

## DESIGN OF THE IN-FLIGHT SENSOR SYSTEMS PYREX, PHLUX AND RESPECT FOR THE EUROPEAN CAPSULE EXPERT

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Three miniaturized flight instrumentations are developed at IRS for the European capsule EXPERT.

PYREX, a pyrometric entry experiment, measures rear side temperatures and heat fluxes on ceramic TPS. It has already been flown twice (EXPRESS, MIRKA). PYREX-KAT38 is a fully qualified six-channel measurement system and was intended to be operated aboard the X-38. A similar design is being further developed for temperature and heat flux measurements in the nose structure of the EXPERT capsule.

PHLUX (Sensor system for catalytic experiments) is based on the experiences with PYREX. It is a pyrometric sensor for catalytic heat flux measurements developed for the EXPERT capsule. Here, a probe with two sensors opposite each other has already been developed for ground tests by means of plasma wind tunnel experiments to qualify the sensor functionally and to investigate the catalytic behavior of surfaces. The flight experiment aims to estimate the dissociation degree during the entry using measured heat

fluxes on different catalytic surfaces. This information is important to understand the thermo-chemical interactions between plasma and TPS wall.

RESPECT is a spectrometer to be used to gain spectral data in the flow field around EXPERT during its entry. The main goal is to obtain more detailed information about the plasma state in the post shock regime of EXPERT by measuring the spectrally resolved radiation onto the surface. The measured data will provide a database consisting of radiation of multiple species. These data will be used for the comparison with results of numerical simulations using e.g. the IRS URANUS code for validation of aerothermodynamic models.

### Introduction

Upon entering the atmosphere of celestial bodies, spacecraft encounter gases at velocities of several km/s, thereby being subjected to great heat loads. This makes it necessary to use high temperature thermal protection systems (TPS) to prevent the destruction of the space

vehicle. The TPS as well as the plasma environment during the entry have to be investigated by means of computational and ground facility simulations. The four plasma wind tunnels PWK 1-4 which are in operation at IRS reproduce thermal, aerodynamic and chemical load on the surface of a space vehicle entering a celestial body's atmosphere. Various plasma generators have been developed: Magnetoplasmadynamic plasma generators are used to produce high enthalpy plasma flows. Thermal plasma generators produce moderate enthalpies at higher stagnation pressures to simulate the follow-on flight path. In addition, inductively heated plasma generators for basic material investigations (catalycity / plasma wall reaction processes) and the simulation of entry scenarios for celestial bodies such as Mars or Venus have been developed [1]. Numerous material test diagnostic tools e.g. mechanical probes for heat flux and Pitot pressure measurements and TPS material tests have been developed and qualified. Parallel to these methods, further intrusive probes like electrostatic probes and non-intrusive diagnostics were applied for detailed investigation of high enthalpy plasma flows and material behavior during the tests [2].

These tools provide an excellent opportunity to develop and qualify radiation-cooled materials for re-useable spacecraft and ablative material systems to be used for capsules and interplanetary probes. Additionally, they are much less expensive than space flights. Atmospheric entry mission phases encounter challenging problems, such as hypersonic aerothermodynamics and TPS performance of the spacecraft. Goals include managing the guidance navigation, control, landing technology and inflatable technologies such as ballutes that aim to keep vehicles in the atmosphere without landing [3]. The requirement to save mass and energy for planned interplanetary missions such as the Mars Society Archimedes Balloon Mission, the Mars Sample Return Mission, Mars Express or Ve-

nus Sample Return mission led to the need for new atmospheric manoeuvres like aerocapture, aero-breaking and hyperbolic entries e.g. for sample return missions [4-6]. All three of the mission phases are characterized by very high kinetic vehicle energies to be dissipated by the atmospheric manoeuvre. Actually, in this field no flight has been performed yet. But the importance of these manoeuvres and the need to increase the knowledge of the required TPS designs and the TPS behavior during such mission phases point out the need for ground testing facilities [7, 8], numerical codes and, in particular, flight experiments as the aerothermodynamic and aerochemical problems can not be completely solved by ground tests and the supplementary computer simulations. The high-temperature non-equilibrium, the gaskinetic gas-wall interactions (catalycity, rarefaction effects, turbulent flow) and gap flows between flaps and TPS components in the TPS structure are fields where ground testing and CFD calculations cannot fully replace flight experiments. Concepts of such flight experiments require experience and the ability of feasibility analysis using both analytical tools, which can often be used in simplified versions, and testing facilities to come up with overall information on the abilities and design steps needed for the successful experiment. As a result of the experience within the plasma diagnostic tool development and the plasma wind tunnel data base acquired during the last 20 years, flight experiments like the PYrometric Entry Experiment PYREX (capsules EXPRESS and MIRKA) and HEATIN (HEATshield INSTRumentation) on MIRKA have been developed at IRS, qualified and successfully flown [9]. Flight experiments such as PYREX on HOPE-X [9] and COMPARE (COMBined Planetary entry And trajectory Rebuilding Experiment), an experiment where a radiometric sensor, a pyrometric sensor and a pressure sensor are combined [9], are in the conceptual phase.

The MIRKA mission profile is shown in Fig. 1; a scheme of the capsule's instrumentation is depicted in Fig. 2.

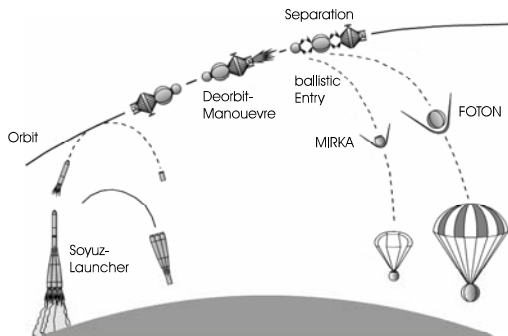


Fig. 1. Diagram of MIRKA mission, flown in 1997

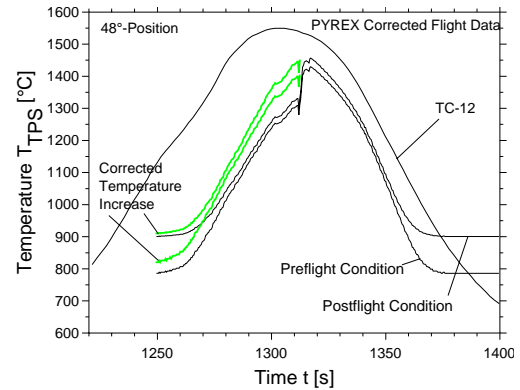


Fig 3. Measured data of the PYREX-MIRKA 48° sensor and corresponding HEATIN TC 12.

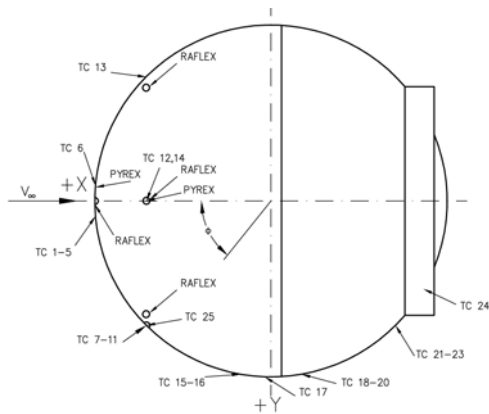


Fig 2. View of the Sensors along the MIRKA countour

Fig. 3 shows some results for PYREX-MIRKA and HEATIN measured during re-entry. After dismantling the PYREX 48° sensor (see Fig. 2, sensor related to TC 12, TC 14 and one of the RAFLEX sensors) minor pollution was found in the optical path. This pollution led to a decrease of measured radiance intensity which resulted in lower temperatures. Hence, the photodiode current and the temperature for a given calibration were recalculated as a function of the aperture diameter [10]. For this an iterative calculation was used with a decreasing SiC tube aperture until a smooth transition without the sudden increase was reached (Fig. 3).

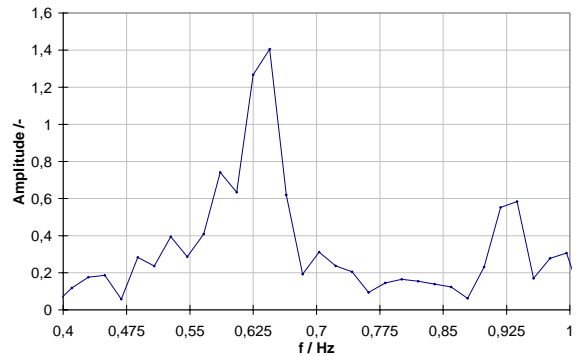


Fig. 4. MIRKA Capsule Oscillation Frequencies (PYREX measurement)

In Fig. 4 the oscillation frequencies of the capsule are shown. These frequencies have been determined by a Fourier analysis of the PYREX data. Two dominating frequencies are depicted in the figure ( $f_1 \approx 0,64$ ,  $f_2 \approx 0,93$  Hz)). A comparison with measurements of other systems such as the MIREX shows that the frequencies correspond pretty well within a maximum deviation of 20 % [11]. Most likely this is due to structural effects such as the transient thermal behavior of the TPS.

In order to continue to increase the knowledge in the fields related to atmospheric manoeuvres and entries, data bases have to be created that combining both the existing 3-D calculations [12] and with obtained flight data. Experience in this field as well as feasible flight data are rare in the world. However, there are such successful data bases in the United States, but apart from few exceptions [13] public access is often difficult. Such information

mostly deals with the reusable launch vehicle technology (RLV) which is a major concern for a better understanding of the entry missions to Earth and for the aim goal to reduce payload transportation costs in the future. Within the program X-38, for example, about 40 international partners have been collaborating in order to develop, qualify and fly the X-38 vehicle, which was planned as a technology demonstrator for the Crew Return Vehicle (CRV) of the International Space Station (ISS). A set of about 1000 sensors were integrated to obtain a data base which will be combined with a numerical aerothermodynamic data base provided by the European partners [14].

Additionally, a lot of instrumentation has been contributed. The temperature measurement system PYREX-KAT38 (PYrometric Entry EXperiment), measuring the temperature distribution in the X-38 nose structure, was the contributed by of the Space Transportation Division of IRS [9].

Despite the cancellation of the X-38 program the technologies that were developed and designed will be used for the European EXPERT capsule program where three sub-orbital capsule flights using Russian Volna launchers will be performed [15]. The first flight is issued for 2007. At IRS three in-flight sensor systems are developed within the Phase B of the program.

### **EXPERT-Payload 2: PYREX (PYRometric RE-entry eXperiment)**

PYREX is a miniaturized pyrometer to measure rear side temperatures of ceramic thermal protection systems during entry. Two basic systems PYREX-E and PYREX-M have already been used for the EXPRESS and MIRKA missions. The success of these missions in terms of the high thermo-mechanical loads during the system tests and the flights, the functionality of both PYREX systems after the missions, the measured temperatures

and the short response time which allowed for the determination of rotational speed of MIRKA justify the statement that the PYREX-system is space qualified.

With the 6-channel PYREX-KAT38 system that was intended to be used for the X-38 an advanced measurement system capable to be integrated with respect to the vehicle's data analysis system is provided [9].

PYREX-EXPERT will deliver the temperature distribution and related temperature profiles of the EXPERT nose structure during entry. The results will enable the validation of the applied numerical codes and statements on the behavior of the TPS-materials during entry. Thermal effects resulting from manoeuvres e.g. rolling during the entry phase will be seen. A post-flight numerical analysis will deliver heat flux profiles.

In Fig. 5 a schematic view of the PYREX EXPERT system is shown. It consists of several subdevices. Each of the six sensor heads has a lens system to focus on the specified position on the C/C-SiC nose cone structure. The fibre optics are attached to the sensor heads and transmit the radiation to the sensor unit containing electronics. Data transfer, power and control signals are transmitted to the vehicle system. A portable computer, which can be switched to the sensor unit, enables preflight tests. Both EXPERT's power system and the data system are attached to the sensor unit. The sensor unit is equipped with an independent memory bank (flash disc).

Figure 6 depicts the proposed PYREX SH positions based on the present design contour of the EXPERT nose structure. SH 1 is placed in the vehicle axis region while the 5 other SHs are distributed spirally in order to obtain the maximum information with respect to the overall temperature and heat flux distribution. SH 6 is almost at the edge of the nose structure. Therefore, the system can be combined with the adjacent PHLUX sensors (see section below) in order to have a maximum information

e.g. by the performance of a relaxation experiment, see also ref. [15].

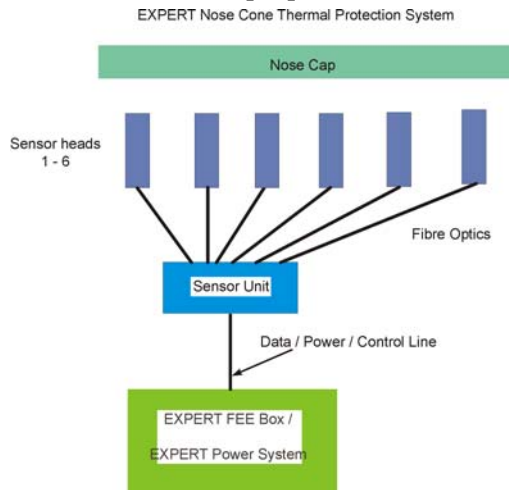


Fig. 5. Schematic view of PYREX EXPERT system

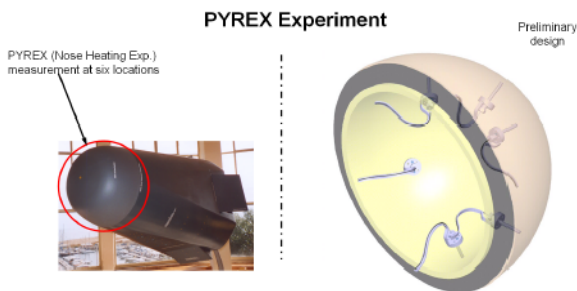


Fig. 6. Positions of the 6 PYREX sensors (SH 1-6) in EXPERT's nose structure; left image: plan view, right image: isometric view

*Sensor Heads (SH), Sensor Head Brackets and Fiber Optics (FO)*

The SHs are used to fix the lens systems with the attached FOs behind the nose TPS structure points to be measured and guarantee a precise adjustment to the measurement positions. Figure 7 shows a SH attached to the sub-structure of EXPERT behind the C/C-SiC structure of the nose cap. It consists of a SiC tube that provides the optical path, an inconel flange and the lens system made of sapphire. The SiC tube protects the lens system from pollution by dust particles. The distance between the tip of the SiC-tube and the TPS rear side is tbd. It is required in order to prevent the tube from touching the TPS. The mass of one SH is about 0.25 kg. Its diameter is

roughly 50 mm; its height is about 50 mm. A temperature resistant seal is attached to prevent hot gas flows through the SH. The lens system and the attached FOs can be easily removed from the SH, e.g. to check the transmission of the FOs, and can later be re-installed with a high reproducibility in regard to the optical adjustment.

The routing of the six fiber optics is a major concern as there is a minimum bend radius of about 70 mm. General damage caused by other systems or parts must be prevented. Therefore, each SH is equipped with a fiber optic bracket to prevent the fibers from being damaged (see Fig. 7, bracket mounted to SH).

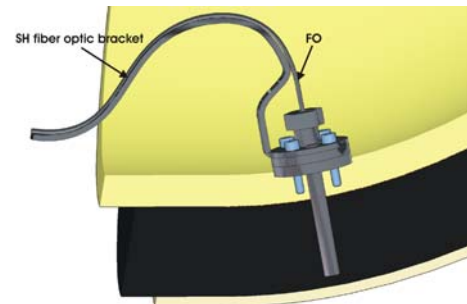


Fig. 7. Preliminary SH, integrated with FO and FO bracket

The radiation collected from the lens system of the SHs is carried through the bundled FOs to the photodiodes of the sensor unit (SU). The FOs can be dismantled on both sides: from the SU and the SHs. This fulfills an important requirement that the whole nose cone must be able to be dismantled from the remaining EXPERT vehicle without a lot of effort provided that there is accessibility.

*Sensor Unit (Electronic Housing) (SU)*

The SU is shown in Fig. 8. It contains the optical system in front of the six photodiodes. In addition, there are three high Ohmic resistors per channel, an AD-converter and the Peltier cooling system to keep the photodiodes at constant 293 K. This is necessary to reduce thermal noise during measurement.

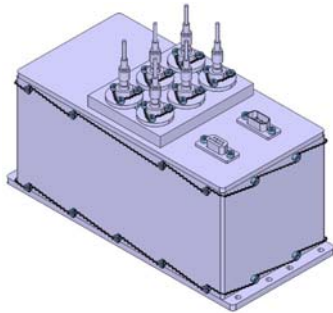


Fig. 8. PYREX / PHLUX EXPERT SU with FO adapters

A controller arranges internal data storage and output via RS422 interface to the vehicle data system. Power supply is guaranteed by integrated DC/DC converters powered by a voltage of 28 VDC. The mass of the SU is roughly 2.5 kg. Its size is about 100x130x200 mm. The housing consists of three mechanical parts: The bottom part serving as mechanical interface of the SU, the mid part, a modified standardized profile, and the top part or lid with FO adapters of the FOs and the filter systems.

The filter system is placed between the FOs and the photodiode. Individual wavelengths will be used to take into account the different expected temperature ranges for the locations of the SH (Fig. 6).

Data corrections, if necessary, are simplified. Such corrections can be required due to a soiled optical system or damage to the FOs. The Peltier system requires most of the power, which is less than 20 W. The SU includes a complete independent memory bank for data storage versus the PYREX EXPERT system time which is related to the mission time after the flight. This memory is preserved even in the case of a power failure.

#### *Performed test and qualification procedures*

In particular, the experiences with successfully flown flight instrumentations such as PYREX and HEATIN are the basis for the IRS experience in developing and qualifying in-flight measurement systems. Just briefly a typical list of qualification and approval tests as e.g. performed for the

as e.g. performed for the PYREX-KAT38 system is shown here [9]:

- Calibration and functional tests during and after system integration using a black body source
- Thermo-mechanical tests on sub system and system level e.g. test of PYREX-KAT38 as integrated in the X-38 TETRA nose structure.
- Engineering model and flight model qualification and approval using the IRS plasma wind tunnels.
- Mechanical shaker tests of electronics and sensors together with ongoing functional and calibration tests.
- Hardware / Software tests with respect to interface tests such as e.g. the data interface to a vehicle's data management system (e.g.: X-38).
- Flight model integration.
- Flight model functional tests.

Detailed information is given in ref. 3 and is based on experiences within former programs such as EXPRESS, MIRKA and X38. Of course, similar qualification procedures are planned to be applied to the EXPERT instrumentations PHLUX and RESPECT as well.

#### **EXPERT-Payload 3: PHLUX (Pyrometric Heat flux eXperiment)**

A further payload to be contributed for EXPERT is a catalytic experiment. It has the purpose to improve and support the chemical models used for the CFD calculations by flight data. The design of the system is based on the experiences with PYREX [9].

Since the heat flux on materials in dissociated air strongly depends on catalytic activities of the materials, comparison of two materials with different but known catalytic properties gives information about the recombination heat fluxes on these materials. From this information the dissociation degree of the re-entry plasma can be concluded employing both Goulard's theoretic investigations for stagnation

point heating [16] and numerical simulations using codes with surface reaction models as e.g. URANUS. In ref. 16 both recombination coefficients and emissivities for the PHLUX candidate materials measured in the inductively heated plasma wind tunnel PWK3 [7] using a pyrometric double probe are presented.

The system is able to record data independently from the board computer, only the power supply is required.

Figure 9 shows the PHLUX sensor as it was designed for the EXPERT capsule in combination with one of the RESPECT sensors (see also section for payload 10). No metallic TPS materials are desired around the sensor samples and flow ahead of them, because this can influence and adulterate the measured data.

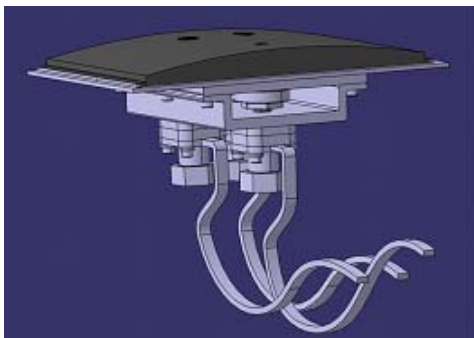


Fig. 9. PHLUX sensor head system, here coupled with one RESPECT sensor (see below).

The proposed experiment consists of two sensor heads with inserts of different materials, whose catalytic activities differ. Each of the sensor heads contains a pyrometric device for the temperature measurement of the rear side of the material samples.

The measured temperature history on the sensor materials is the basis for the calculation of the heat flux on the sensor. An optical path is needed through the thermal insulation between the relatively cold supporting structure of the vehicle TPS, where the optical sensors are mounted, and the rear side of the sensor sample, where the temperature is measured. The optical signal from the sensor rear side is led through the optical path (silicon

carbide tube) in the thermal insulation to the PYREX lens where it is focused. Furthermore, the fibre optic cable leads the optical signal to the conversion unit with the photo diodes. The converted (optical to electric) signal is recorded by the electronic unit of the three sensors. This unit has the same mechanical design as the PYREX SU, see fig. 8. With the help of calibration curves the recorded signal can be transformed to temperatures. Finally, the heat flux on the sensor samples can be calculated from the samples' temperature response during re-entry.

For the qualification and calibration of the sensor the plasma wind tunnels (PWT) at the Institut für Raumfahrtsysteme (IRS), University of Stuttgart will be used during the phases C and D of the EXPERT program. The PWTs allow for the simulation of the aerothermodynamic conditions around re-entry vehicles for the altitude range of 90 – 60 km [8]. In particular, the inductively driven PWK3 is being used for calibration purposes as this facility is able to generate high enthalpy oxygen, nitrogen and air plasmas.

In Fig. 10 one of the positions of the PHLUX sensors adjacent to the nose cone of the EXPERT capsule is presented. The first option allows gaining information about the relaxation along the vehicle and the second one allows estimation of the rotation of the capsule during the re-entry flight.

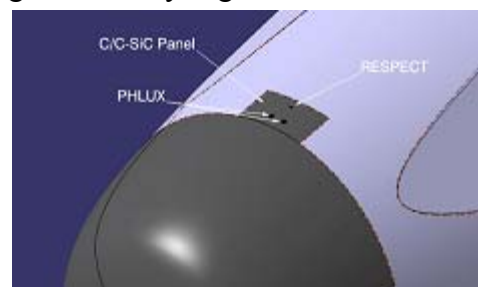


Fig. 10. PHLUX position (together with one of the RESPECT sensors)

*PHLUX Laboratory Model (PHLUX LM)*

To evaluate the functioning of the catalytic based sensor system PHLUX a bench-scale model was built and tested in the plasma wind tunnel PWK3 at IRS. The PWK3 is equipped with an inductively heated plasma generator (IPG3) and can be driven with such aggressive gases as oxygen or carbon dioxide [8]. The test condition that has been used for the PHLUX benchscale model is a oxygen condition with 3 g/s oxygen mass flow, ambient pressure of 40 Pa and about 110 kW electrical power on IPG3. The set up of the PHLUX bench-scale model is similar to EXPERT design. The sensor samples are embedded in a round plate made of sintered silicon carbide (SSiC). One sample is made of SSiC and the other one of PM1000, the latter of which is foreseen as the TPS-material for the EXPERT mission. The plate's rear side is isolated with high temperature insulator. The sensor specimens have been held by two ceramic tubes (see also Fig. 11). Behind the samples two PYREX systems are mounted on the aluminum plate. This assembly is placed in the water cooled probe made of brass.

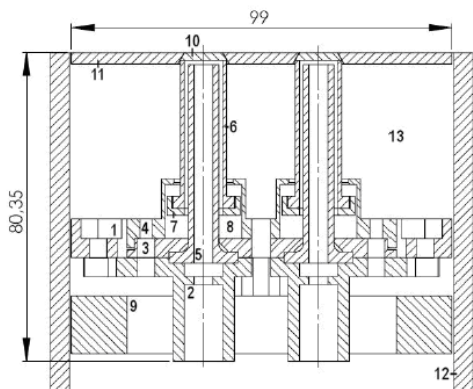


Fig. 11. Design of the PHLUX laboratory model

In Fig. 11 the PHLUX bench-scale model is shown in oxygen plasma flow. During the test the probe was moved within the plasma flow towards the plasma source and the temperature on the samples' rear side was recorded (see Fig. 12).

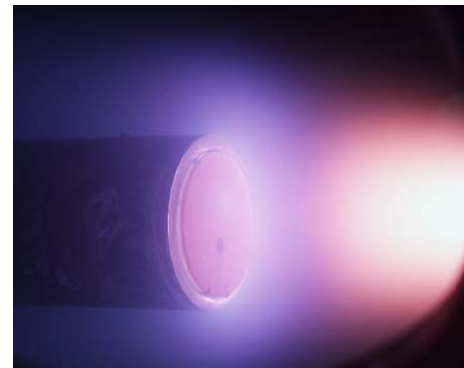


Fig. 12. PHLUX in oxygen plasma

From the recorded temperatures the heat fluxes and eventually the dissociation degree in plasma flow have been calculated. The estimation of the catalytic efficiency of both specimen materials using Goulard's theory are taken from Pidan [16]. Figure 14 shows the dissociation degrees in the oxygen plasma flow in the PWK3 as well as reference values determined by Herdrich [17]. A good agreement with the reference data can be reported whereas again Goulard's theory is applied for the calculation of the dissociation degrees.

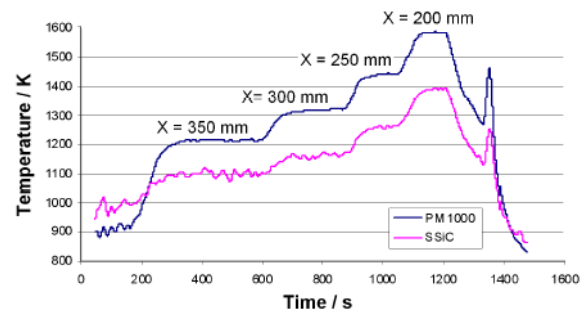


Fig. 13. Rear side temperature for both samples depending on distance X to the generator exit

Similar tests in nitrogen and air plasma with PHLUX bench-scale model are planned. To perform the planned experiments the catalytic efficiency of the used material for nitrogen and air are required. The determination of these values is in progress at IRS.

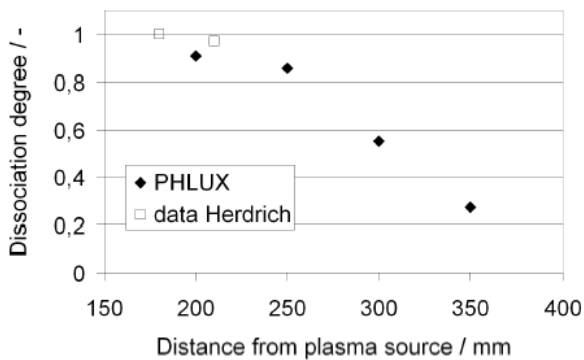


Fig. 14. Dissociation degrees measured using PHLUX in oxygen plasma

### EXPERT-Payload 10: Re-entry Spectrometer System RESPECT

The thermal and mechanical loads onto a space vehicle surface during re-entry are closely related to the plasma state and, therefore, to its chemical composition close to the wall. One way to gain the information about these quantities is given by emission spectroscopic measurements during re-entry flight. The main goal is to obtain more detailed information about the plasma state in the post shock regime of a re-entry vehicle by measuring the spectrally resolved radiation onto the surface. Due to the integrating character of the measurement, an extraction of temperatures or densities directly from the measured data is not possible. The obtained database will provide the radiation of multiple species for a comparison with the results of numerical simulations. The comparison will deliver the chemical composition spatially resolved and therefore help to validate the chemical models, which are implemented in the codes, if successful. If not, important information on necessary code improvements will be obtained.

#### Payload description

For EXPERT, two measurement positions on the vehicle are planned to enable a

monitoring of the spatial evolution of the plasma along the flow field. Each spectrometer will cover a minimal wavelength range from 200 nm to 800 nm with a resolution of about 0.5 nm. Therefore, the emission of relevant radiating air species such as  $N_2$ , NO, N, O and  $N_2^+$  will be obtained. Simulations of the expected spectrometer signal are under investigation. They will be used to decide whether the spectral range will be needed continuously or if a two channel version for each channel with restrictions in terms of spectral range but therefore improved resolution will be better suited. The use of a modified commercial spectrometer is planned. Different spectrometers are under consideration. At present, the S2000 model from Ocean Optics is favoured since it has been already used for space applications [18].

For a theoretical study of the spectrometer system, a virtual spectrometer is simulated using a numerical simulation of the flow field provided by the URANUS code [18] in combination with a spectral simulation of the emission with the plasma radiation database PARADE [18]. Two grid lines were chosen for a preliminary investigation of the integrated radiation along these lines, one located at the edge of the nose cap (sensor position 2) and one on the stagnation line.

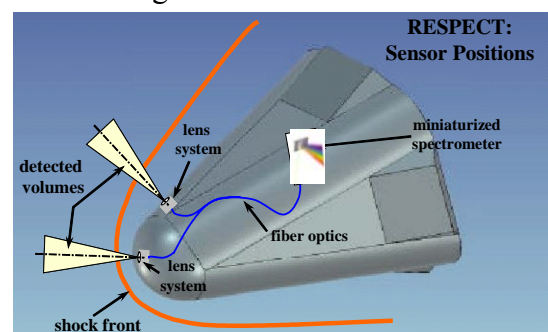


Fig. 15. Sensor positions of RESPECT on the EXPERT capsule.

Based on the numerically computed plasma state an emission spectrum is computed in each grid point of the two optical paths. Then, all spectra are integrated along the line of sight yielding in combination with a transfer function obtained from calibration measure-

ments and ray tracing computations the simulated spectrometer response. Simulations with the URANUS code were performed for altitudes of 70 km/s where strong radiation under non-equilibrium conditions is expected and of 35 km at the point of maximal heating for entry velocities of 5 km/s and 6 km/s according to the first two EXPERT flights. Additional simulation at higher altitudes performed with a DSMC code [18] at Alta S.p.A. – Space Division in Italy showed that detectable radiation is expected up to altitudes of about 80 km.

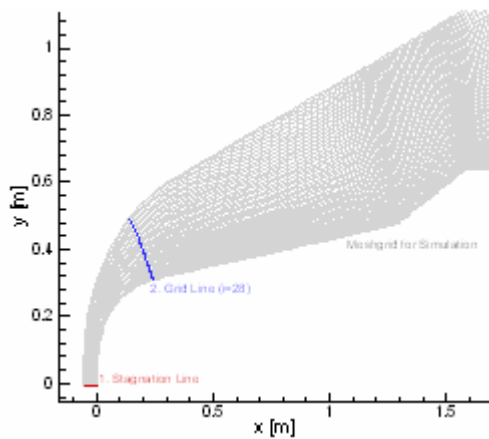


Fig. 16. Integration lines used for the preliminary simulations.

### Sensor Design

One important component of the spectrometer system is the coupling to the hot structure. A duct through the heat shield material with optical access to the surrounding plasma is necessary. Based on the experience with the PYREX-system [9] and in cooperation with DLR, a sensor head design for a coupling to the nose cap was developed [18]. Like the PYREX sensor head, the lens system is mounted to the cold structure with no rigid connection to the hot structure. In the hot structure, a conical SiC inlet with a 5 mm hole for optical access to the plasma is fixed from the inside by an SiC mount which contains a sapphire window (diameter 14 mm, thickness 3 mm) at a distance of 30 mm to the

outer surface. Sealing is realized by carbon sealings at both sides of the window. Between the hot structure mount and the ceramic tube that guides the light to the lens system, a 3 mm gap can compensate different thermal expansion of hot and cold structure.

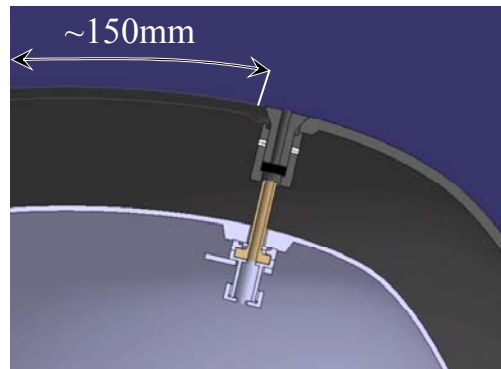


Fig. 17. RESPECT sensor head in the EXPERT nose cap

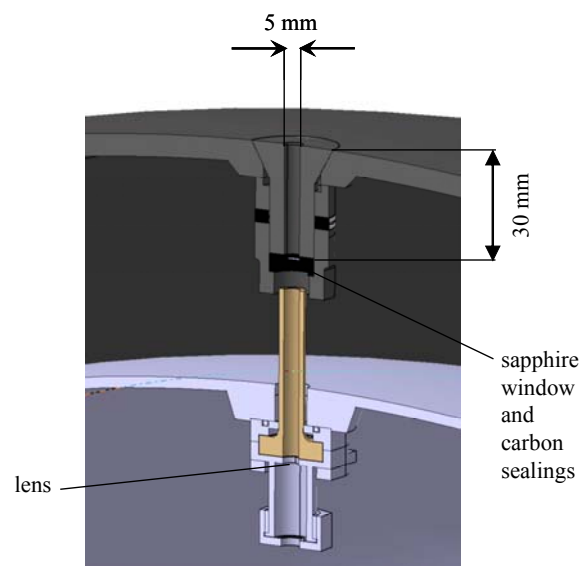


Fig. 18. Cross-sectional view the RESPECT sensor head in the EXPERT nose cap

During the design process, a thermal analysis of the sensor head design based on numerical simulation at the point of maximal heating for an entry velocity of 6 km/s was performed to assure that the critical parts will withstand the thermal loads. The results showed a maximal surface temperature of almost 2500 K [18]. The maximal temperature of the sapphire window is estimated to 1200 K which stays within the tolerable limits and does

not show remarkable gradients. In addition, the highest window temperatures are obtained at the end of the flight.

The optical signals are transferred to the spectrometers via fibre optics. The electronics are mounted in an electronic box similar to the PYREX electronic box which also includes a computer to control the spectrometers and a mass storage device for local storage of the measured data. The data transfer to the on board data handling system (OBDH) is done via RS 422 data link. Since the OBDH capabilities and the transfer rate of interface limit the data transfer rate, only every fourth spectrum is transferred to the OBDH but all measured data are stored locally for post flight analysis after recovery. Therefore, a measurement rate of 10 Hz is realized locally yielding a transfer rate to the OBDH of 2.5 Hz. All electronics are already flight qualified with the PYREX system.

*Simulation of spectrometer response*

A 2-D non-equilibrium simulation of the flow field around EXPERT vehicle was performed for altitudes of 70 km and 35 km (max heating point) using the URANUS code. Figure 19 shows the temperature distribution in the flow field for an entry velocity of 6 km/s at an altitude of 70 km.

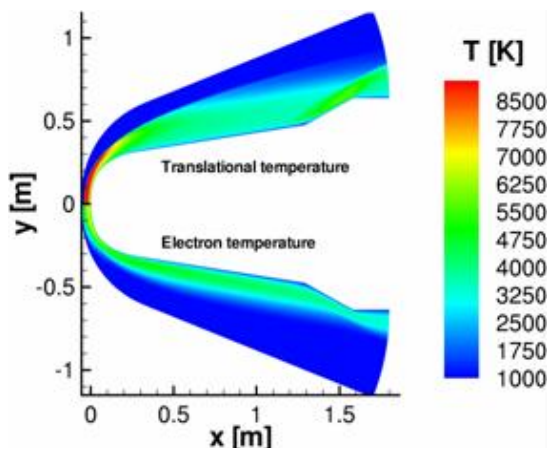


Fig. 19. Distribution of translational and electron temperature around the EXPERT vehicle

Particle number densities and temperatures were extracted along the integration

lines of the optical sensors. Figure 20 shows the particle number densities along the stagnation line for an entry velocity of 5 km/s at 70 km. In general, ion concentrations are negligible and atom concentrations are rather low. As expected, this trend intensifies for sensor position number 2 and weakens for higher entry velocity. At higher altitudes, remarkable differences between the different temperatures can be seen which diminish at lower altitudes with increasing pressure as the plasma approaches equilibrium conditions.

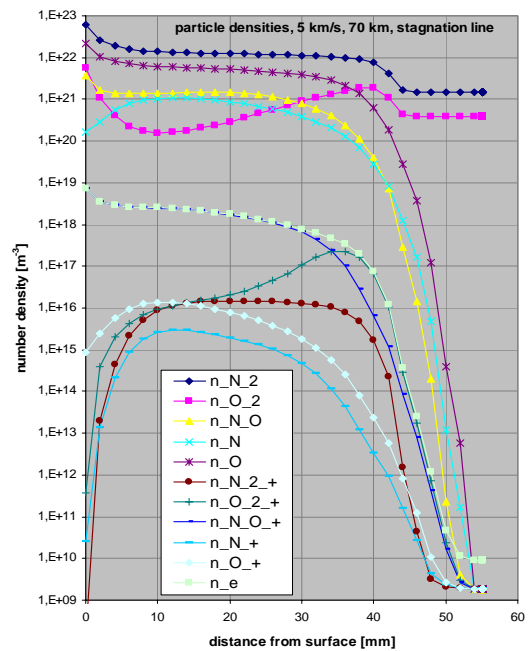


Fig. 20. Particle densities along the stagnation line for an entry velocity of 5 km/s at an altitude of 70 km

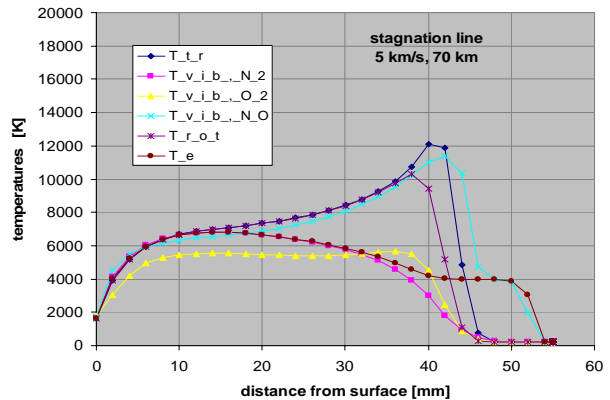


Fig. 21. Temperatures along the stagnation line for an entry velocity of 5 km/s at an altitude of 70 km

The parameters obtained from the numerical simulation were fed into PARADE to compute the spectrally resolved radiation for each available grid point.

Fig. 22 shows a 3-D diagram of the PARADE data along the stagnation line. The main statement to be extracted from this picture is that the radiation is very weak at the first few millimeters close to the surface. The main radiation is generated between 5 mm and 40 mm distance to the surface. This statement holds for all trajectory points under investigation.

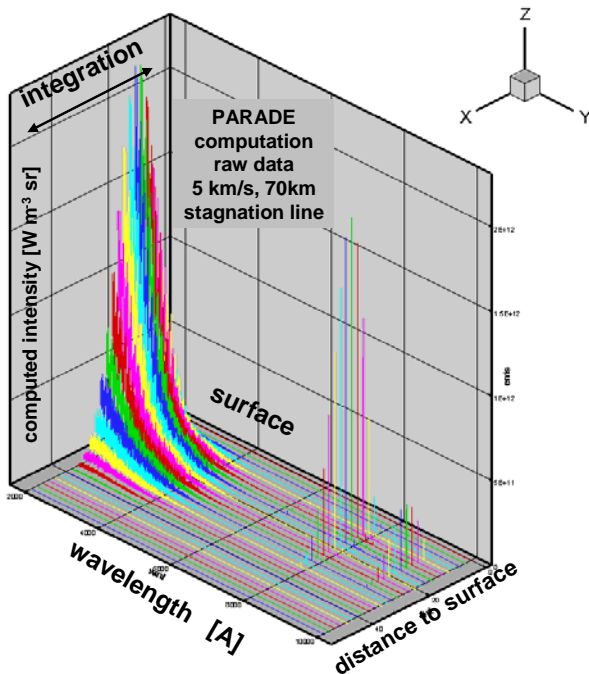


Fig. 22. 3-D diagram of the PARADE data along the stagnation line, 70 km, 6 km/s

For a valid simulation of the spectrometer signal which is needed to design the optical system knowledge of the absolute spectrometer sensitivity is necessary. To obtain the spectrometer response, the numerically simulated spectra must be converted to a spectrometer signal with the sensitivity determined from measurements with calibration lamps, namely a tungsten band lamp for the visible and infrared region and a deuterium lamp for the UV. For these measurements, the

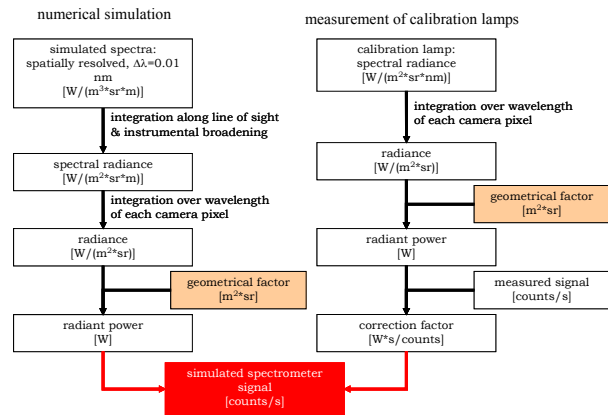


Fig. 23. Scheme of the data evaluation procedure to determine the spectrometer response

sensor head was substituted by a simplified set up with two apertures, and one quartz lens focussing the radiation on the fibre optics. A scheme of the data evaluation procedure is shown in Fig. 23.

Beside conventional intensity calibration in the measurements, the system response due to the radiation volume must be taken into account. This was done by ray tracing yielding a geometrical factor which captures this part of the sensitivity. The ray tracing computations include the influence of chromatic aberration which causes the position of the sharp image in the post shock layer to change with wavelength.

Implementing these calibration factors, a simulated signal in spectrometer counts was obtained. The maximum signal of 4000 counts must be obtained by a variation of the apertures sizes in the optical path and the acquisition time yielding a design optimization of the optical design. Figure 24 shows exemplarily the simulated spectrometer response at an altitude of 70 km with an entry velocity of 6 km/s including aperture sizes, acquisition times and species identification for both sensor positions.

Detailed analysis with respect to the experimental determination of the system's absolute sensitivity and simulated spectrometer responses are reported in [18].

## Conclusions

Three flight experiments are being developed at IRS for the entry capsule EXPERT.

For the nose heating experiment, a pyrometric system (PYREX) has been designed for measurement of heat shield temperature and heat flux distribution during reentry. An integration analysis for six sensor positions in the nose structure has been performed. The sensor design was developed. Test and qualification procedures have been issued. The design with particular respect to electronic housing and interfaces is chosen according to the already space qualified system for X-38. The electronic housing (sensor unit) and components are also to be used in slightly modified versions for both the PHLUX and RESPECT experiments.

For investigation of the plasma composition close to the vehicle surface, the PHLUX sensors based on pyrometric heat flux measurements onto surface elements with different but known catalytic efficiency have been designed. Appropriate sensor positions were investigated. Catalytic efficiencies of candidate materials have been determined [16]. Calibration procedures are described.

A re-entry spectrometer system (RESPECT) based on a commercially available miniaturized spectrometer (Ocean Optics

S2000) was designed and investigated theoretically and experimentally. For two sensor positions, one in the stagnation region and one adjacent to the nose cap, a spectrometer response was calculated theoretically based on numerical simulation of the flow field around the EXPERT vehicle with the flow field code URANUS at altitudes of 70 km and 35 km (maximum heating) for the entry velocities of the first two flights (5 km/s and 6 km/s). Different optical configurations have been considered. In collaboration with the DLR Stuttgart, the design for the sensor head and the duct through the heat shield in the nose region based on the already space qualified PYREX sensors was developed and preliminary thermal analysis was performed. Already performed absolute system sensitivity analysis done using a combination of ray tracing investigations and measurements of calibration lamps showed that detectable emission can be expected starting from altitudes of about 80 km, if the proposed measurement frequency of 10 Hz is maintained. Spectra will be recorded along the whole trajectory.

As soon as a frozen configuration for both vehicle and trajectory are available and the final sensor positions are fixed, the design will be reviewed. The upcoming activities will be to build engineering and flight models which will be functionally qualified in the IRS plasma

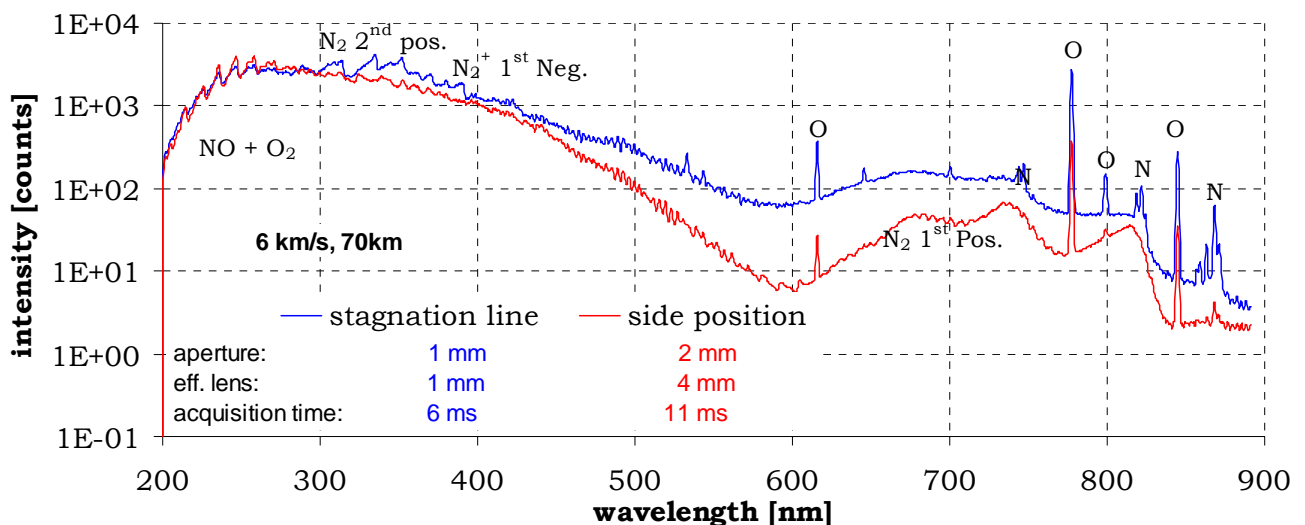


Fig. 24. Simulated spectrometer response at an altitude of 70 km for an entry velocity of 6 km/s

wind tunnels. The first flight of EXPERT is planned in 2007.

### Acknowledgements

Many thanks to ESA-ESTEC for the support within the “Flight Test Measurement Technologies for In-Flight Research” program i.e. the Phase B of the EXPERT capsule program. Thanks to all partners involved in the project.

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