

EXPERT - The ESA experimental re-entry test-bed: System overview

F. Ratti¹ and J. Gavira²

European Space Agency ESA-ESTEC, Noordwijk, The Netherlands

G. Passarelli³ and F. Massobrio⁴

Thales Alenia Space TAS-I, Turin, Italy

EXPERT is developed by the European Space Agency (ESA) in order to provide the scientific community with quality data on critical aero-thermodynamic phenomena encountered during hypersonic flights as well as to provide industry with system experience of re-entry vehicle manufacturing and development of hypersonic instrumentation.

EXPERT is equipped with 14 experiments provided by several scientific institutions all around Europe. The experiments address the following phenomena: TPS material characterization, surface catalysis and oxidation, plasma spectroscopy, laminar to turbulent transition, flow separation and reattachment, shock-boundary layer interactions, base flow characteristic and aerodynamic characterization of flap control surfaces.

The paper focus on the status of the EXPERT project: the design activities and the on going manufacturing, the main challenges and the expected flight data results. EXPERT will benefit future atmospheric re-entry activities ranging from cargo to human orbital transportation systems as well as re-usable launchers and scientific probes.

Nomenclature

<i>ARD</i>	= Atmospheric Re-entry demonstrator
<i>ARV</i>	= Advanced Re-entry Vehicle
<i>AIV</i>	= Assembly Integration & Verification
<i>CFD</i>	= Computational Fluid Dynamics
<i>EGSE</i>	= Electrical Ground Support Equipment
<i>ESA</i>	= European Space Agency
<i>EXPERT</i>	= European eXPERimental Re-entry Test-bed
<i>ICBM</i>	= Intercontinental Ballistic Missile
<i>IXV</i>	= Intermediate Experimental Vehicle
<i>I/F</i>	= Interface
<i>IR</i>	= Infrared
<i>LV</i>	= Launcher Vehicle
<i>OBDH</i>	= On Board Data Handling
<i>PCDU</i>	= Power Control and Distribution Unit
<i>PL</i>	= Payload
<i>PT</i>	= Pressure Transducer
<i>PWT</i>	= Plasma Wind Tunnel
<i>SH</i>	= Sensor Head
<i>SU</i>	= Sensor Unit
<i>SLBM</i>	= Submarine Launched Ballistic Missile
<i>SWBLI</i>	= Shock Wave Boundary Layer Interaction
<i>S/W</i>	= Software
<i>TAS-I</i>	= Thales Alenia Space Italy
<i>TPS</i>	= Thermal Protection System
<i>WT</i>	= Wind Tunnel

¹ System Engineer at ESA, Francesco.Ratti@esa.int, AIAA Member

² Project Manager at ESA, Jose.Gavira.Izquierdo@esa.int, AIAA Member

³ System Manager at TAS-I, Gianluca.Passarelli@thalesaleniaspace.com, AIAA Member

⁴ Project Manager at TAS-I, Federico.Massobrio@thalesaleniaspace.com, AIAA Member

I. Introduction

The aerodynamic know-how needed to design and safely fly future hypersonic space vehicles is obtained via computational predictions (CFD), ground-based experimental simulations (WT), and flight extrapolation methodologies. The best approach to improve confidence in aerothermodynamics design tools is to validate them against flight experiments. Flight experimentation is however limited due to high costs and risks associated to fly re-entry hypersonic vehicles.

Lessons learned from past European flight-test programmes, such as ESA Atmospheric Re-entry Demonstrator (ARD)¹, and development work on lifting-body vehicles such as the X38 crew-return vehicle² have underlined the need for more accurate and extensive hypersonic flight data. This is particularly the case for the characterization of hypersonic phenomena such high-temperature and chemistry effects, gas-surface interaction, catalysis and oxidation.

EXPERT is developed to provide the scientific community with quality data that can be used to improve tools for the design of hypersonic vehicles. EXPERT is classified as a flight test-bed to pursue the investigation of specific hypersonic phenomena and to investigate new technologies such as advanced TPS materials and sensors.

EXPERT is therefore a building block toward experimental vehicles and demonstrators (e.g. IXV) which aims to prove flight technologies in a reduced scale system to then pave the way to full operational system (e.g. ARV) designed to accomplish clearly defined missions (e.g. cargo and human transportation system).

EXPERT is therefore developed to benefit future atmospheric re-entry activities ranging from cargo to human orbital transportation systems as well as reusable launchers and scientific probes.

CLASS 1	
Full scale demonstration and qualification. Performance envelopes are gradually extended	
Example:	Shuttle, Buran, Apollo, ARD, X38, Hermes
In development:	ARV
Class 2	
Experimental vehicles for in-flight qualification of system and subsystems	
Example:	IRDT for inflatable systems, BOR4 and HYFLEX for TPS, BOR5 and ALFEX for GNC, etc..
In development:	IXV
Class 3	
In flight research for design tool/physical model validation and improvements	
Example:	Mika, Express, SHARP B1, B2 flights, HYSHOTs
In development:	EXPERT

Figure 1: Hypersonic vehicle classification

II. EXPERT mission overview



Figure 2: EXPERT trajectory

EXPERT will fly a suborbital ballistic trajectory from the Pacific Ocean to a landing site located on the peninsula of Kamchatka as shown in figure 2.

The re-entry speed selected at the entry gate of 100km altitude is 5 km/s. Such a speed is compatible with the conditions that can be achieved on ground facilities, allowing therefore extensive comparison between flight and ground data which is of primary importance to validate mathematical models and establish ground to flight extrapolations.

EXPERT will be launched with a Russian converted ICBM, Volna from a submarine. After the re-entry phase EXPERT will be slowed down using a 3 stage parachute system that will allow a landing speed lower than 10m/s. The recovery will be done via helicopters that will track the signal of an on board beacon. EXPERT is equipped with a crash proof and redundant memory unit in order to protect the data in case of a crash landing.

III. Overview of scientific experiments

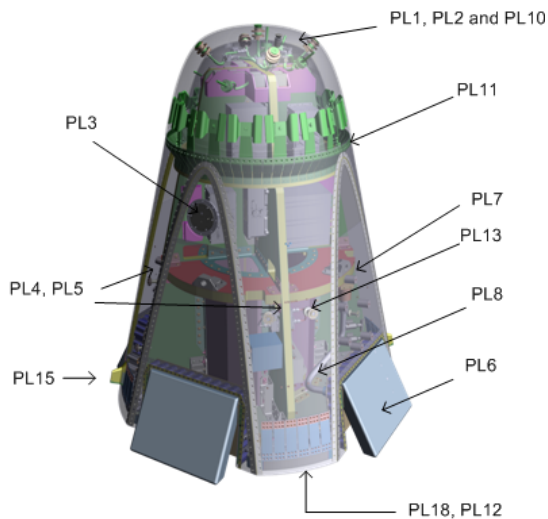


Figure 3: EXPERT Payloads

EXPERT contains a set of Payloads (PL) for a total of 14 experiments here listed:

- PL 1 – Flush Air Data System
- PL 2 – Nose Heating Experiment PYREX
- PL 3 – Catalytic Experiment
- PL 4 – Natural Transition Experiment
- PL 5 – Roughness Induced Transition
- PL 6 – SWBLI on the open flaps
- PL 7 – SWBLI upstream of open flaps
- PL 8 – IR Thermography
- PL 10 – Re-entry Spectrometer
- PL 11 – Junction Experiment
- PL 12 – Base Pressure and Heat Flux
- PL 13 – Skin Friction Sensors
- PL 15 – Sharp Hot Structures
- PL 18 – Intermetallic Tile

The payloads have been selected to form a complete and consistent set of experiments^{3,4,5,6}.

PL1 gathers flight data for the air free stream conditions in order to rebuild angle of attack and side slip angle of the vehicle during re-entry⁷. A total of 5 sensors are mounted directly on the nose.

PL2 measures the temperature of the ceramic nose in six different locations. Each of the sensor head carries a lens which focuses on an area of the rear part of the nose. The light intensity is transmitted to the lens system via a SiC tube and then via a fibre optics bundle to a photo sensor located in a dedicated housing on the cold structure. The system is able to measure temperatures of up to 2000 °C,⁸.

The objective of PL3 is to measure the rear side temperature of selected material samples with known catalytic behaviour in order to derive the property of the gas flow and the dissociation status.

EXPERT presents two experiments about the transition from laminar to turbulent on two opposite side of the metallic TPS. PL4 determines the condition at which natural transition begins on the TPS⁹, while PL5 presents a roughness element which is designed to trigger transition at a certain Mach number¹⁰.

The aim of the PL6 experiment is to measure the pressure and surface temperature of the flap in order to detect the region of flow reattachment. It also instruments the cavity for determination of the heat flux due to re-radiative effects from the flap¹¹.

PL7 targets the study of the flow separation upstream of the open flap which is induced by the interaction between the shock wave and the boundary layer (SWBLI). Measurements of pressure, temperature and heat flux are performed to assess the three dimensional viscous interactions between shock wave and boundary layer¹². A combined test campaign of PL6 and PL7 has been performed in the large scale arc-jet plasma wind tunnel facility Scirocco which reproduced the same condition of EXPERT for one point on the trajectory at high altitude.

PL8 measures the temperature distribution on the inner surface of one of the four open flaps. The temperature of the flap and the use of computational fluid dynamics predictions will allow characterizing the behavior of the reattachment area on the upper side of the flap¹³.

PL10 RESPECT aims at obtaining information about the plasma state in the post shock regime by measuring the spectrally resolved radiation onto the surface¹⁴.

PL11 measures the catalytic effect at the joint between the ceramic nose and the metallic TPS¹⁵.

PL12 measures the pressure and the heat flux characteristic on the base of the vehicle.

PL13 measures the absolute and differential pressure and the calorimeter temperature for a slip-flow regime in the free molecular region and for skin friction in the continuum region.

PL15 is an advanced ultra high temperature ceramic winglet¹⁶.

PL18 is a intermetallic tile which will be integrated in the bottom panel of the vehicle where it will reach temperatures close to 650 °C.

IV. Aerothermodynamics environment

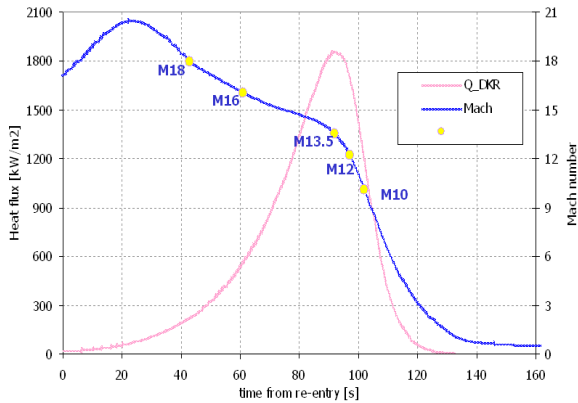


Figure 4: Mach number and heat flux evolution during re-entry

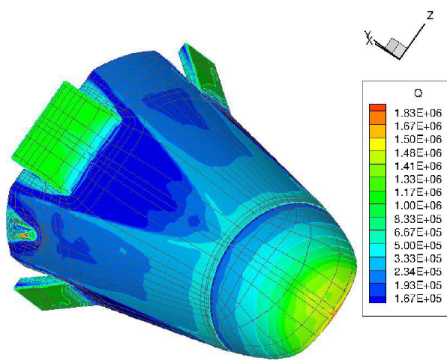


Figure 5: Heat distribution at peak heating

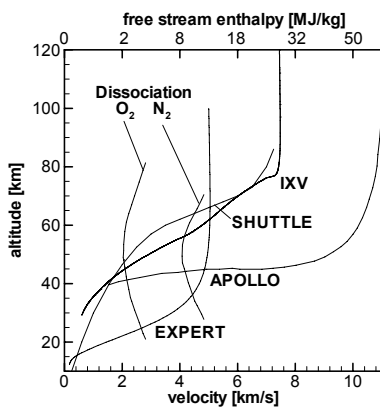


Figure 6: EXPERT dissociation in comparison with IXV and US Shuttle trajectories

EXPERT is injected with a velocity of 5km/s at the entry gate which is defined at an altitude of 100 km. In this initial condition the flight path angle is -5.5 deg. The EXPERT flight will last 140 seconds before the drogue parachute is opened. The evolution of the Mach number is shown in figure 4.

The shape of EXPERT and the location of the center of gravity has been chosen such that EXPERT is inherently stable in order to maintain a small angle of attack (AoA), lower than 3 deg, in the experimental phase and up till the last portion of flight, till M=2. At such Mach number it is expected that the AoA will tend to diverge. The onset of the instability drives the triggering of the drogue parachute.

Extensive aerothermodynamics simulations^{17, 18} and wind tunnel tests have been performed to characterize the aerodynamic behavior in the different regions of the atmosphere: free molecular flow, transitional and continuum regime. This led to the compilation of an aerothermodynamics database¹⁹. Bridging functions have been used to compute the coefficients in the transitional region. Such values have been also cross checked with DSMC simulations²⁰.

The maximum heat flux is expected to happen on the stagnation point which is located on the nose. The maximum heat flux is at M=13.5 and will be at max 2MW/m². The total heat load is expected to be lower than 70 MJ/m². Figure 5 shows the heat distribution at peak heating.

The regions which will be more heated will be the nose, the flaps which are located in the lower part of EXPERT in the region of flow reattachment after the boundary layer separation which happens before the flap. The area across the junction will see a local increase of heating due to the different catalytic property of the materials.

Figure 6 shows the expected molecular dissociation. Compared to vehicles with higher initial velocity, EXPERT will encounter Oxygen dissociation and also some Nitrogen dissociation. The interaction between the plasma and the material surface is subject of investigation by the many experiments (e.g. spectrometer).

EXPERT will address the possible active oxidation onset on the surface of the CMC nose. An extensive test campaign²¹ has been performed to characterize the behavior of the nose material at different heat fluxes and pressure conditions leading to the conclusion that the nose will encounter a region of possible active oxidation for a very limited portion of the flight. This is compatible with the nose and vehicle design.

V. Mechanical design and architecture

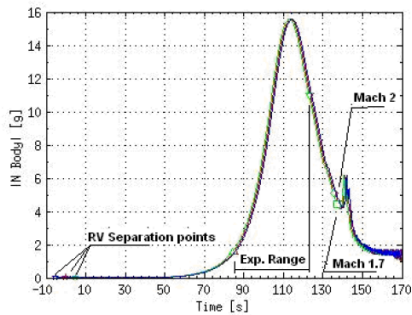


Figure 7: EXPERT deceleration bell

the volume between the second stage tank and EXPERT, followed by rapid depressurization. The pressure wave of 0.5×10^5 Pa travels at 500 m/s and acts for 0.2 ms. The acoustic load of 170 dB occurs for 0.05 seconds and the rapid pressure drop is from 0.6×10^5 Pa to approximately zero in 0.1 seconds. In addition to the low frequency shock event, EXPERT experiences high frequency shock loads due to the pyrobolts at separation from the 3rd stage.

The VOLNA launcher imposes first natural frequencies of 20 and 35 Hz for the payload in lateral and axial axes respectively. The Quasi-Static Loads (QSL) for Volna is 8 g longitudinal and ± 2 g lateral.

In order to cope with the high shock loads at stage separation some avionic equipments like the data handling, power supply and vehicle memory units have been mounted on dedicated anti-vibration mounts to reduce the mechanical environment.

The main drivers for the mechanical design are the loads during launch and the deceleration due to the aerodynamic drag and parachute opening which will be experienced during re-entry. Figure 7 shows the deceleration peak which is expected to be at max 16gs. As described in more details in ²² the VOLNA launcher poses challenges compared with conventional spacecraft launchers such as Ariane 5 and VEGA. EXPERT is housed inside the second stage tank, in an upside down configuration with the nose pointing downwards, as shown in figure 8 (left side).

At 2nd/3rd stage separation the pyrocord is detonated separating the two stages and exposing the payload to the surrounding environment. Figure 8 (right side) shows the separation event inside a drop tower.

The resulting loads consist of a mechanical shock load acting almost simultaneously with a shock wave and acoustic load inside

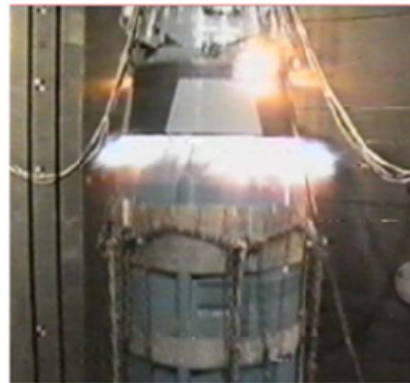
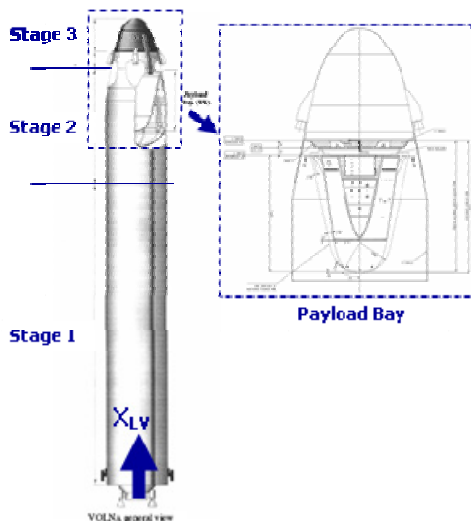


Figure 8: EXPERT inside VOLNA second stage tank (left) and VOLNA 2nd/3rd stage separation event in a drop tower in Russia (right), courtesy of Makeyev Design Bureau, Miass, Russia

The mechanical architecture of EXPERT includes an internal metallic cold structure and an external hot structure and thermal protection system (TPS).

The cold structure is made of Aluminium sandwich panels assembled in a symmetric tower shape. It is the primary structural support for payloads, service equipment, parachute system and TPS. The cold structure has been designed to satisfy the stiffness requirement of the launcher.

The TPS is defined by three main elements: a C/SiC nose cap, an outer metallic shell having conical and flat surfaces and 4 ceramic flaps, which are hosting several experiments. A Rear Thermal External Insulation is foreseen in order to protect the rear plate.

The following sub-systems are accommodated on the cold structure: payload electronics boxes, 2 batteries, the Power Control and Distribution Unit (PCDU), the Data Handling Unit (DHU), the Vehicle Memory Unit (VMU), the beacon, the Inertial Measurement Unit (IMU) and the Descent and Landing System (DLS).

The Expert capsule at launch is mated to the third stage of Volna via an adapter ring resulting suspended upside-down w.r.t. the positive launcher direction. The parachute bay is accomplished in the central volume of the capsule.

The hot structure is attached to the cold Structure through four brackets, mounted at bottom panel level, in order to minimize the thermal paths between external and internal structures. The hot structure is made of oxide dispersed strengthened alloy PM1000.

The memory of the vehicle is redundant and crash resistant to protect the data in the event of a hard landing.

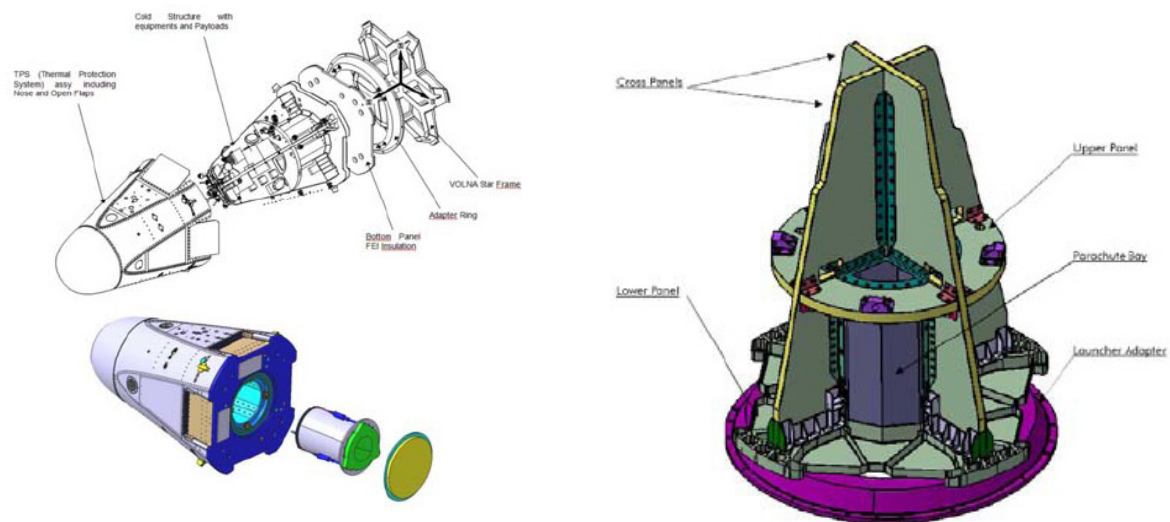


Figure 9: EXPERT capsule configuration (left), cold structure (right)

VI. Thermal design

The external surface of the TPS is subjected to a transient heat flux during the atmospheric re-entry. The heat flux profile is computed using Computational Fluid Dynamics (CFD) methods. The computed heat flux is then applied to the outer surface of the TPS. The application of the aero-thermal load map allows the computation of the wall temperatures. In an iterative process the computed wall temperatures are then used in the next iteration of CFD calculation. This allows a coupled computation between CFD and thermal model of the structure taking into account the heat sink effect of the TPS and the heat redistribution inside the vehicle during the re-entry flight.

Some assumptions are done about catalycity of materials. The most conservative heat flux on the metallic TPS occurs when the nose is considered not catalytic and the metallic TPS is fully catalytic, while for the nose the most conservative case is to consider it partially catalytic. The influence of roughness elements, winglet and sensor heads on the TPS has also been taken into consideration when computing the heat fluxes.

A thermal mathematical model of the cold structure which includes all the avionic sub-systems has been built and the maximum temperature of the equipments has been computed to verify that the avionic boxes and the sensor units are within the design margin.

The maximum temperature of the equipments occurs during the post landing phase when the heat is diffused inside the structure. Particular care has been taken in the design of the thermal control system to maintain the beacon and antenna within their operational limits and to protect the VMU from overheating.

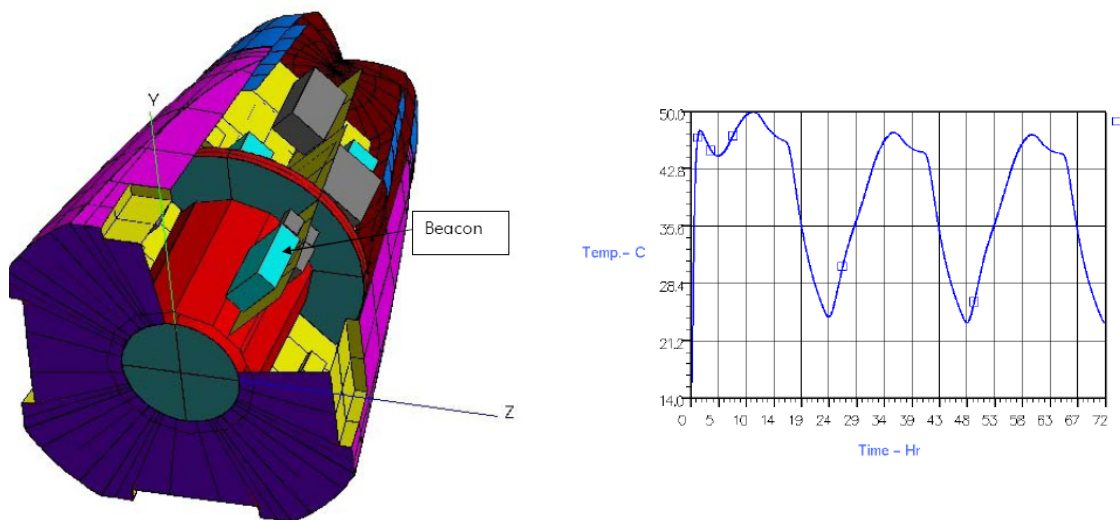


Figure 10: Thermal model (left) and evolution of beacon temperature till end of post- landing phase (right)

VII. Avionics and software

The Avionics system controls and monitors EXPERT during the mission. It also collects the mission data and records it on on-board redundant memory units. A schematic is shown in figure 11.

EXPERT mission is managed on the basis of pre-stored timeline and sequential key-events. Some automatic corrective actions have been implemented on-board to cope with possible malfunction or off-nominal events.

The avionics architecture includes the following main functions, on-ground tracking support, on-board data handling, electrical power supply distribution and control.

The EXPERT data handling subsystem provides the timer sequence reference and issues the command for the mission profile events. It is also able to store on the memory the EXPERT housekeeping payload and system data, since the de-orbiting until the EXPERT earth touch down. Other main functions are the equipments power on/off control, the payloads experiment data acquisition and storage, and the parachute pyro-commands generation.

The EXPERT on-board software embeds a set of Computer Software Configuration Items (CSCI's) supporting the implementation of the EXPERT automated control and monitoring functions. The following macro-functions are executed by the software: autonomous activation and modes co-ordination, separation monitoring, mission phase determination, polling of the on-board units, formatting and storage of the gathered data, distribute and control power to on-board units, control of the parachute opening process, ground test support and verification, acceleration and angular rate monitoring via the IMU.

The electrical power sub-system distributes the power provided by the batteries via the power control and distribution units to all the sub-systems of the vehicle and to the payloads. Additional cells have been foreseen inside each battery for redundancy. A stand-alone, low voltage battery is dedicated to the beacon unit which is functioning after landing for up till 3 days.

The power and data handling systems are switched off during the travel in the submarine and during the launch phase and after the experimental phase.

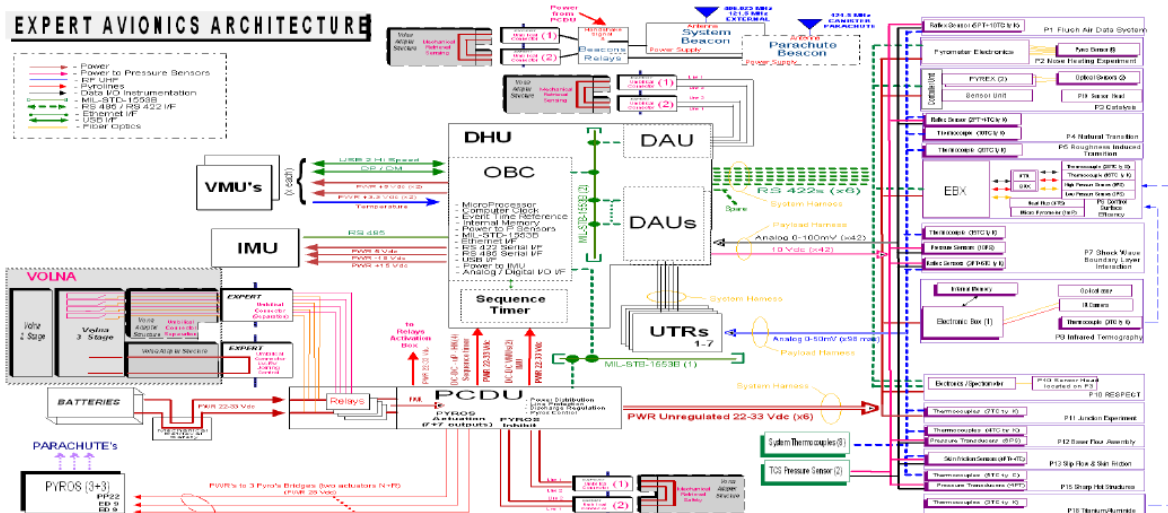


Figure 11: avionics architecture

VIII. Descent and landing system

A three stage Descent and Landing System (DLS) has been selected as baseline.

The system includes an auxiliary parachute (AP) that provides the extraction of the drogue parachute (DP). The DP decelerates the vehicle through the transonic region up to the main parachute (MP) actuation entry conditions. The DP provides also the extraction of the main canopy. The MP provides the landing conditions to reach a landing speed lower than 10m/sec.

When the vehicle reaches the nominal deployment conditions, pyropushers are activated by a dedicated signal and the parachute bay cover is jettisoned. The cover extracts the auxiliary parachute (AP). When the AP is completely inflated, the drag provided by the canopy is sufficient to extract the bag of the drogue parachute. The DP is first deployed in a reefed configuration. The activation of a pyrotechnic device that will cut the reefing line is activated when the drogue parachute lines are stretched. The vehicle continues the descent trajectory under the DP up to the time selected for the deployment of the MP at an altitude of approx 5km.

The pyrocutters are activated by a dedicated signal provided at system level. The cutting of the drogue parachute bridles takes place after the deployment of the main parachute bag that is connected by a dedicated line to the DP bridle.

The extraction of the MP is guaranteed by the drag of the DP. The space vehicle completes the descent trajectory under the main parachute. The main parachute is not released after the ground impact due to the fact that one of the beacon antennas is linked to the MP bridle and also due to the fact that the local wind speed is predicted not high enough to drag the re-entry vehicle along the landing site.

A sketch of the proposed parachute system architecture is shown in the following picture.

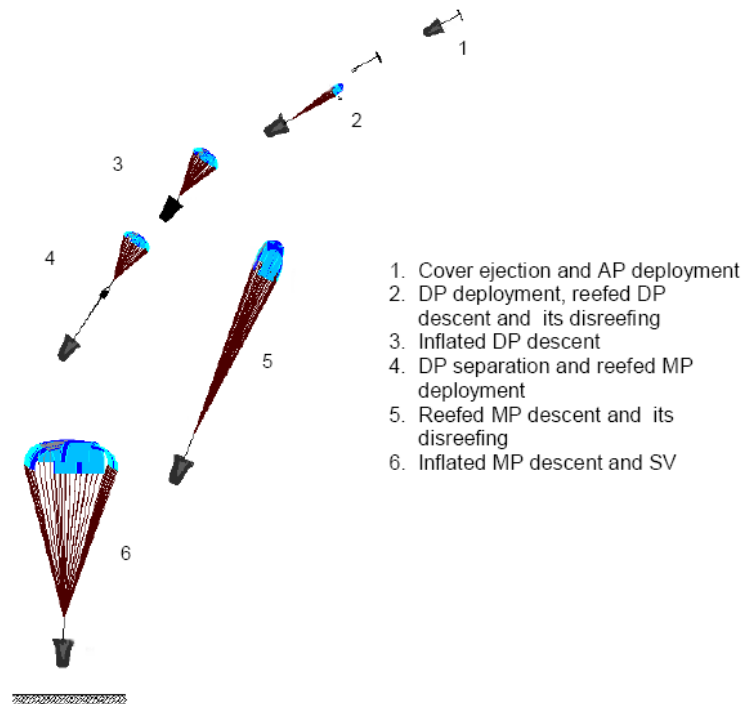


Figure 12: DLS architecture

IX. Manufacturing and AIT

The fourteen payloads underwent an extensive qualification test campaign in 2008, involving over 70 individual tests. All payloads passed their qualification successfully, despite some issues encountered during testing. Some modification were needed for one pyrometer and spectrometer, a reset occurred during shock testing and the electronic boards of one experiment had to be reinforced to comply with the mechanical environment which is very stringent. The shock test of the nose was particularly impressive and was performed mounting the 50 kg nose assembly on a plate and impacted with a tuned projectile. That way an input load of 1000 g at 1 kHz was achieved, with minimal cross coupling.

Extensive plasma wind tunnel testing was performed to verify the payload sensors and TPS materials for the re-entry environment. A test to represent one point of the trajectory at high altitude was performed in Scirocco facility as well as a test of the winglet at maximum heat flux. The qualification flap, infrared camera and winglet will be tested in the Scirocco plasma wind tunnel within 2009.

EXPERT vehicle is based on a Proto Flight model (PFM) philosophy to reduce the cost.

All equipments and payloads are verified at sub-system level and then EXPERT is integrated in the flight configuration. Environmental tests at system level are performed to verify that EXPERT complies with the mechanical environment. The system level mechanical testing will consist of a sine vibration and a random vibration test, as well as an additional test necessary to qualify the low frequency shock load. The high frequency shock loads will be verified during the separation test on a representative mass dummy. A transmissibility test will then be performed on the EXPERT PFM to verify the shock levels at all important interfaces within the vehicle. The results will be used to verify the specifications of the vehicle equipment, payloads, nose and flaps, which were derived by shock zoning and used for the qualification tests at sub-system level. The transmissibility test will use pyrohammers specifically designed to reproduce point shock sources with good repeatability.

An extensive functional campaign is foreseen at the beginning of the AIT campaign using a functional validation facility to verify the software functionalities and the communication between subsystem and data handling.

The parachute tests include mock-up tests, static strength tests, extraction tests, main parachute flight tests (subsonic parachute) and functional tests.

The VMU will be tested for landing impact in off-nominal conditions as well, in order to verify that the housing and crash protection is robust enough to prevent damage to the memory in case of parachute failure.

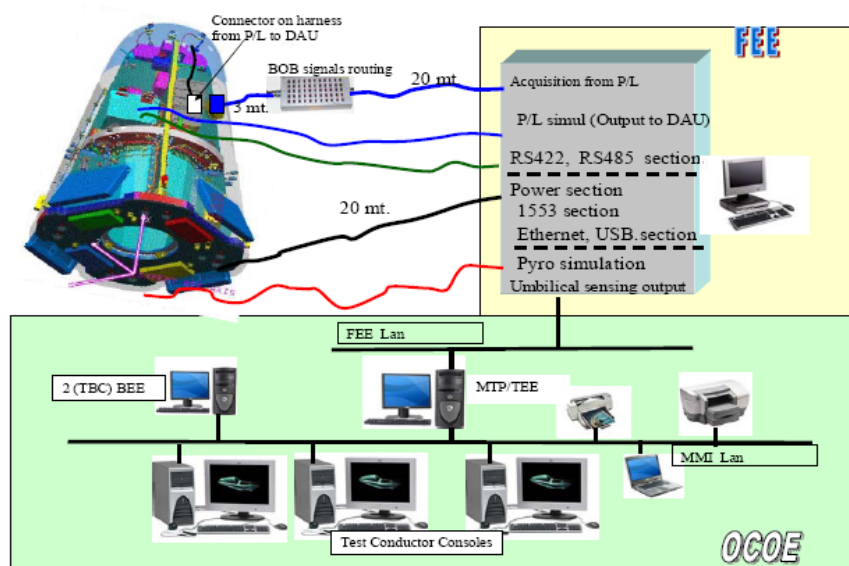


Figure 13: EXPERT Electrical ground support configuration

X. Conclusion

All the EXPERT Payloads have been successfully qualified for the launch environment and for the re-entry conditions. They are expected to be ready to be shipped at the beginning of 2010 for integration into the EXPERT vehicle.

The design activities of the vehicle have been concluded with a successful system CDR in 2009 and the manufacturing activities for all the sub-systems are on-going. The system level tests are expected to start in 2010, targeting then the earliest launch date compatible with the constraints imposed by the VOLNA launcher and by the weather condition of the landing site.

The flight data acquired by EXPERT will be distributed to several European Institutes and Industries and is expected to bring a much needed boost to the European competence in the strategic field of re-entry.

Acknowledgments

The authors wish to thank all the people who are working on the EXPERT project from Industries and Institutes, thanks to their dedication and professionalism EXPERT project has been made possible.

References

- ¹ A. Thirkettle, M. Steinkopf, and E. Gabriel, "The Mission and Post-Flight Analysis of the Atmospheric Re-Entry Demonstrator", ESA Bulletin 109, February 2002
- ² E.D. Graf: "The X-38 and Crew Return Vehicle Programmes", ESA Bulletin 101, February 2000
- ³ F. Ratti et al: "Payloads on board the European Experimental Re-entry test bed: status of development and future activities", IAC-07-D2.6
- ⁴ F. Ratti et al: "European Experimental Re-entry test-bed EXPERT: qualification of payloads for flight", 6th European Aerothermodynamics Symposium, Paris, France, 2008
- ⁵ A. Del Vecchio , J. Thomel et al.: "EXPERT – The ESA Experimental Re-Entry Vehicle: Overview of the Experiments and Payloads qualified and accepted for the flight", 39th AIAA Fluid Dynamics Conference, June, 2009, San Antonio, USA
- ⁶ F. Cipollini et al, "European Activities on Advanced Flight Measurement Techniques for Hypersonic Space Vehicles", AIAA 2006-3832, 2006.
- ⁷ J. Häuser et al. "Inverse problem solution for determining spacecraft orientation from pressure measurements", 5th European Symposium on Aerothermodynamics for Space Vehicles, November 2004, Cologne, Germany
- ⁸ G. Herdrich et al: "Advanced Pyrometric In-flight Sensor Systems for EXPERT", 4th International Symposium Atmospheric Re-entry Vehicles and Systems, March 2005, Arcachon, France
- ⁹ R. Donelli et al.: "Design of a Laminar-Turbulent Transition Flight Experiment", 13th International Space Planes and Hypersonics Systems and Technologies Conference, May 2005, Capua, Italy
- ¹⁰ S. Tirtey et al.: "In-Flight Hypersonic Roughness Induced Transition Experiment", 46th AIAA Aerospace Sciences Meeting, January 2008, Reno, Nevada, USA
- ¹¹ A. Gulhan et al.: "EXPERT Open Flap Instrumentation and its Ground Qualification", 6th European Aerothermodynamics Symposium, Paris, France, 2008

- ¹² M. Di Clemente et al.: “Shock Wave Boundary Layer Interaction in EXPERT Flight Conditions and Scirocco PWT” 13th International Space Planes and Hypersonics Systems and Technologies Conference May 2005, Capua, Italy
- ¹³ C. Pereira et al.: “Inverse Temperature Mapping of Re-Entry Vehicle Control Surfaces Using Infrared Thermography”, 6th European Aerothermodynamics Symposium, Paris, France, 2008
- ¹⁴ S. Lein et al.: “Development of the re-entry spectrometer RESPECT for the ESA capsule EXPERT”, Acta Astronautica, Volume 64, Issue 4, February 2009
- ¹⁵ J. Thoemel et al.: “Design of a Catalysis In-Flight Experiment”, 46th AIAA Aerospace Sciences Meeting, January 2008, Reno, Nevada, USA
- ¹⁶ R. Gardi et al.: “Thermostuctural Design of a Flying Winglet Experimental Structure for the EXPERT Re-entry Test”, Journal of Heat Transfer, July 2009, Volume 131, Issue 7
- ¹⁷ J. Muylaert et al.: “Aerothermodynamic Environment of EXPERT and Flight Measurement Technique Integration”, IAC-05-2363, 2005.
- ¹⁸ H. Ottens et al. : “Aerothermodynamic Flight Measurement Techniques and Environment Issues of EXPERT”, IPPW-3, Anavysos, 2005
- ¹⁹ A. Schettino et al.: “Aerodynamic and aerothermodynamic data base of Expert capsule”, West-East High Speed Flow Conference, November 2007, Moscow, Russia
- ²⁰ P.V. Vashchenkov and M.S. Ivanov: “Numerical analysis of high altitude aerothermodynamics of Expert Re-entry vehicle” , Institute of Theoretical and Applied Mechanics SB RAS, ICMAR, July 2002, Novosibirsk, Russia
- ²¹ T. Reimer, et al.: “Testing of EXPERT Nose Material and Sensor Heads in the DLR ARCJET Facilities”, 6th European Aerothermodynamics Symposium, Paris, France, 2008
- ²² A. C. Thirkettle et al.: “Mechanical Design and Engineering of the European Experimental Re-entry test bed EXPERT”, 11th European Conference on spacecraft structures, materials and mechanical testing, September 2009, Toulouse, France