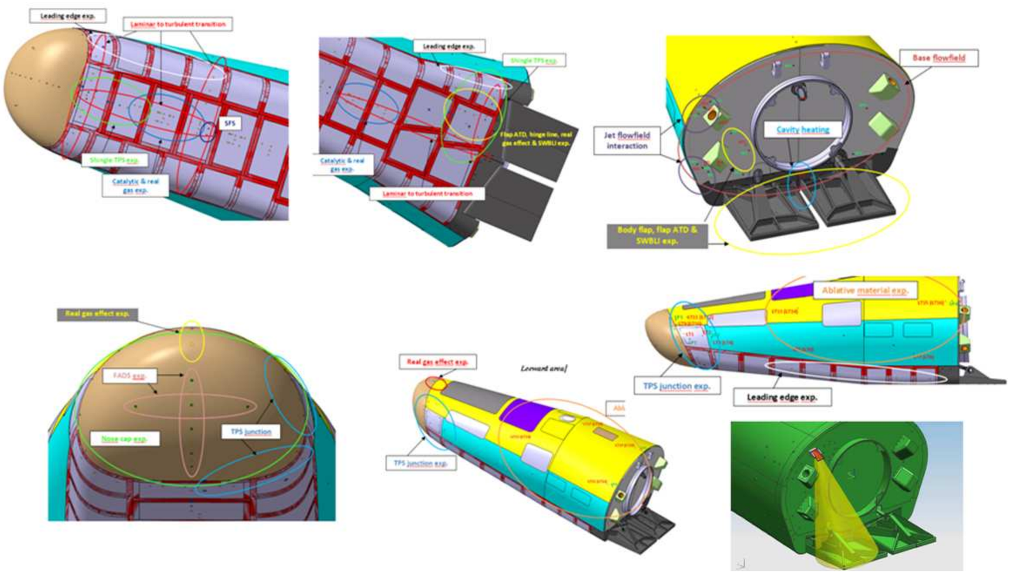

Figure 11: In Flight Experiments Plan

Avoiding any duplication, most of the sensors are defined to be used for several experiments.

As example of an iterative process at system level is given in Figure 12 about the implementation of sensors on ablative material covering leeward and base surface which creates a challenging situation, because of the pyrolysis of the material expected after a given material temperature limit and a surface recession out of this limit. The quality of the pressure measurements once the surface recession has started is thus questionable, since the pressure port will not be in a flush position any more. Considering also the small thickness foreseen for the IXV applications (about 22 mm), it could be implemented several thermocouples through the thickness. So, the baseline is to integrate one thermocouple close to the external surface (which will be operational up to the starting of the surface recession) and a co-located thermocouple on the substrate for some areas, so as to identify the thermal load reaching the substrate.

For demonstrating that such instrumentation would be operative in flight conditions, an ablative material (thickness representative of the flight one) sample was tested in VKI plamastron facility. The test specification was established thanks to the mission analysis giving the sizing re-entry trajectory which was used by ATDB for predicting the maximum heat flux, maximum heat load and pressure time history to be sustained during tests for being representative of flight conditions (as shown in Figure 12).

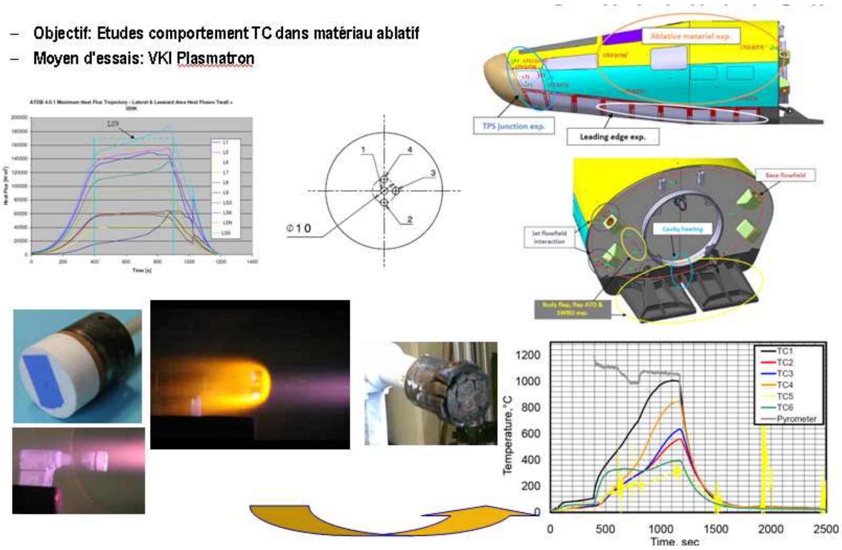

Figure 12: In Flight Experiments, Ablative material, thermocouples instrumentation, Plasmatron tests VKI

On the final result, it is observed that the thermocouples worked rather well reproducing the temperature staging expected even if the current instrumentation would request some refinement before to be Assembled Integrated and Tested in the IXV flight model.

3. Concluding remarks

The AED /ATD /IFE activities remain a fundamental part of the system loop for securing the design of a re-entry spacecraft.

As on ground (i.e: wind tunnel) for high altitude and high Mach number, it is still challenging to reproduce the flight conditions, the extrapolation ground-to-flight is based on CFD which remains to be validated thanks to a robust In Flight Experimental plan.

The aerodynamic and aerothermodynamic databases associated with the mission analysis and GNC are providing the main inputs for sensors location regarding the main flow field phenomena and aerothermodynamic behaviour predicted by ground prediction tools.

The AED /ATD/ IFE system loop provide dimensioning (sizing data, range of measurement, sensor accuracy, etc) data as well as reference data useful for the flight itself.

In such a way for the reference re-entry trajectory, a pre-flight analysis report will be edited describing the relevant assumption, utilized methods, techniques and results etc. to be compared further with the flight data.

4. Acknowledgement

The authors would like to express their appreciation to ETHZ, CFSE, CIRA, NLR, ONERA, RTECH, RUAG, STARCS, UNIROMA, VKI for their expertise and support all along the IXV phase C2.

Acronyms

AEDB	Aerodynamic Data Base
ATDB	AeroThermodynamic Data Base
IFE	In Flight Experiment
CFD	Computational Fluid Dynamic
FES	Flight Engineering System
WTT	Wind Tunnel Tests
TAS-I	Thales Alenia Space Italy
ESA	European Space Agency
FQA	Flying Quality Analysis
GNC	Guidance Navigation and Control
ETE	End to End
SWBLI	Shock Wave Boundary Layer Interaction
TPS	Thermal Protection System

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