Sounding Rockets for Entry Research: SHEFEX Flight Test Program

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Abstract

Within research for space vehicles with Re-entry capability and hypersonic airplane development in the last decade sounding rocket systems became a major and important test bed. This paper will present an overview of the national development and flight test program SHEFEX (SHARP EDGE FLIGHT EXPERIMENT) of the German Aerospace Center DLR. After 2 successful flight campaigns in 2005 and 2012 DLR is now preparing the next test vehicle SHEFEX III, which is planned for launch in 2016. The paper will focus on the strategic test approach and scientific experiments on board in interaction and possibilities of the sounding rocket system. Also some spin off effects will be prescribed which will enhance the performance of the rocket system also outside re-entry research.

Main goal of re-entry experiments is to verify technologies and simulation tools regarding hypersonic gas flow and structural response. A full scale re-entry test flight is expensive and needs in general a launch system with orbital capacity. To simplify and to reduce costs a step by step approach seems to be practicable and less risky. Thus, sounding rockets are a very attractive vehicle to perform related research. Even, they do not cover the whole performance to accelerate the entry vehicle to real re-entry conditions; they allow generating interesting flight conditions to verify aerodynamic simulation tools.

Within SHEFEX the step by step development results in stepwise increasing velocity and test duration. SHEFEX I performs a Mach 6 flight for 20 Seconds. SHEFEX II reaches Mach 10-11 for 45 Seconds. SHEFEX III is aimed to reach Mach 20 for 15 minutes, a significant and ambitious step which require a big sounding rocket which is currently not available, but under development in Brasil.

In the field of hypersonic aircraft and air breathing propulsion development the SHEFEX launch systems could be a standard rocket family for flight tests. The improvement in high temperature stable stabilizers, huge lift fairings to cover complex vehicles and high accurate pointing and control systems are applicable especially to such kinds of flight tests, which partially is already done within the HiFire and Scramspace Programs.

Introduction

One key technology for returnable space transport vehicles, hypersonic aircraft or winged first stage of a space transportation system is the structural design of hot structures at exposed locations of the vehicle (e.g. nose, wing leading edges, control flaps, air intake etc.) and the overall fuselage design considering the thermal loads. Besides high temperature resistant materials, also structures or single components cooled by special physical effects are candidates for extremely exposed locations at the fuselage and the engine. For the fuselage and wing design different design solutions are possible. In addition to the classic variants like TPS protected conventional structures or hot skin structures, the basic shape approach may influence the system performance and cost frame of the vehicle.

Another key technology is simulation and prediction of aerodynamic and aerothermodynamic phenomena and effects occurring during atmospheric re-entry. Thus accuracy and reliability of simulation tools and ground testing facilities control margin policy and safety of vehicle lay out and mission success.

In addition, GNC technology, autonomous aerodynamic control during re-entry and final approach using moveable rudders, flaps or fins is an essential technology for future re-entry vehicles.

A lot of development effort can be done on ground or using ground based test facilities. However, a flight test is extremely important to set a reasonable development step forward. The challenge to deliver flight hardware which has to operate in a very reliable way during the mission speeds up development process and supports learning curve significantly. However, a rather complex test vehicle or demonstrator requires a reasonable time frame and financial resources. Thus, an optimal

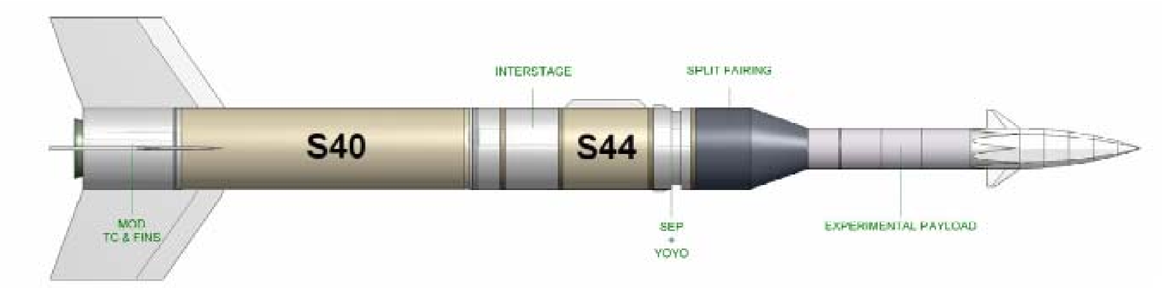


Figure 2: S 40 Launcher system for SHEFEX II and payload configuration

compromise is to reduce size and complexity of the test vehicle, to simplify trajectory requirements and to use a cheap launcher system and existing ground support.

After demonstration within the SHEFEX I mission sounding rocket systems are suitable to perform re-entry related flight experiments. Having the SHEFEX I in a “passive” re-entry configuration only stabilized by a conic tail and fins, the SHEFEX II payload was provided by an active aerodynamic control system.

Lay Out of the Launcher

After a trade off of different launcher configurations and examination of each possible performance and related trajectory, a final 2 stage configuration was chosen considering Brazilian solid rocket boosters derived from the S 40 family. Within table 1 the basic characteristics of both configurations are summarised.

	SHEFEX I	SHEFEX II
Payload	250 kg	500 kg
Apogee	210 km	180 km
Downrange	230 km	800 km
Max. Speed	Ma 6.5	Ma 10-11
Stages	2	2
Experiment time	20 sec	45 sec
Re-Entry angle	84 °	35°

Table 1: main characteristics of the SHEFEX I and II launcher configurations

As a rocket vehicle to fulfil the demands on payload capacity and re-entry velocity, the two-stage Brazilian VS-40 sounding rocket was considered.. The S-40 motor is part of the VLS vehicle operating as the third stage. The S-44 motor and also the interstage adapters are lightweight structures built of Kevlar composites. The VS-40 was first launched successfully in April 1993 achieving an apogee of 950 km and a ground range of 2680 km with a payload mass of 197 kg and 81.8 deg of launch elevation. Up to now, two flights are recorded, both successful.

Description of the SHEFEX II Test Vehicle

In the opposite to SHEFEX I the shape of the test article was chosen to create a facetted symmetric re-entry body stabilized by tail fins and 4 movable small canards

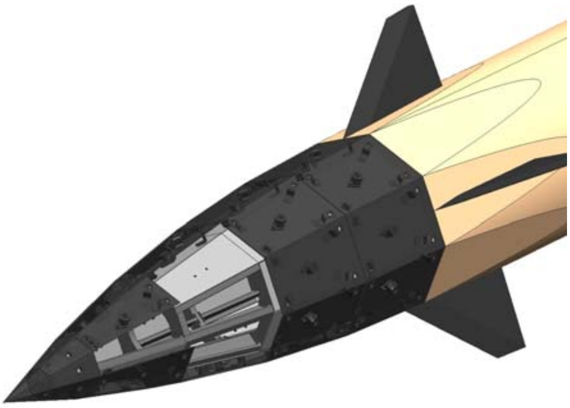


Figure 3: Detail of the payload Tip including TPS (dark grey) inner Alu substructure (light grey) and actuator module.

near the front area of the cylindrical pay load segments. Within the cylindrical segments all necessary subsystems like navigation platform, power cells, RCS- unit, data acquisition, parachute and recovery system, telemetry, etc. are integrated.

Mounted on top of the second stage the payload was separated before re-entry to begin an autonomous flight till final breaking manoeuvre and parachute deployment.

Including the payload the overall length of the system was 12, 7m. The overall mass of the system was 6,7 tons.

The flight envelope enabled a max. Mach number during entry up to Ma 10 (approx. 2.8 km/sec) for 45 seconds. This high Mach number caused extreme heat fluxes at the payload tip and sharp leading edges at the canards and stabilizers. So temperatures above 1800 °C occured at these exposed locations. The dynamic pressure increased up to 4 bar at the end of entry trajectory at 20 km.

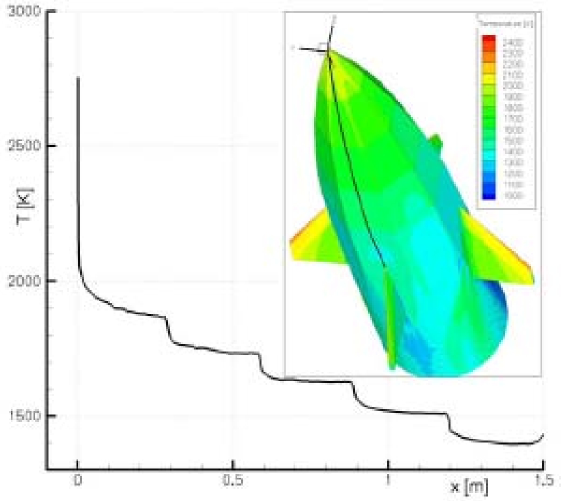


Figure 4: predicted temperature distribution at radiation adiabatic boundary conditions

Key Experiments

The primary substructure of the payload tip is similar to the SHEFEX I concept and consists of a aluminium frame created by stiff booms and spares. The free space is closed by flat aluminium panels, which create an inner mould line (IML). The panels are also used for mounting the TPS facets and experiments. Inside the frame, some measurement equipment is integrated. These items are boxes for thermocouple connection and compensation, pressure transducers, a pyrometer system, data processing boxes and subsystems for passenger experiments.

The tip geometry is symmetrically divided into 8 identical facets in circular direction and consists of 5 segments along the tip to the actuator module interface. Thus, the payload tip houses 40 single flat areas. 32 of them were available for different experiment positions.

As shown in figure 5 with exception of the forward tip area, the heat fluxes have individual nearly constant values at each segment. The heat flux decreases from segment to segment in rearward direction. Thus, each segment is suitable for different TPS concepts and materials due to their specific limit temperature.

Flush Air Data System (FADS)

Within the nose cone tip some special arrangement of 8 pressure sensors were implemented to investigate possibility of a flush air data system, which may be useful for vehicle control (pitch and yaw) against gas flow direction during hypersonic flight. However, this was a passive experiment with no interaction of SHEFEX II active control. But pressure data assessment shall allow a comparison of vehicle orientation data got by GNC platform and advanced algorithms for pressure data processing. From a structural point of view, the integration of pressure holes and tubing within the hottest area of the vehicle was a challenging issue.

Thermal protection systems TPS

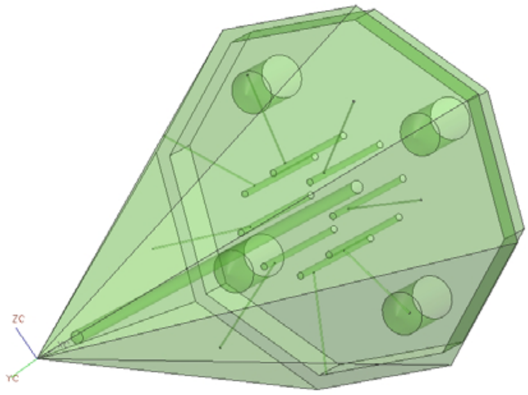


Figure 5: CMC Nose with integral pressure sensor holes for the FADS

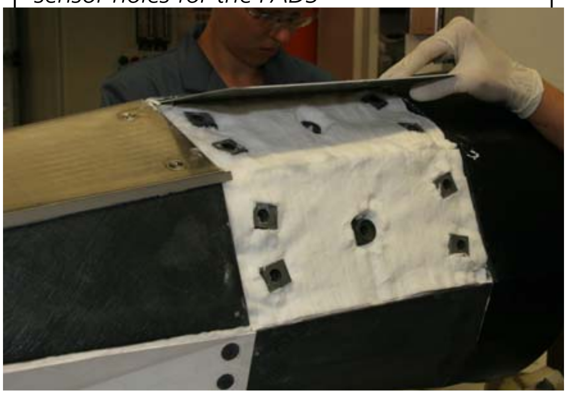


Figure 6: C/C-SiC standard TPS as mounted on SHEFEX I

The second section includes 8 single TPS or material experiments designed very similar to those, which are flown already on SHEFEX I. Main element of the concept is a fiber ceramic cover plate, supported in all directions by a so called central post and flexible stand offs at the corners. Thus, the thermal expansion will be not suppressed. Beneath the cover plate a lightweight fibrous ceramic insulation felt is inserted. Key element of this TPS concept is a ceramic fastener, used for the connection of the panel to the CMC stand off and central post.

A new approach was performed within the SHEFEX project. Within DLR an oxide ceramic based CMC material was developed during the last years. The so called WHIPOX material can be used as an oxidation stable alternative to carbon based CMCs. However, temperature stability is limited and a special coating is necessary to improve emissivity and catalytic behaviour. Nevertheless, this material provides a flexible intermediate state during the manufacturing process. Thus, it is possible to shape a component (in case of SHEFEX the rigid seal) during assembly. Hardening will occur during operation.

Using this property, it is possible to shape and cut all required seal components from one uniform unfired WHIPOX tape. A typical seal interface was tested within a plasma wind tunnel and handling procedure, seal performance and temperature stability could be demonstrated successfully.

Besides DLR`s C/C-SiC material for the cover panels, 3 facets of the second segment are covered by passengers on SHEFEX II, two different C/SiC materials developed by EADS ASTRIUM and one C/SiC Panel developed by MT-Aerospace.

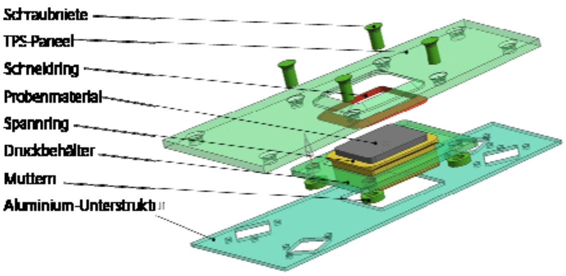
4 TPS-elements of the third segment are provided with patch antennas behind. This is to demonstrate functionality of "hot" antennas which are able to be integrated within a heat shield of a re-entry vehicle. The cover panels are made from DLR`s WHIPOX oxide based ceramics to take benefit from their electromagnetic permeability.

This technology enters also usage for standard hook antennas which were covered by a small WHIPOX fairing. Thus, also useable for standard Sounding rocket applications this is a direct spin off from the SHEFEX program.

Within the 4th and 5th segment a number of passengers and standard TPS elements are located. Besides the surface protected flexible insulation SPFI 2 metallic TPS elements from EADS ASTRIUM are integrated. Additional Experiments from, AFRL (USA) were also integrated

Actively cooled TPS AKTIV

At DLR an actively cooled TPS concept is under investigation. Based on the very good experience got during development of an effusion cooled ceramic rocket engine burning chamber, it seems to be possible to transfer this technology for the design of extremely loaded sharp leading edges or flat TPS elements exposed to heat fluxes beyond materials temperature limits. First screening tests of different porous ceramic materials and cooling gases showed a promising potential for this technique. Significant cooling effects at rather low gas consumption could be demonstrated within a plasma channel test sequence at hypersonic gas flow conditions. However, a large effort has to be invested to investigate and understand the responsible parameters for an optimal cooling effect considering the thermal conductivity and interactions between the surrounding gas flow and boundary layer.



Active cooling systems are of special interest for use in severe thermal environments where the passive systems are inadequate. The transpiration cooling experiment uses a porous ceramic material at the outer surface through which a coolant flows into the boundary layer. Thus, transpiration cooling is effected by two physical phenomena, as there are the porous structure being convection cooled by the coolant and the coolant layer on the outer, hot surface, lowering the heat transfer from the high-enthalpy environment to the vehicle surface.

The flight results showed a very high cooling efficiency in comparison to the uncooled reference set up.

Active aerodynamic control

The first cylindrical part behind the facetted payload tip includes the aerodynamic flight control unit. The active part is an actuator system to move the 4 canards. Interaction with the RCS system at altitudes above 70 km and continuously changing aerodynamic sensitivity till payload split at 20 km require challenging advanced control algorithms and high speed actuators.

The canards themselves are highly thermomechanically loaded structures. Due to limited shaft diameter and very high bending loads, a CMC/metallic hybrid structure was chosen for structural design. The leading edge structure is made from C/C-SiC fiber ceramic to withstand the expected high temperatures of 1700°C at the leading edge. The canard main structure is made from a Titanium alloy to carry bending loads and to transfer torsion from the actuators. Special attention has to be paid for the attachment design between Titanium and CMC to balance thermal expansion mismatch.

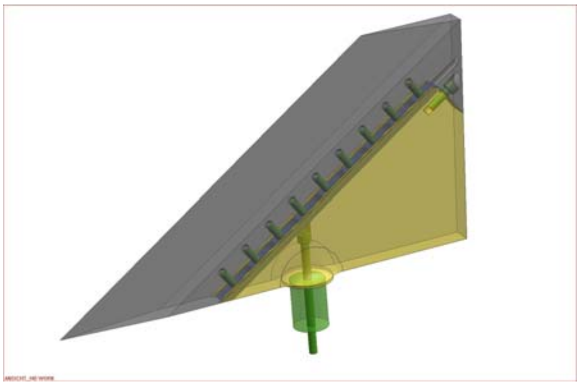


Figure 8: Hybrid CMC (grey) and metallic (yellow) canard structure

Instrumentation

The whole tip structure was instrumented with up to 60 thermocouples, 1 pyrometer, 24 pressure sensors and 8 heat flux sensors. Special care was applied to the integration of the pressure and heat flux sensors within the TPS elements. This is to minimize secondary gas flow effects at the sensor/ceramic interface at the outer surface. Otherwise, the heat flux signal may be disturbed by local turbulence or stagnation areas. All signals were processed and send to the data storage and telemetry system by special multi function cards also integrated within the payload tip. Lessons learnt from SHEFEX I and parallel on ground testing and calibration promises a high quality of flight data, which will allow optimisation and calibration of CFD tools for further reliable aerothermodynamic vehicle lay out.

The uncovered tip allowed also aerodynamic measurement during the up leg of trajectory which is a valuable data base to estimate heat and aerodynamic loading of standard sounding rocket missions.

The University of Stuttgart provides additional instrumentation in terms of fiber optic sensor and a pyrometer and radiometer sensor combination respectively.

Mounted on top of the second stage the payload was separated before re-entry to begin an autonomous flight till final breaking manoeuvre and parachute deployment.

Secondary structural developments

The VS 40 launch system needed some modifications to meet the SHEFEX mission requirements. Especially the stabilizer fin leading edges and fairing structure were specially developed for SHEFEX II. During SHEFEX I the stainless steel leading edge structures of the second stage aluminium stabilizers showed a thermal buckling effect during ascent and re-entry which was caused by a thermal expansion mismatch of the structural materials used. This resulted

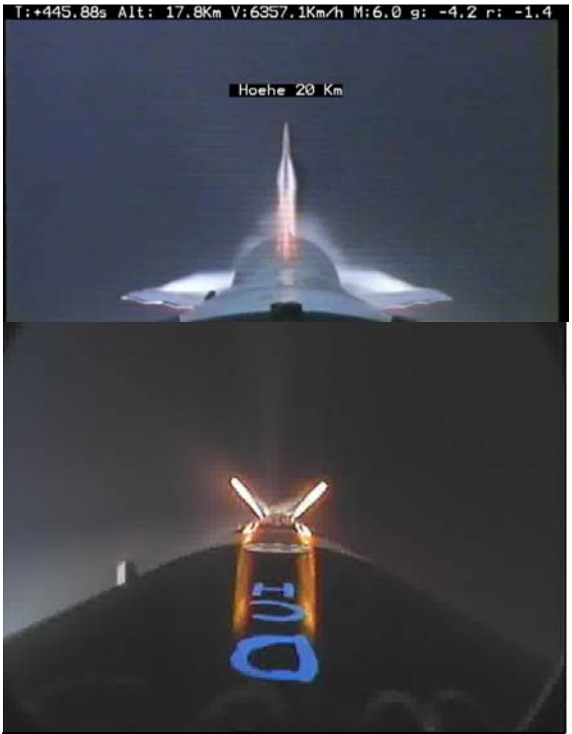


Figure 9: Fin leading edges of SHEFEX I (top, tainless steel) and HiFIRE 3 (Glass/Phenol) during entry at approx.. Ma 6-7 at 20 km.

in uncontrolled spin effects during flight. Thus, the leading edges of the first stage of SHEFEX II were made from a CFRP material with well adapted fiber orientation to balance the Aluminium expansion. That results in a spin rate which was very close to the predicted value. The Stabilizers of the re-entry vehicle were completely made from CFRP with special resin to act as an structural ablator at the leading edge. Not used within SHEFEX II, but important for the VS-30/ improved Orion system which was used within SHEFEX I the second stage stainless steel stabilizers were replaced by an glass fiber reinforced phenol. This reduced thermal deformation dramatically and was applicated during the HIFIRE 3 and 5 flight. Especially during HIFIRE 3 these stabilizers worked reliable during the whole mission down to 20 km altitude.

The fairing structures for SHEFEX II were designed as a CFRP sandwich structure with a 2 mm thermal ablative protection cover. This cover worked as estimated and shields the load carrying sandwich till fairing release. The weight reduction in comparison to a conventional aluminium structure reached 50 %.

Outlook

After successful flight of SHEFEX II the next step, SHEFEX III is under development. In the opposite of recent SHEFEX Flights, SHEFEX III will be a free flying vehicle with continuous deceleration during entry at full aerodynamic control. The interface velocity is aimed above Ma 20 at 100 km. Tha vehicle mass is estimated with 500 kg.Thus, the recent SHEFEX launch systems are to small. In coopartion with brasil a suitable launcher called VLM is underdevelopment, which could reach the required performance. However, the SHEFEX II launcher configuration keeps alive and will be used for the Australian/US Hifire 8 and the European/International HEXAFLY Hypersonic experiment missions.

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