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DLR project TRANSIENT: Testing reusable cryogenic insulation and thermal protection systems

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Abstract

Reusable launch vehicle stages face intense heat fluxes, particularly during reentry. Thermal protection systems (TPS) are essential for winged stages decelerating through aerodynamic forces, requiring coverage of large vehicle areas. In the case of reusable systems with integral cryogenic tanks, the TPS is exposed to extremely low propellant temperatures. Joint design and integration of TPS and cryogenic insulation are necessary, considering their interdependent nature. The AKIRA project initiated by the German Aerospace Center (DLR) initially explored this area, continued through the TRANSIENT project. Test objects representing RLV propellant tank sections were manufactured with combined TPS and cryogenic insulation, undergoing mechanical and thermal load testing. Initial integration and experimental results are presented.

1. Introduction

At sufficiently high launch rates, Reusable Launch Vehicles (RLV) promise to be more cost-effective than their expendable counterparts. However, the safe return to and deceleration within Earth's atmosphere places additional requirements on the vehicle design. One of these additional requirements is the need for a thermal protection system (TPS). Specifically, RLV experience a large range of thermal boundary conditions during their mission, ranging from the temperatures of the propellant over the heat loads encountered during reentry to the vacuum of space during ballistic phases. This range of temperatures is extended substantially when using cryogenic propellants, especially hydrogen. While within Europe the use of hydrogen as a rocket fuel has been mastered for expendable launch vehicle stages, the use within RLV's comes with new challenges. As one critical technology for future hydrogen-fuelled RLV reusable cryogenic insulation is being investigated by the DLR.

The number of operational RLV in the history of spaceflight is limited. None of them have made use of a cryogenic tank insulation on their reusable stages. The Space Shuttle and the Soviet Buran were orbital stages without any large cryogenic tanks. The Falcon 9 is a booster stage with integral tanks but without cryogenic insulation. Therefore, no practical experience with an operational RLV with reusable cryogenic tank insulation exists. For future RLV's however, the use of hydrogen as fuel has large benefits with regard to vehicle mass, size and environmental impact [7]. For a winged system the cryogenic insulation has to be integrated with the TPS on the propellant tank, imposing new design requirements on both. Additional complexity arises from the fact that multiple cycles of thermal and mechanical loads have to be survived without substantial refurbishment in order to assure a cost-effective design.

Within this paper the current status of the DLR project TRANSIENT is shown, which addresses this technological challenge. This overview represents an update of previously presented papers [1]-[3], with first results from the integration and testing of three Integrated Test Objects (ITO). The ITO's were designed to represent a slice of an RLV tank structure, including the structural material, the cryogenic insulation and the external TPS.

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1.1. Technical challenge

The understanding of the behaviour of reusable tank insulation is of crucial importance for an RLV with cryogenic propellants. The insulation not only reduces the losses through vaporization on the launch pad but also prevents ice from forming on the outer hull of the vehicle. If icing occurs at the outside of a winged stage it can cause serious damage to the vehicle structure or the TPS when it is shaken off during ascent of the vehicle.

As a winged RLV is subject to elevated temperatures during re-entry, the combined cryogenic insulation with external TPS becomes a complex system considering the high temperature gradients between TPS and cold propellant tank wall. Typical cryogenic insulations are usually limited to around 100°C to less than 200°C maximum operating temperature. On the other hand, fibrous open-pore high-temperature insulations of the TPS should be kept above the dew point of air during ground operations to prevent internal moisture condensation or even icing.

This thermal coupling as well as the joint integration onto a vehicle propellant tank surface means that these two previously separate subsystems have to be designed and tested together. Further complexity is introduced by the fact that these systems are expected to have a major impact on the refurbishment cost of the vehicle and thus a robust and low maintenance design is highly desirable.

1.2. DLR project AKIRA

Within the DLR project AKIRA this topic was first investigated within the DLR. The work and its results have been previously presented [4] - [6].

2. DLR project TRANSIENT

The DLR project TRANSIENT (**T**he**r**m**a**lko**n**troll**s**ystem für w**i**ederverw**en**dbare **T**räger) was initiated in the beginning of 2020. The main goal is the further advancement of the technologies necessary to integrate a reusable cryogenic insulation with external TPS through thermo-mechanical experiments with representative test objects. Building on the work done in AKIRA, the designs are further refined and applied to both metallic and composite base structures. Within the experimental campaigns both versions are put through dozens of cycles of thermal and (in some cases) mechanical loads representative of a first stage RLV mission.

2.1. Reference configurations

In order to assure that the boundary conditions of the following development efforts are applicable for future reusable first stages, reference configurations are needed. For this purpose, two consolidated DLR-studies of winged reusable stages were chosen, the ENTRAIN 2 HL [8] stage and the SpaceLiner 7 Booster [9]. The main requirement was the existence of an aerothermal database for the descent phase in order to accurately assess the heat loads. Both stages are also deemed sufficiently representative for future winged reusable stages. Their separation Mach numbers are 9 and 13 and thus cover the expected range for future systems. Both stages use hydrogen as fuel. While DLR system studies [7] indicate that hydrogen is the most attractive option for a European reusable first stage, the lessons learned remain valid for other fuels such as methane, since its storing temperature is similar to oxygen and thus the design for the oxygen tank can be applied to potential methane-fuelled vehicles.

2.2. Integration of reusable cryogenic insulation with external TPS

The core of the TRANSIENT project is the further development of a reusable cryogenic insulation which is jointly integrated with an external TPS onto the propellant tank structure. Due to the developments in rocket fuel tanks made of CFRP structures, TRANSIENT investigated composite base structures in addition to the aluminium base structures, which have already been considered in the previous AKIRA project. For both tank material options, a combined TPS/cryogenic insulation system is designed and is investigated in experimental campaigns under thermal loads. Two of the three experimental campaigns also include the application of mechanical loads. In addition, for the CFRP structure variant, the design will incorporate a thermal management system that consists of an integrated purging system to control the internal temperatures in the insulation stack via flushing pre-heated gas through the CFRP structure. Planar test objects are manufactured for the experimental investigation in a geometrical size that allow a transition of the expected thermo-mechanical loads from the reference configuration (see [3]) to the experimental setup in the available test facilities. The investigated test setups comprise thermomechanical tests using the THERMEX facility for representative test objects (aluminium tank structure in section 2.2.2, tests ongoing, and CFRP tank structure in section 2.2.1, tests finished) and aero-thermomechanical tests using the L3K wind tunnel (section 2.2.3). These experimental setups study the thermal and mechanical behaviour under demanding conditions as faced by reusable re-entry configurations and aim to validate the design of the described subsystems. An aspect of special interest is the change in performance over multiple mission cycles, a critical feature for RLV.

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2.2.1. Carbon fibre tank structure

The CFRP ITO is designed along the concept of a linerless cryogenic composite fuel tank with an added lightweight reusable insulation system including mechanical attachments of TPS surface panel components. The tank structure itself is designed as a so-called fluted core structure composed of two CFRP skins on both sides of an internal corrugated CFRP core. Note that, strictly speaking, fluted core structures feature circumferentially closed internal tubular structures as core. Internally stiffened fluted core structures are very effective in terms of load bearing capability versus mass and offer interesting additional functional options such as the purging capability. The selected material composition was the prepreg system CYCOM® 5320-1 [13] in combination with the IM7 carbon fibre. The design roughly follows the guideline from the CCTD project of Boeing and NASA [12] and provides for out-of-autoclave manufacturing, offering low temperature curing capability with low resulting void content [13].

The thermal boundary conditions are taken from the design studies of the winged booster stage of the SpaceLiner7 (SL7) concept [9]. For the sizing of the insulations, two important load cases were identified and corresponding criteria were defined to account for them. The first load case is the steady-state condition with filled tanks on the launch pad leading to low temperatures in the structures and insulations. The second load case is the transient heat load profile experienced during the reentry of the vehicle. As a consequence, two thermal requirements R1 and R2 were defined.

R1: Minimum temperature of 0 °C for the TPS during pre-launch condition.

R2: Maximum temperature of 170 °C for the cryogenic insulation during booster reentry.

The R1 criterion is established to avoid condensation or icing of air moisture inside of the porous TPS insulation which could lead to a deterioration of insulation performance. To achieve the criterion, R1 drives the underlying cryogenic insulation thickness. The R2 criterion determines the thickness of the TPS insulation to avoid overheating of the underlying cryogenic insulation. The presence of the mechanical connection elements of the TPS surface panels complicates the situation, because they represent thermal shorts through the insulation stack and thus, local effects around these connections need to be considered. The sizing of the insulations considering R1 and R2 leads to large thickness values for the cryogenic insulation, which is a mass penalty. Therefore, the concept of a gas purging system as means of thermal management was included in the design. This allows the control of the temperatures in the insulation during the steady-state pre-launch condition, thus achieving the R1 criterion with less wall thickness of the cryogenic insulation. This type of thermal management system was already investigated during the preceding AKIRA project, during which it had been implemented in the form of a dedicated purge gap between the cryogenic and the high temperature insulation [6]. In the AKIRA project it was estimated that a mass reduction of 2.67 kg/m² can be achieved on the tank structure area when this is compared to a system without purging.

In the AKIRA project the purging system was realized via a dedicated spacer gap between the insulations and an internal tubing system. In order to reduce the hardware complexity, the purging system is integrated into the fluted core CFRP tank structure in the TRANSIENT test object. The detailed numerical design of the ITO with regard to the insulation thickness and the material choice of the TPS attachment components is described in [28].

The detailed ITO design is shown in Figure 1. It is indicated in blue colour that only every second channel of the fluted core structure with the narrow span facing towards the propellant is purged with gas to control the internal temperatures during steady-state conditions, thus limiting heat transfer into the cryogenic fluid. CMC panels form the outer surface which will be exposed to thermal loads during the transient heating phase of the experiment campaign. A 25 mm thick layer of the silica fibre high-temperature insulation ALTRA®Mat [29] protects the underlying structure from exceeding the material's temperature limit. The cryogenic insulation consists of a 30 mm layer of Rohacell® which was selected because it is easily available and has good thermal properties at cryogenic temperature.

The CMC surface panels are attached directly to the CFRP structure by four multi-part standoffs. Connecting the hot outer surface with the cold tank structure, the standoffs must provide sufficient strength and flexibility to compensate the thermal expansion mismatch between TPS surface and cold tank wall. At the same time, it is crucial to manage the thermal bridge effect of the standoffs in order to keep the required limit temperatures within the cryogenic insulation material and at the CFRP tank structure. This is realized by dividing the standoff into multiple parts of different thermal conductivity. For the transient heating phase representing the RLV's atmospheric re-entry, thermal simulations proved that the standoffs can be effectively utilized to dissipate thermal energy into the cold structure without exceeding the cryogenic foam's or the composite's limit temperature.

The design of the TPS surface panel attachment components (standoffs) was changed as a result of the numerical simulations preceding the tests. In the initial design, it was intended to insulate the upper metallic part of the standoff thermally from the lower CFRP part as much as possible by placing an insulating plate between them. The simulations showed, however, that it is much better to have a good thermal contact between the lower standoff part (and also the

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tank) and the upper metallic part to take advantage of the cold heat sink of the tank during the reentry phase. The picture displayed in Figure 1 shows the updated version as tested.

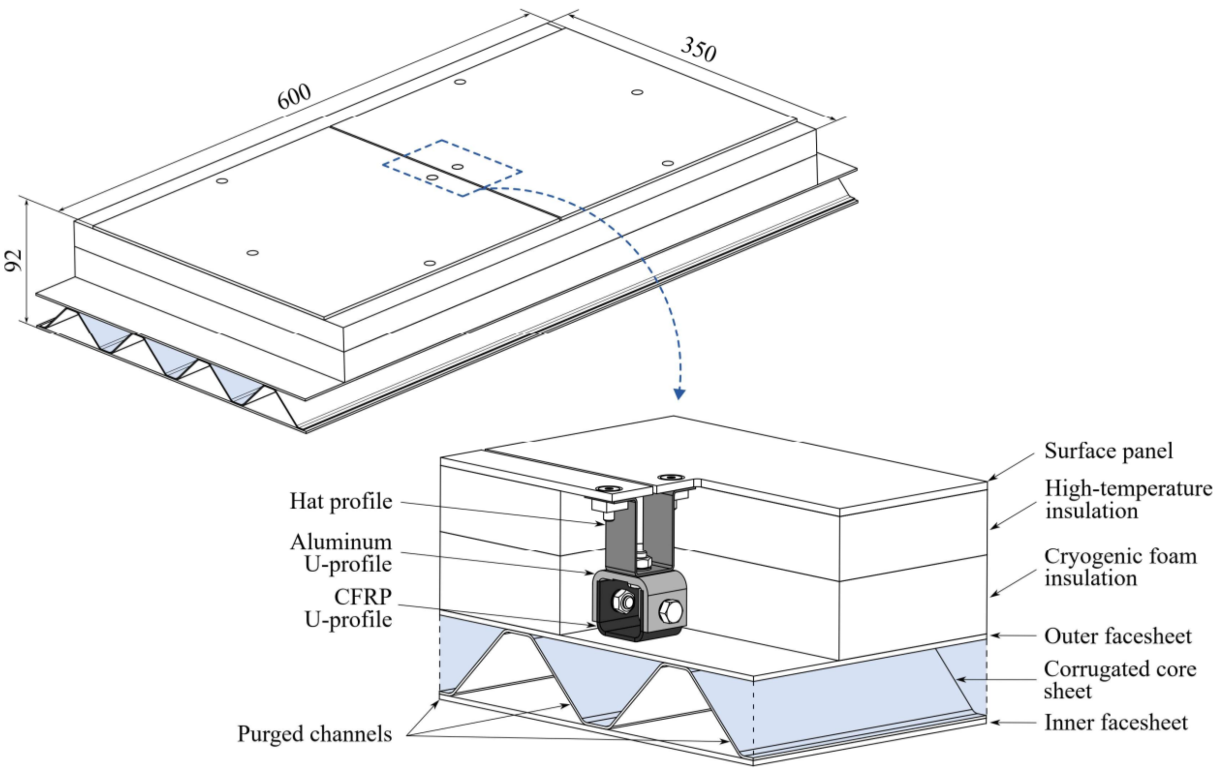

Figure 1: Concept of the CFRP base-structure ITO for the thermo-mechanical test campaign

Manufacturing of the CFRP test object

The integrated test object represents the assembly of cryogenic propellant tank structure, cryogenic insulation and TPS and has a size of 700 mmx 350 mm x 92 mm. The manufacturing process is described in detail in [30]. The CFRP structure was made from unidirectional tapes from the fibre/resin system mentioned earlier via employing the vacuum bag method in a furnace process. The corrugated core sandwich consisted of the two facesheets of each 2 mm thickness and the corrugated core of 1 mm thickness, which was fabricated separately using a dedicated mould. The facesheets and the core were bonded together using a structural paste adhesive. Holes are drilled in one of the facesheets on the same side of the structure to provide for the insertion of the purging tubes into the channels of the structure.

Figure 2: Corrugated core prepared for upper skin sheet bonding (left) and cross section view of bonded CFRP structure (right).

The CFRP structure is equipped with thermocouples and also strain gauges, both on the face sheets but also inside of the structure on the corrugated core. In addition, there are thermocouples on the different interface layers between structure and insulation and also between the insulations as well as between the high temperature insulation and the

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CMC surface panels. In Figure 3 a cross section schematic is shown that depicts the different interface layers where thermocouples had been placed, as well as a schematic of the purge system flow.

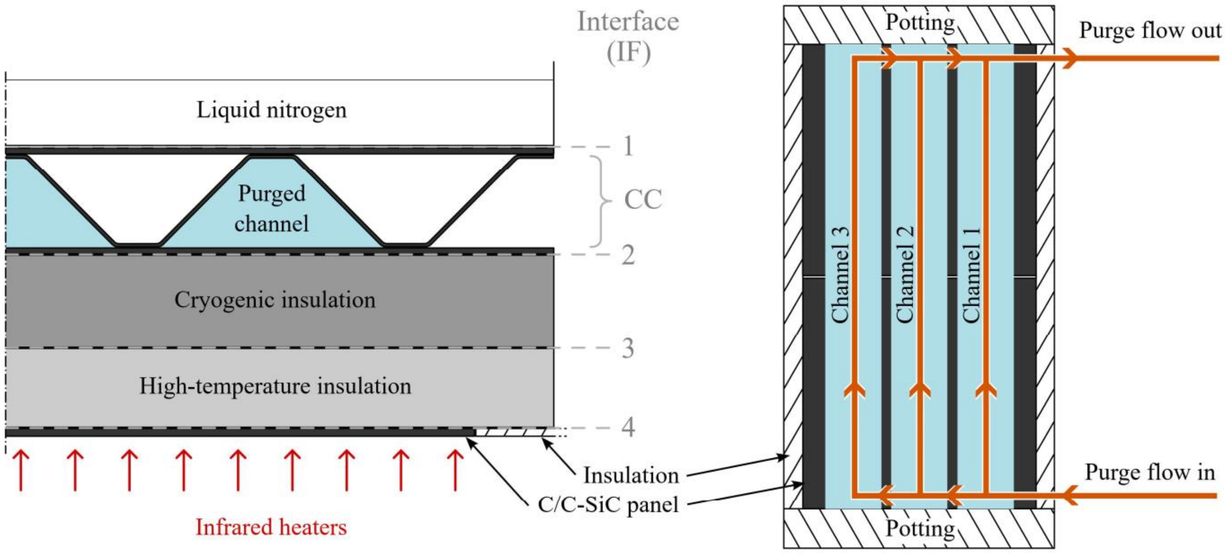

Figure 3: Schematic cross-section view of the ITO as mounted in the THERMEX facility with layer interface indication (left), schematic view of the three purged channels with purge flow indication (right).

In particular, the centre standoff was also equipped with thermocouples to collect temperature data of the hardware components where the maximum temperatures for the cryogenic insulation and the CFRP standoff components were expected. Table 1 gives an overview about the total numbers of thermocouples, strain gauges and pressure sensors that were installed in the ITO.

Table 1: Summary of installed sensors within the ITO.

	IF1	IF2	IF3	IF4	CC	Attachment	Purge line	**Total**
Thermocouples	13	16	10	6	0	4	6	**55**
0°/90° Strain gauges	5	5	0	0	5	0	0	**15**
Pressure transmitters	0	0	0	0	0	0	2	**2**

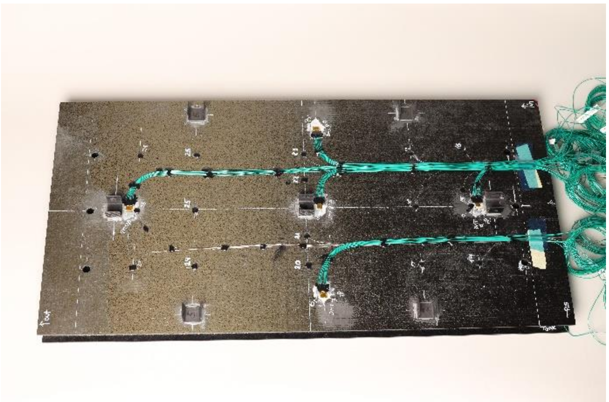

Figure 4: CFRP structure with thermocouples, strain gauges and bonded CFRP standoff parts.

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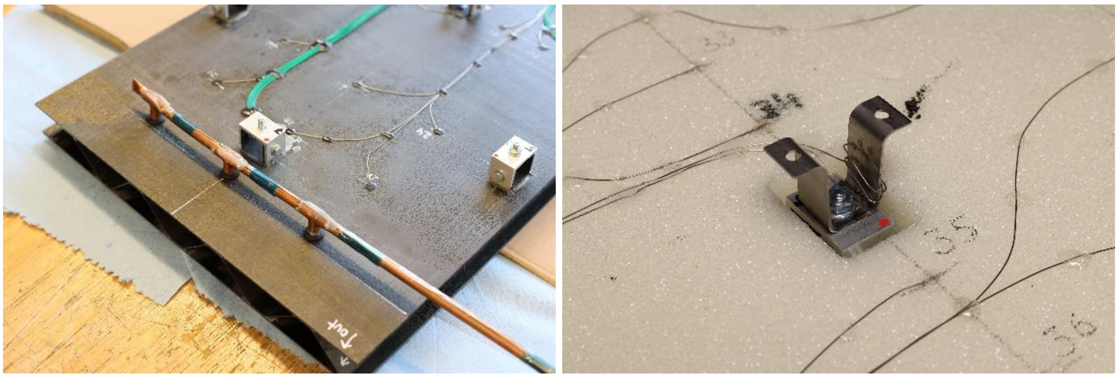

Figure 5: Lower standoff-components and purge tube (left) and steel hat profile of the standoff (right).

The TPS insulation was wrapped and sewed into a flexible silica-fibre textile to ease handling during assembly and test and avoid excessive dust creation. Cut-outs for the standoff elements and slots were made to feed the thermocouple wires from the cryogenic insulation layer underneath to the top of the TPS insulation. On the top of the insulation package, the thermocouple wires were guided to their measurement positions by feeding them into and out of the insulation cover fabric in various locations. The final assembly step was the placement and fixation of the two CMC panels of 300 mm x 300 mm size. Each panel was fixed with four countersunk Inconel bolts that were flush with the panel surface. On the lower side of the steel standoff flanges, stainless steel custom-made nuts were used. The image displayed in Figure 6 shows the finished ITO.

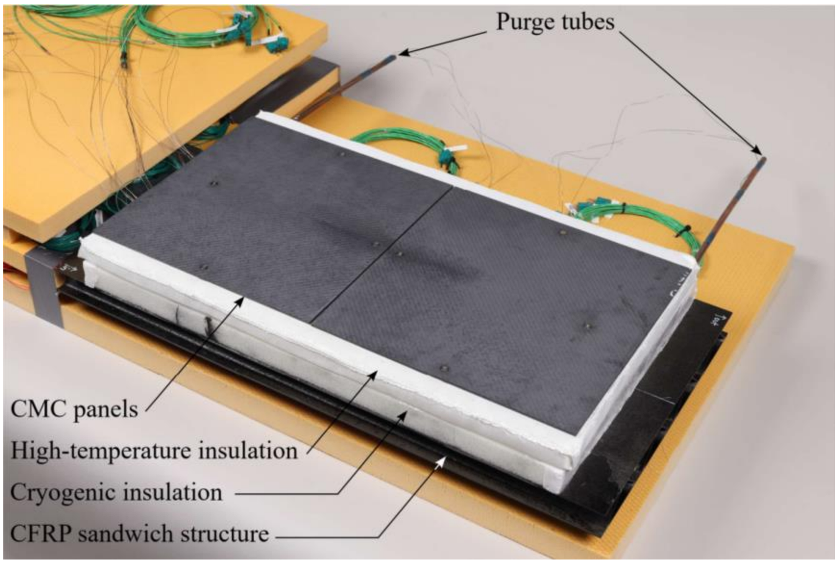

Figure 6: ITO fully assembled.

Thermo-mechanical test facility THERMEX

The THERMEX facility at DLR Brunswick is capable of investigating the behaviour of structures or assemblies under simultaneously coupled thermal and mechanical load conditions. Test objects can reach maximum dimensions of up to 1000 mm x 800mm. Thermal loads are typically applied by radiant heating with electrical power of up to 190kW and based on sensor-control. Mechanical axial loads of up to 400kN can be introduced through the frontal cross-section surfaces. It has been used in the past for similar investigations [23] of TPS systems. The investigation of stiffened CFRP panels has been part of past studies [24] and has recently become of interest again [25][26]. The facility is shown in Figure 7.

Structure test programs usually focus on the structure performance under various thermomechanical load conditions. In the TRANSIENT project, the focus is more on the large thermal gradients, through the cryogenic insulation and TPS mounted onto a base structure that represents a cryogenic tank wall. The design of the base structure is adapted for the testing in order to apply representative mechanical strains and to investigate the structural mechanical interactions between base structure and TPS layers under the demanding thermomechanical load conditions that are expected during the mission of a reusable first stage.

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In the TRANSIENT project, the ITO is mounted upside down in the THERMEX facility. This is due to the fact that the radiator boxes of the facility are positioned underneath the mechanical load frame, thus the TPS side of the ITO needs to face downwards. In this way, it is also easily possible to have the cryogenic propellant substitute in the form of LN2 in a foil basin on top of the CFRP structure. The CFRP structure is potted into dedicated end frames via a specific cement. These end frames are positioned in the load frame of the machine. On the ITO side which is facing the heater boxes, the surface of the ITO is covered with insulating boards except for the area of the two CMC panels. In addition, the spaces around the ITO are also closed with insulation boards to prevent convective hot air flow from the lower heated side to the upper cold side.

The purging tubes of the ITO are connected to the compressed air supply of the THERMEX lab. A pressure reducer is used to set the pressure do a desired value which is the regulating parameter for the purging mass flow rate. The pressure is measured at the purge gas inlet tube and at the outlet tube. The mass flow rate is measured before the purge gas inlet. The purge gas is pre-heated via feeding the gas through a copper coil in a heated water bath which is temperature controlled.

Test Program for the CFRP-ITO

The test program was sub-divided into five parts as follows:

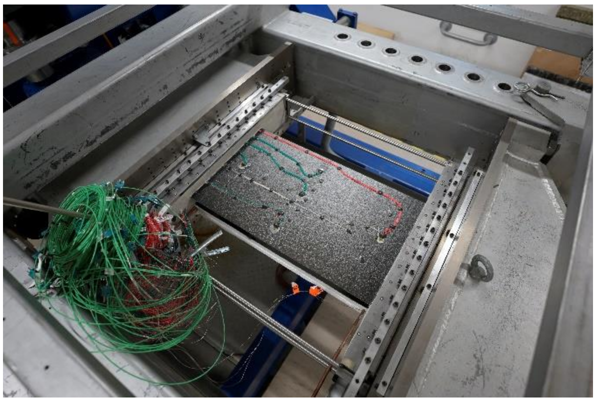
Part I: Preliminary purge tests were done to assess the possible inlet gas temperature and to determine the mass flow rate at a given pressure. Also, preliminary heating tests were conducted to determine the settings for heater power and heating duration to replicate the reference vehicle conditions during the transient phase. A purge gas temperature of 40° C and a mass flow rate of 2gs-1 were chosen for the majority of the testing.

Part II: Full thermal cycles without purging were carried out as a reference case. These included the filling of the basin with LN2 and letting the temperatures settle down to steady-state conditions. When steady-state was reached, the heat load was applied. The cycle was completed when the ITO had reached room temperature afterwards.

Part III: Full thermal cycles as in Part II but with activated purging during the cooling down and the steady-state phase. When steady-state was reached, the purging was stopped and the heat load was applied. In addition, tests were also carried out for comparison with the purging still activated during the application of the heat load.

Part IV: Mechanical loading of the CFRP structure via compression load.

Part V: Full thermal cycles as in Part III but with the ITO taken out of the load frame of the facility and still connected to the purging system and the data acquisition. These tests were done to better understand the thermal boundary condition imposed on the ITO by the large thermal mass of the facility.



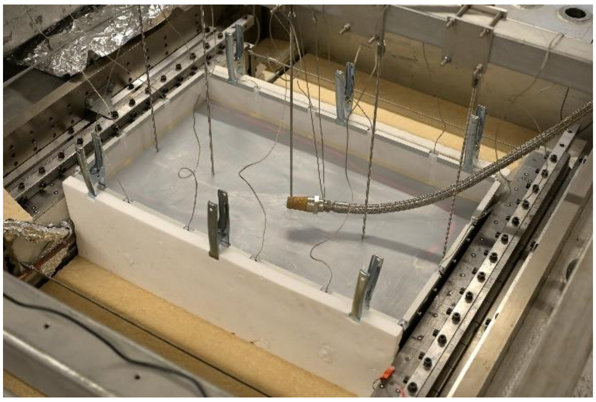


Figure 7: ITO mounted in the THERMEX facility without LN2 basin and thermal shields (left) and with LN2 basin and mounted shields (right).

Preliminary Results

The test campaign was comprised of 20 full thermal cycles plus numerous pre-tests to determine parameter settings. The data evaluation is still ongoing. However, it can already be stated, that the ITO does not show signs of deterioration with regard to its thermal properties. Measured temperatures ranged from approximately -180 °C on the CFRP facesheet under the LN2 basin to 690 °C under the CMC surface panels that were exposed to the radiative heat load, resulting in a temperature difference of 870 °C for the entire ITO.

A brief overview of results is given in Figure 8, with the comparison of the transient heated phase for a purged test run (P, solid lines) to an unpurged test run (UP, dashed lines) on the left side, showing that there is a significant effect of the purging. On the right side of Figure 8, the comparison is made again for the transient heated phase between a

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purged test run in the beginning of the test campaign (solid lines) and an unpurged test run late in the test campaign (dashed lines), showing that there was no significant change in the behaviour of the ITO.

The comparison is made at the location of the centre standoff. Signal 01 was measured at the CFRP U-profile close to the structure facesheet, signal 02 and 03 were measured at the steel hat profile's web radius and centred at the web, respectively. Signal 04 was measured between the hat profile flange and the underlying nut, close to the CMC surface panel.

On the left side of Figure 8, the graph shows the measured temperatures of the purged (P) and of the unpurged (UP) test run. The steady-state temperatures at the start of the transient heated phase are significantly different as a result of the purging that was active until the start of the heat load. The purging leads to increased temperatures during steady-state, in particular at the measurement locations that are closer to the CFRP structure. At the location 01 the steady-state temperature difference between purged and unpurged case is 68 °C, at position 02 the steady-state temperature difference is 32 °C. In position 03 the temperature difference is again smaller, and in position 04, close to the surface panel, it is negligible. The difference in the starting temperature as the result of the steady-state phase is maintained throughout the test. The peak temperature of position 04 reaches 430 °C within 200 s after the beginning of the heat load, the other signal peaks are reached with a certain delay due to their position further inside of the ITO. The results show that the internal steady-state temperature in the ITO can be controlled (i.e. raised) to a certain extent by the purging system.

On the right side of Figure 8 a comparison is made between two purged test runs, again at the location of the centre standoff. The test run P1 (solid lines) was carried out early in the test campaign, the run P2 (dashed lines) was done late in the test campaign. There is no significant difference in the measured temperatures, neither with regard to the steady-state starting value of the transient heating phase, nor with regard to the transient behaviour and peak values, except for the signal of the thermocouple at position 01 which was lower by 19 °C for the later test. Overall, this shows that the ITO did not experience measurable deterioration with regard to its thermal properties. The difference in the steady-state temperature value of sensor position 01 can be explained by a modification to the LN2 basin and its related filling procedure that was introduced during the test campaign. The basin is essentially a foil container in a surrounding aluminium frame. After a couple of tests, it was observed that the temperatures measured on the CFRP skin underneath the basin were somewhat inconsistent, as a result of changing LN2 filling levels. Then, steel nuts were placed inside the basin to ensure proper contact of the basin floor to the CFRP structure and the LN2 filling level was kept higher and more constant, leading to constantly lower temperatures of the CFRP structure, as can be observed in Figure 8.

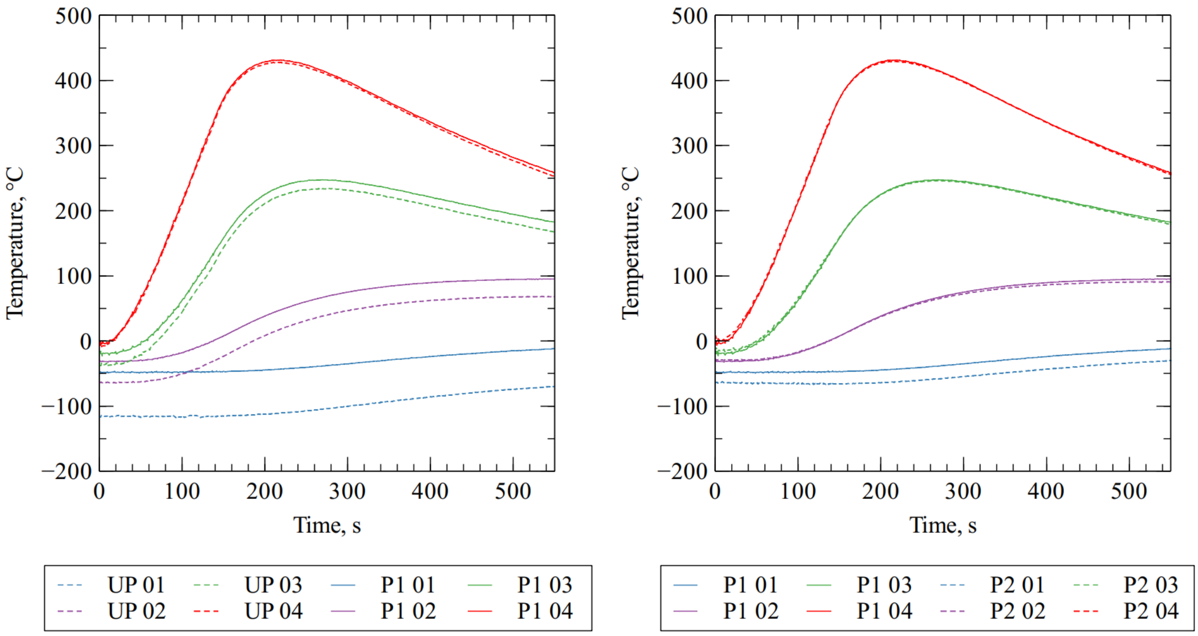

Figure 8: Transient temperature profiles of the attachment element thermal sensors for a representative unpurged and a purged test run (left) and purged test runs at the beginning and at the end of the test campaign (right).

2.2.2. Aluminium tank structure

Based on the findings of the AKIRA study, a refined design was derived for an insulation structure based on a metallic tank wall. One main focus of the current study is the investigation of the behaviour of the cryogenic insulation at

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similar strain conditions compared to a reference configuration for a re-entry vehicle. Special interest lies in the combination of applied mechanical loads in addition to the extreme thermal boundaries. An integrated test object was constructed based on aluminium AW 6085 as base structure material, which represents the propellant tank wall. For the cryogenic insulation a closed-cell, thermoplastic polymer foam (Airex) is used.

For the hot thermal protection, a combination of a loose wool material based on aluminium silicate is used. The applied outer thermal protection system (TPS) consists of six individual CMC plates. A picture of the finished ITO is shown in Figure 9.

Figure 9: Assembled metallic ITO

During the experimental investigation liquid nitrogen (LN_2) will be used as a substitute for cryogenic propellants. The LN_2 bath provides the cold temperature to the aluminium wall plate, while the heat load is applied from underneath. The aluminium base plate has integrated stiffeners to avoid bending when axial forces are applied. In addition, these stiffeners are used to support stand-off components, which carry the thermal protection plates.

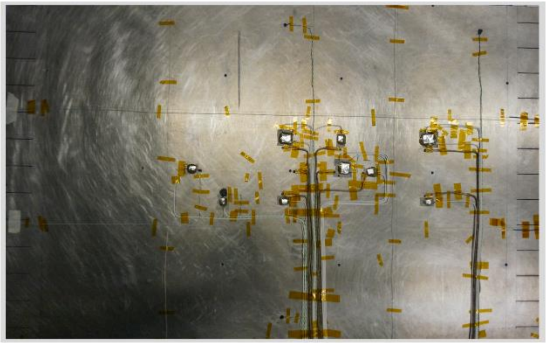

Figure 10: mITO strain gauge and RTD installation on the aluminium wall (left) and thermocouple installation on the high temperature insulation (right)

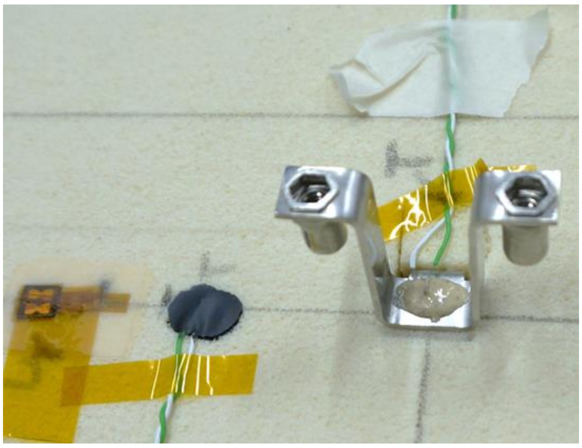

Figure 11:mITO strain gauge and thermocouple installation on the cryogenic insulation side (left) and detailed view on the central stand-off (right)

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Several temperature sensors are integrated between the insulation layers to measure the horizontal temperature distribution temperature and profiles through the layer structure at distributed points. Resistance Temperature Detectors (RTD) sensors are used for cold and ambient temperature regions and thermocouples are used where high temperatures are expected to occur. Strain gauges are installed at the surfaces of the aluminium plate and the cryogenic foam insulation. In addition to the conventional sensor types fibre optical sensors are included in this setup as reference.

The experiment campaign for the mITO is being carried out at the THERMEX test facility at DLR Braunschweig. The mITO is installed similarly to the CFRP ITO (described in section 2.2.1) with the TPS on the bottom and the tank wall on the top. This setup allows for a LN2 bath to be used as thermal boundary condition representing the propellant tank condition while being capable to heat the outer CMC wall through thermal radiation. The heat is applied from radiators underneath the setup. Figure 12 shows the top view on the mITO installed within the THERMEX facility. An extensive sensor system was installed to monitor the thermal and mechanical behaviour of the test article.

The planned test campaign is envisaged to investigate several thermal cycles combined with mechanical loads. The aim of this study is the validation of the chosen design as well as the observation of a possible change over time in the mechanical or thermal behaviour of the components.

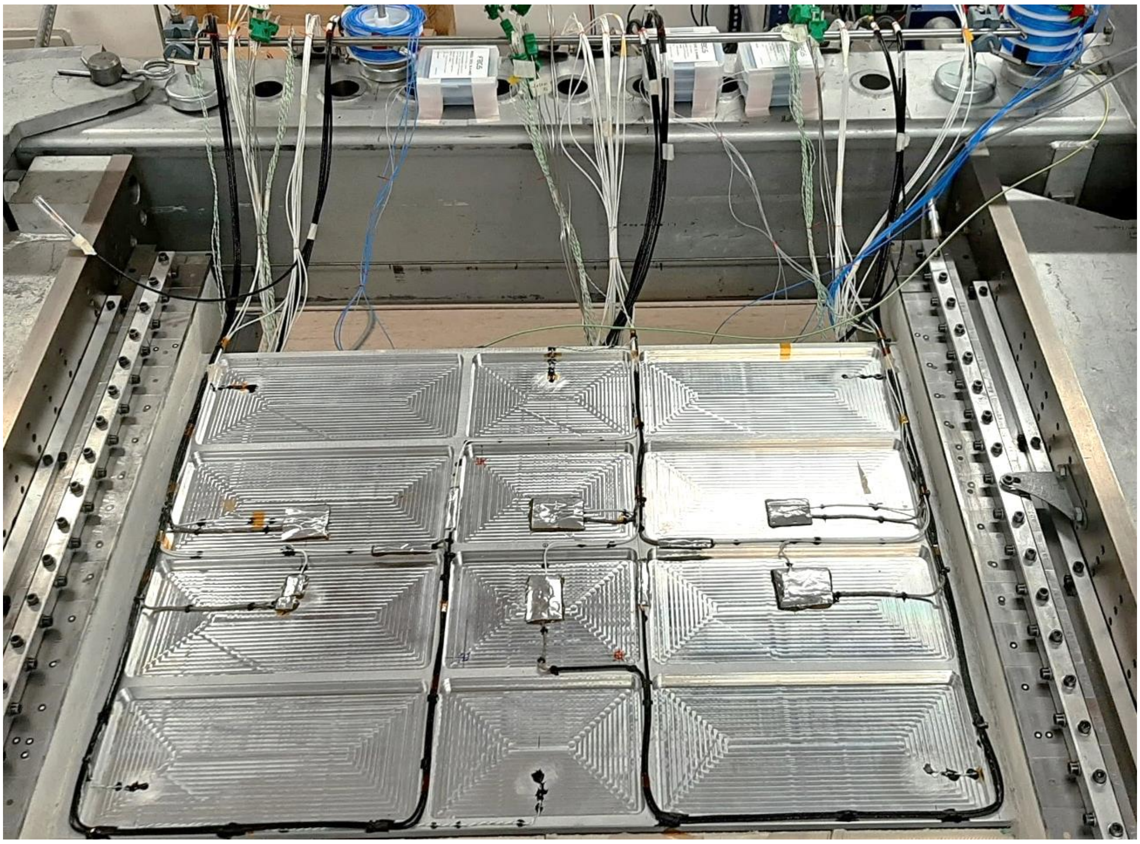

Figure 12: metallic ITO setup integrated in the DLR THERMEX test facility

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2.2.3. Experiments under Aerothermal Loads in the Arc-Heated Wind Tunnel L3K

Arc-Heated Wind Tunnel L3K

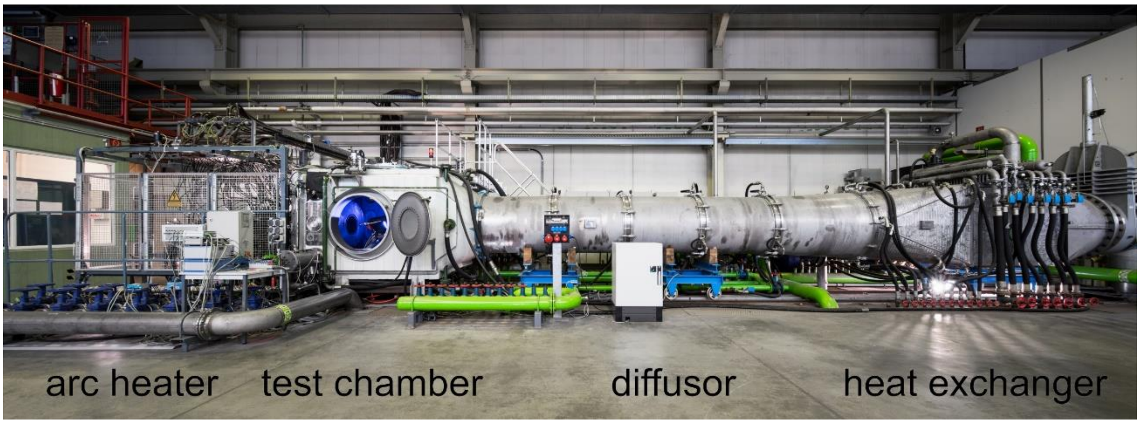

Figure 13: Arc-Heated Wind Tunnel L3K at DLR, Cologne [15]

A smaller ITO with a metallic tank structure was tested in the arc-heated wind tunnel L3K at DLR, Cologne (Figure 13, see also [14] for a full description of the facility). In this facility, air is heated to total temperatures between 4000 and 7000 K by an arc-heater, and then expanded and accelerated in a conical nozzle. A free jet forms in the test chamber that is evacuated before the wind tunnel run. The model is moved into the free jet after steady flow conditions are established. During the wind tunnel run, optical measurements of the surface temperature by infrared camera and pyrometers as well as surface deformation by a digital image correlation (DIC) system were conducted in addition to temperature measurements inside the wind tunnel model (see [16] for an example of the DIC system at the L3K facility). The flow conditions are equal to the conditions previously used in [15][16]. The wind tunnel model was mounted at an angle of attack of 5° for most wind tunnel runs. For the last two runs, the angle of attack was increased to 10°. In reference experiments, cold wall heat fluxes of 49 kW/m² for 5° angle of attack and 73 kW/m² for 10° angle of attack were measured at the centre of the model.

Experiment Description and Objectives

In the experiments conducted, an ITO with the same TPS and cryogenic insulation design as for the mITO in the THERMEX facility was used, including an internal tank filled with liquid nitrogen. The wind tunnel model was adapted in size to the requirements of the L3K facility.

The main objectives of the wind tunnel experiments were:

- Investigation of the performance of TPS and insulation under repeated aerothermal load cycles
- Investigation of the effect of icing (as it may occur on the launch vehicle prior to launch) on the behaviour of the reusable cryogenic insulation
- Observation of potential deformations of the TPS surface

The latter point is relevant as it has been shown in various studies on generic configurations that structural deformations can lead to significant increases in local heat flux and temperature [15][16][17][18][19][20]. Regarding actual vehicle structures, such behaviour was for example investigated regarding X-33 TPS panels [21] or observed on the SR-71 [22]. In the present case, it would thus both be useful to show the absence of such effects or to observe to what extent they occur.

Wind Tunnel Model

Figure 14 shows a sketch of the wind tunnel model used in the wind tunnel L3K. Nose, base, and side walls of the model holder are water-cooled. On top, Incoloy TPS panels can be mounted with a varying number of attachment points. The setup enables either the permission or prevention of thermal expansion of the TPS panels to investigate the influence of panel mounting on deformation of the structure. The configuration of the insulation layers was the same as in the mITO used in the THERMEX facility. The liquid nitrogen tank is located underneath the insulation and can be supplied with liquid nitrogen before and during the wind tunnel run. Figure 15 shows the model during the first run in the L3K facility.

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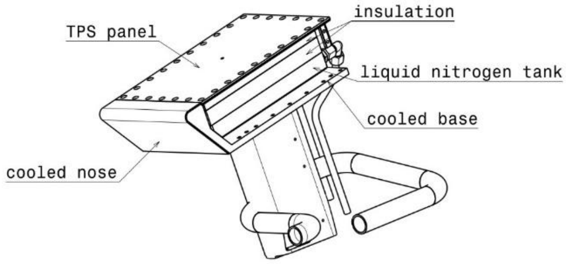

Figure 14: Sketch of L3K wind tunnel model (without side wall)

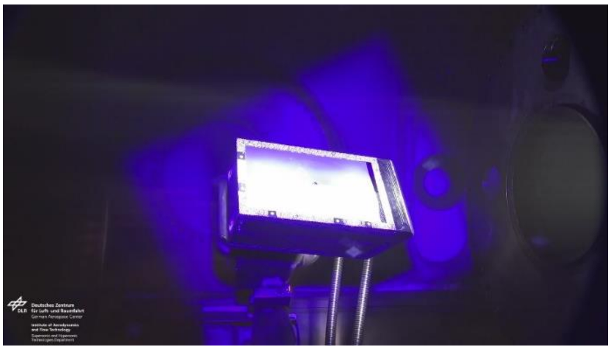

Figure 15: Wind tunnel run in L3K

Experimental Results

Figure 16 shows a time-series plot of the temperatures inside the wind tunnel model during a typical wind tunnel run. Figure 17 shows the same run but with adjusted temperature scale to better show the internal temperatures. Temperatures measured on the interface of the liquid nitrogen tank and cryogenic insulation are shown in green (cryo tank/Airex). Temperatures measured on the interface of cryo and high-temperature insulation are shown in red (Airex/ ALTRA®Mat). Temperatures measured on the metallic TPS are shown in black. For t<0 s, the cool-down of the model inside the evacuated test chamber of L3K is shown. Flow start-up was timed such that the model could be moved into the flow when the liquid nitrogen tank reaches minimum temperature. After flow start-up, the TPS heats very quickly while only a modest rise in temperatures inside the insulation can be detected. The only exception is one thermocouple at the Airex/ALTRA®Mat interface that was located close to the standoff in the centre of the TPS panel.

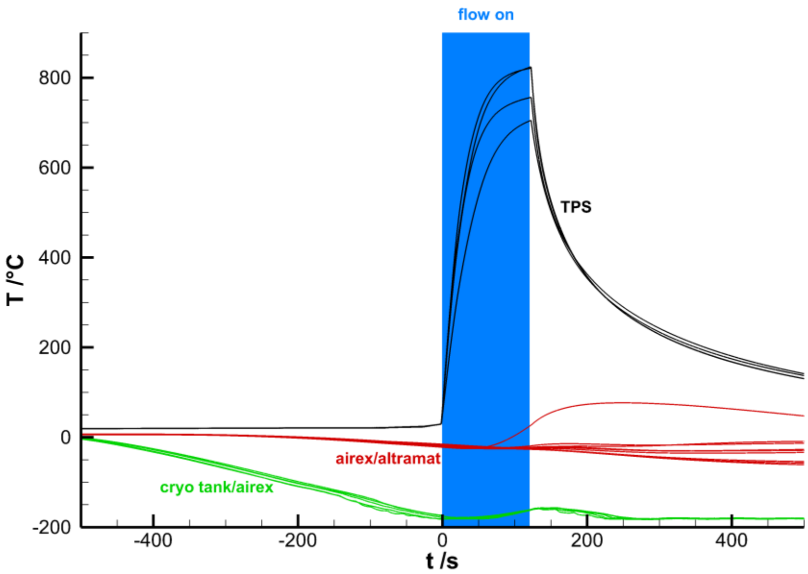

Figure 16: Overview of temperatures inside the wind tunnel model during a typical L3K wind tunnel run

Figure 18 shows a wind tunnel run at the same conditions as in Figure 16/Figure 17. In contrast to that run, the high-temperature insulation (ALTRA®Mat) was put in a bath of water in a freezer to generate ice in the insulation. After freezing, the insulation was quickly installed in the wind tunnel model. Figure 18 shows that this, as expected, leads to a lower temperature at the interface between cryo and high-temperature insulation before flow start-up compared to the reference run. However, the occurring temperature increase during the wind tunnel run is noticeably larger than in the reference run. Interestingly, the location near the standoff that reaches much larger temperatures in the reference run remains at temperature levels similar to other locations on the interface for the iced case. The temperatures on the interface of the cryogenic tank and the Airex also show a slight temperature increase compared to the reference run.

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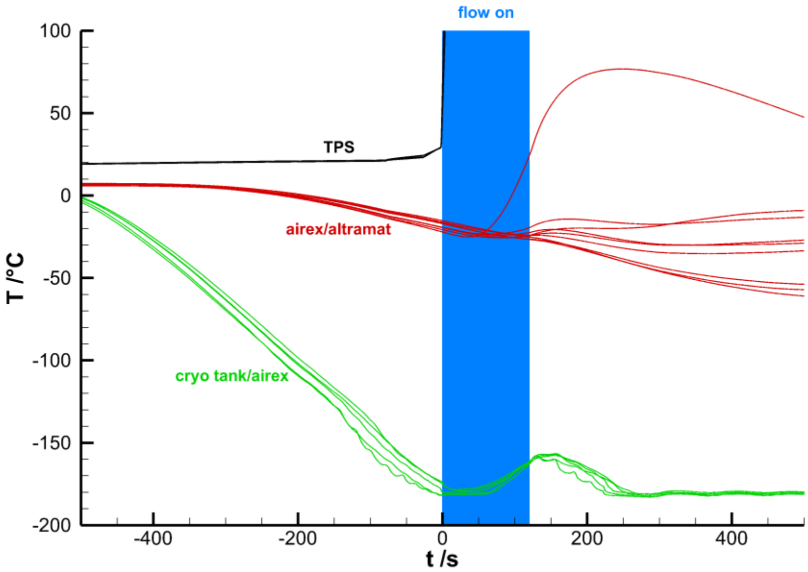

Figure 17: Overview of temperatures inside the L3K wind tunnel model (adjusted temperature scale)

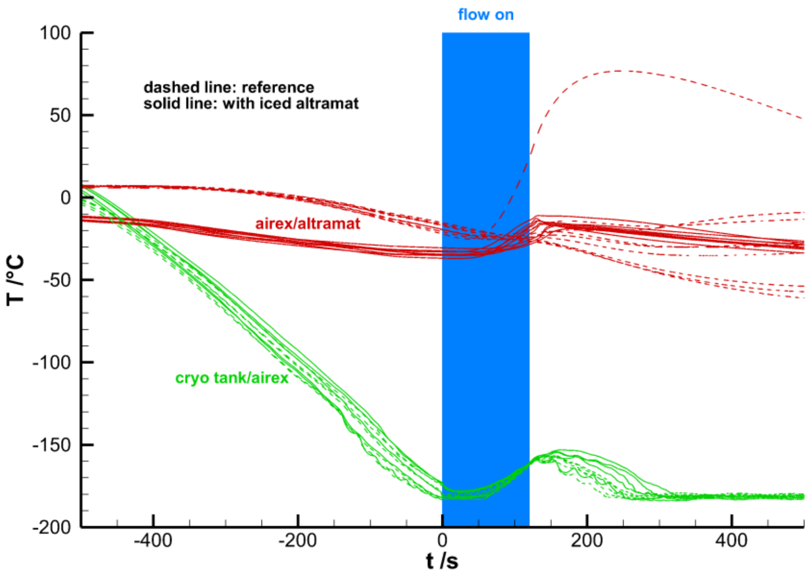

Figure 18: L3K wind tunnel run with iced ALTRA®Mat (solid lines), run without ice included for reference (dashed lines)

Figure 19 and Figure 20 show images of the wind tunnel model surface during the wind tunnel run at 10° angle of attack. It should be noted that the panel has intentionally been clamped on all side for this run to obtain thermal buckling of the panel surface. During other runs, the panel was mounted such that an expansion in lateral direction is possible, however, even in these runs substantial deformation was obtained. Detailed analysis including the DIC deformation measurements and IR surface temperature measurements is ongoing.

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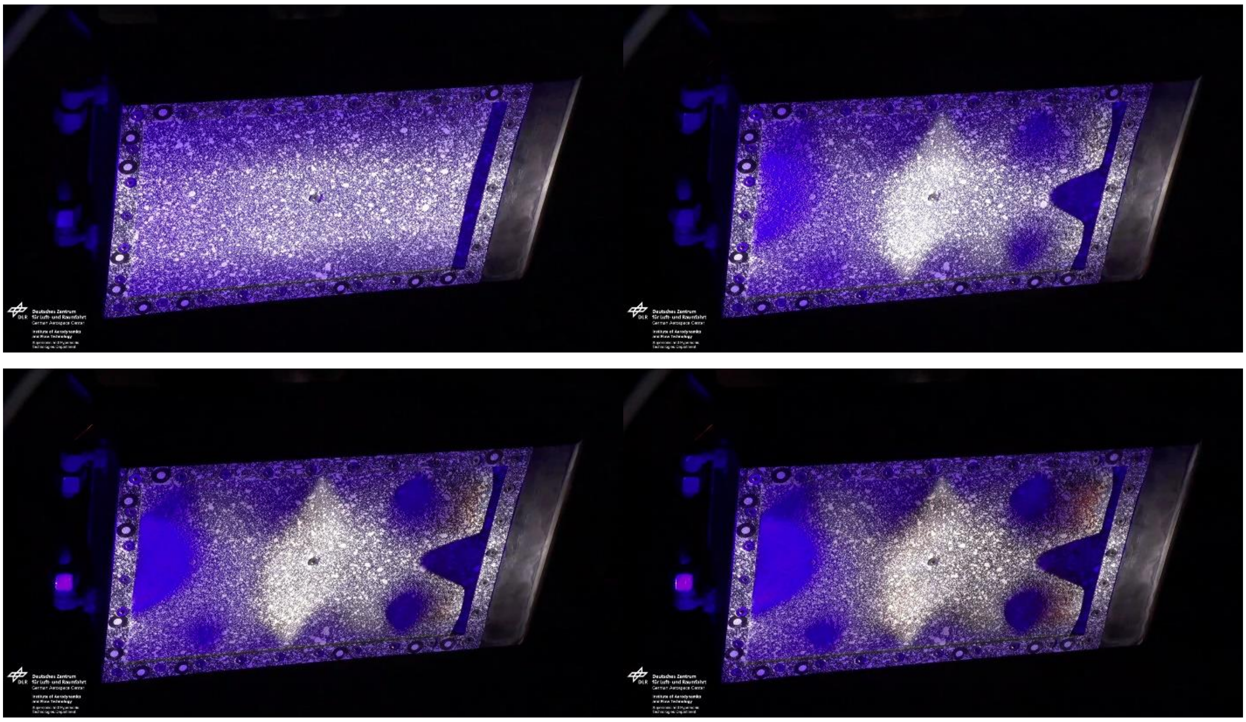

Figure 19: Surface deformation of Incoloy panel during wind tunnel run at 10° angle of attack in 30 s steps

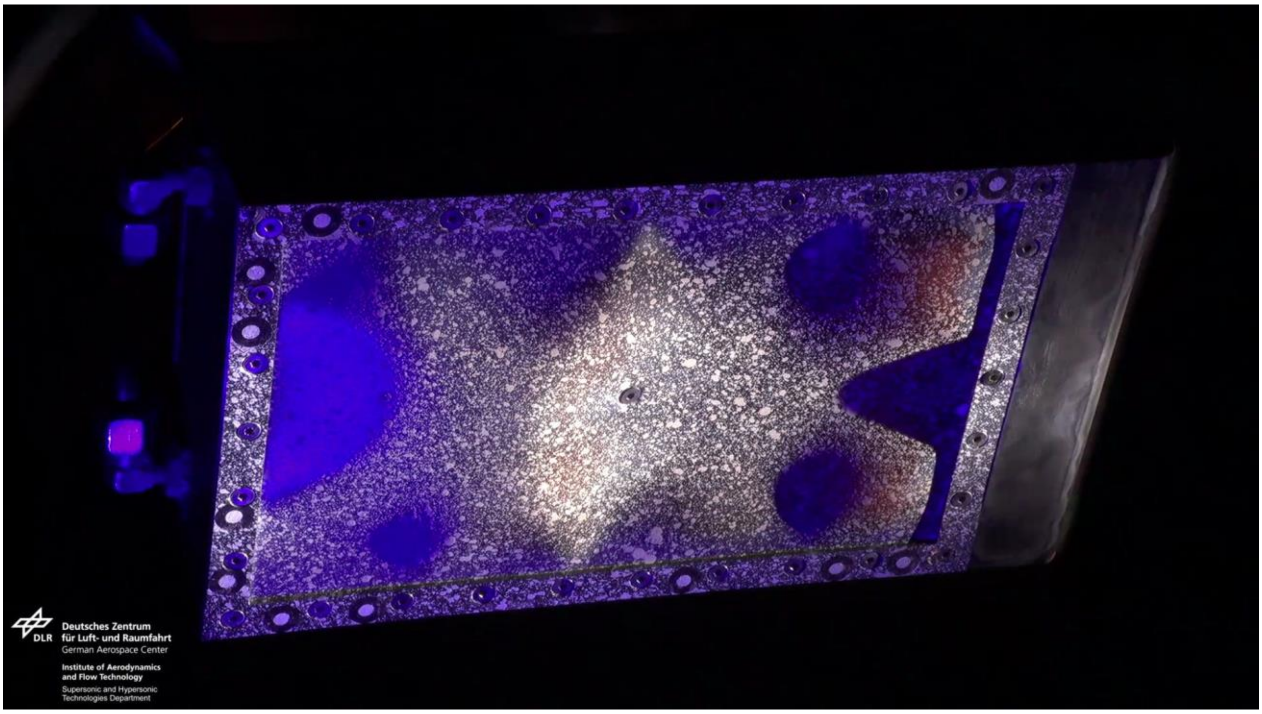

Figure 20: Surface deformation of Incoloy panel during L3K wind tunnel run at 10° angle of attack after 120 s

Figure 21 shows images of the inspection of the wind tunnel model after 16 wind tunnel runs that included cool-down, aerothermal loading and return to ambient temperature. The cryogenic insulation shows no sign of deterioration except some local damage near the standoff that was incurred during the last two wind tunnel runs at heat loads exceeding the nominal design at increased angle of attack.

The main results of the wind tunnel campaign are:

- No damage evident after 16 load cycles of aerothermal loads with cryogenic tank temperatures
- Effects of ice/water in the insulation could be shown

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- Full-field time-resolved surface deformation and temperature could be measured (data processing and analysis ongoing)

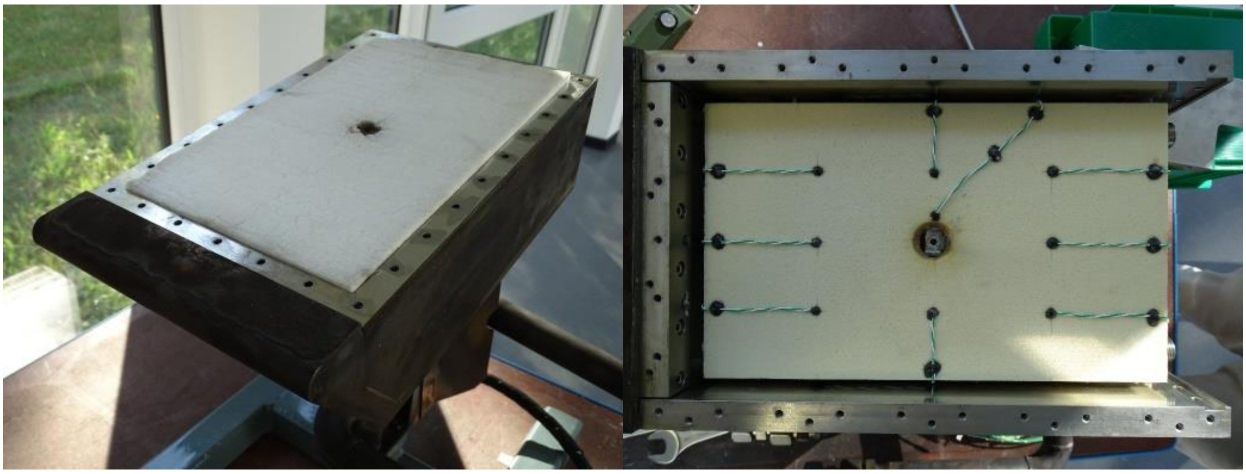

Figure 21: Inspection of the L3K wind tunnel model after last test

The experiments demonstrate the feasibility of the proposed design. However, they also show that the thermomechanical behaviour of such a configuration under repeated aerothermodynamic and cryogenic load cycles needs to be thoroughly understood and considered for the design of such structures to enable reliable reuse. Future studies should additionally include the effects of structural dynamics and considerations regarding structural health monitoring (SHM).

3. Conclusion

The DLR continues to investigate the combined integration of reusable cryogenic insulation with an external thermal protection system onto a cryogenic propellant tank for future reusable first stages. The derived designs have been tested under thermal and mechanical loads in the THERMEX facility and under aerothermal loads in the arc-heated wind tunnel L3K. The third and final test object is currently under investigation in the THERMEX facility.

The initial analysis of the experimental results indicates that the thermal response of the test objects was as expected and does not show degradation over multiple thermal load cycles. Further analysis of gathered data and additional experimental work are underway.

The work done within the TRANSIENT project does not cover experiments with LH2, instead the surrogate LN2 is used. The experimental facilities used for application of the thermal and mechanical loads described above cannot currently be operated with liquid hydrogen. Including this boundary condition in future experiments would be the next step for preparing this critical technology for future reusable launch systems as well as the next generation of in-flight demonstrators of reusable winged first stages.

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