DLR CONCEPTS OF ADVANCED THERMAL PROTECTION SYSTEMS FOR REUSABLE CRYOGENIC PROPELLANT TANKS

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ABSTRACT

Reusable launch vehicles (RLV) require robust and lightweight thermal protection systems (TPS) for cryogenic propellant tanks. These tanks experience extreme temperature gradients during flight, ranging from cryogenic temperatures within the tank to temperatures exceeding several hundred degrees Celsius on the exterior during reentry, demanding innovative solutions. To address this, the German Aerospace Center (DLR e.V.) investigates advanced insulation concepts, including purge gaps to decouple cryogenic and high-temperature insulation layers, enabling independent optimization of each layer and reducing overall thickness and weight. The AKIRA project demonstrated the feasibility of this approach for metallic tanks, while the TRANSIENT project extended it to carbon fiber reinforced polymer tanks. One subject of the ongoing TWEAK project focuses on developing a new TPS attachment system considering lightweight, maintenance and sustainability aspects. This paper summarizes DLR's research in this topic and outlines future directions in developing advanced insulation and TPS concepts for future RLVs.

***Index Terms*—** RLV, TPS, Cryogenic Tank, Purge Gap

1. INTRODUCTION

Reusable launch vehicles (RLV) are pivotal for sustainable space transportation, promising substantial cost reductions through multiple flights with the same hardware. However, realizing this potential necessitates a confluence of factors: robust structures, efficient maintenance, and competitive operating costs compared to expendable counterparts. A critical challenge lies in mitigating the extreme thermal environment RLVs encounter, particularly for cryogenic propellant tanks. These tanks experience a drastic temperature gradient, ranging from several hundred degrees Celsius at the surface during reentry to -253 °C at the tank structure when filled with liquid hydrogen (LH2). To prevent thermal damage to the vehicle structure and minimize propellant boil-off, the development of an efficient lightweight, low-maintenance and reliable thermal protection and insulation system for cryogenic tanks is imperative.

The Thermal Protection System (TPS) is critical for safeguarding vehicle structures from extreme aerothermal loads during atmospheric reentry, ensuring the structural integrity and funcionality of both the cryogenic insulation and substructure by maintaining their respective maximum operating temperatures. Reusable, non-ablative TPS solutions, such as Ceramic Matrix Composite (CMC) panels combined with a flexible felt high-temperature (HT) insulation, have been validated in DLR's hypersonic flight experiments, including SHEFEX I [1], SHEFEX II [2] and STORT [3]. These TPS structures are mechanically fastened to the substructure via attachment elements designed to accommodate differential thermal expansion. In the context of RLVs employing cryogenic propellant tanks, the TPS attachment elements are subjected to a significant thermal gradient during reentry, functioning as thermal bridges between the cryogenic tank and the hot TPS surface. This necessitates attachment designs that provide robust structural connectivity while minimizing conductive heat transfer and accommodating substantial thermal strain differentials. Furthermore, the performance of the HT-insulation must be maintained during pre-launch operations. This requires mitigating air condensation and associated mass accumulation by ensuring the HT-insulation temperature remains above the air's dew point (simplified as above 0 °C for the following investigations) during cryogenic propellant loading, thereby also preventing external ice formation [4, 5]. Consequently, the thermal design of the TPS and cryogenic insulation represents a tightly coupled problem necessitating a comprehensive, integrated approach.

The German Aerospace Center (DLR e.V.) contributes to this field by investigating advanced thermal protection and insulation systems for RLV, using the SpaceLiner winged booster stage as a reference concept [6]. This stage is designed to separate from the upper stage at Mach 12, return to the launch site via in-air-capture (IAC, [7]), and land horizontally, aiming for reusability following inspection and refurbishment. It features integrated cryogenic tanks for LH2, occupying the mid and aft section, and liquid oxygen (LOX)

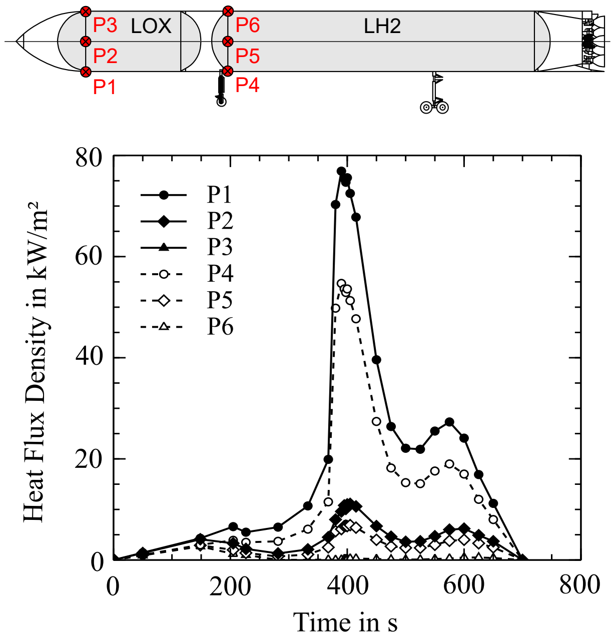

Fig. 1. Heat loads on selected design points of the SpaceLiner7 booster vehicle.

in the forward section of the fuselage. Figure 1 shows the time-dependent heat flux densities for specific design points, derived from the SpaceLiner 7 (SL7) trajectory. According to this, heat load peaks at the windward side of the LOX tank with $78\,\mathrm{kW\,m^{-2}}$. Based on this, two critical thermal requirements were defined for TPS and insulation design:
R1: Minimum temperature of $0\,°\mathrm{C}$ for the TPS during prelaunch operations.
R2: Maximum temperature of $170\,°\mathrm{C}$ for the cryogenic insulation during booster reentry.

An insulation concept featuring a "purge gap" was experimentally investigated for metallic tanks as part of the AKIRA project to thermally decouple cryogenic and HT-insulation layers. Building on these promising results, this insulation concept was considered for the latest aerothermodynamic investigations of the SpaceLiner 8 booster [8]. The TRANSIENT project further advanced this concept by integrating the purge system within a carbon fiber reinforced polymer (CFRP) sandwich tank structure, simplifying the system and reducing tank mass. Both concepts were realized as integrated test objects (ITOs), including dedicated TPS attachment systems, and subjected to thermal cycling simulating the prelaunch and reentry conditions of the reference booster stage. Currently, the TWEAK project is leveraging these advancements to develop an optimized TPS attachment system for lightweight cryogenic tanks.

2. AKIRA – PURGED INSULATION SYSTEM FOR METALLIC CRYOGENIC TANK

The DLR project AKIRA (translated to: specific critical technologies and integrated system investigations for RLV applications), a multidisciplinary research project from 2017 to 2019, focused on technologies crucial for RLV development [9]. One of the key objects was the development and experimental validation of an advanced insulation concept for cryogenic propellant tanks, aiming to enhance cost-effectiveness and reliability in reusable TPS and insulation. To this end, the 'purge gap' concept was selected for testing under thermal conditions representative of the SL7 booster stage.

The purge gap, a dedicated space between HT-insulation and cryogenic insulation, facilitates the injection of dry, preheated gas during the steady-state tank fueling phase. This design aims to prevent condensation within the HT-insulation during pre-launch fueling through two primary mechanisms: heat transfer into the system and prevention of moist air ingress. By adjusting purge parameters such as gas temperature T_{gas} and mass flow rate $\dot{m}$, a balance can be achieved between desired effects and potential drawbacks, such as increased propellant boil-off. Extensive steady-state and transient 2D thermal parametric studies, described in detail in [10], were conducted to determine optimal insulation and TPS thicknesses, as well as purge flow parameters and gap height, to satisfy defined requirements R1 and R2. These studies demonstrated a 45 % reduction in required cryogenic insulation thickness compared to a non-purged system.

Building on the 2D thermal simulations, 3D simulations were performed to design the TPS standoff element and identify an optimal material combination that minimized temperature field disturbances. The design utilized the gas feed tube fixation points, integrating them with the TPS fastener. This allowed for temperature control of the standoffs at the purge gap interface through conductive heating from the purge tube [10].

Finally, fluid simulations were performed to assess the purge flow parameter range for the experiments, specifically gas temperature T_{gas} and mass flow rate $\dot{m}$. A detailed description of the fluid simulations and parametric study can be found in [11].

The resulting ITO and standoff design are depicted in Fig. 2. The $400\,\mathrm{mm}$ x $400\,\mathrm{mm}$ ITO comprised a TPS consisting of a preoxidized Inconel 600 surface panel and a $15\,\mathrm{mm}$ ALTRA® Mat open-pore alumina silica fiber insulation and a $30\,\mathrm{mm}$ Rohacell® polymethacrylimide-based closed-cell rigid foam as cryogenic insulation, bonded to an aluminum tank panel. A $20\,\mathrm{mm}$ high-permeability spacer mesh fabric filled the purge gap. The gas feed system consisted of a single copper tube with regularly spaced small boreholes for gas injection. The ITO featured a central standoff bolted to the aluminum panel, segmented into materials of varying thermal conductivity to minimize thermal bridging. The design allowed for elastic deformation to accommodate thermal expansion mismatches between the hot surface components and the cryogenic tank structure. An insulating footplate reduced the required heating from the purge tube to meet requirement R1. To ensure efficient thermal contact, the purge tube was brazed to copper alloy strips clamped between the standoff elements, effectively directing thermal energy to the cold side. The standoff components exposed to high reentry thermal loads were fabricated from Inconel 600, matching the surface panel, while the remaining components were made of stainless steel. The ITO assembly and standoff details are shown in Fig. 3.

The experimental setup and testing procedure for the ITO, along with the results and scale-up considerations, are presented in [12]. Thermal testing was conducted using DLR's induction-heated thermo-mechanical test facility INDUTHERM, simulating two critical booster mission phases: pre-launch loading and reentry. These phases correspond to design requirements R1 and R2, respectively. For the pre-launch case, the aluminum panel was cooled with liquid nitrogen (LN2), while the ITO was purged with a constant mass flow rate $\dot{m}$ of nitrogen at temperature T_{gas}, under ambient atmospheric conditions. A series of 14 steady-state test runs were performed, systematically varying the purge gas temperatures from $17\,°\mathrm{C}$ to $38\,°\mathrm{C}$ and the mass flow rates from $1.0\,\mathrm{g\,s^{-1}}$ to $2.5\,\mathrm{g\,s^{-1}}$. The objective of the steady-state tests was to find a purge flow parameter combination that satisfies requirement R1, which was determined to be $32\,°\mathrm{C}$ and $2.5\,\mathrm{g\,s^{-1}}$.

To simulate the reentry phase, transient test runs were performed. The ITO sample was initially cooled to replicate the residual cold state of the vehicle tank structure during reentry. Following thermal equilibrium, the purging was terminated, and the test chamber was sealed and evacuated after complete LN2 evaporation. Subsequently, an inductive heating cycle was initiated, replicating the calculated time-dependent reentry heat flux profile for the SL7 design point P1 on the ITO surface panel. In total, 5 transient rest runs were completed. The tests revealed the TPS shielded high temperatures from the underlying insulation layer effectively.

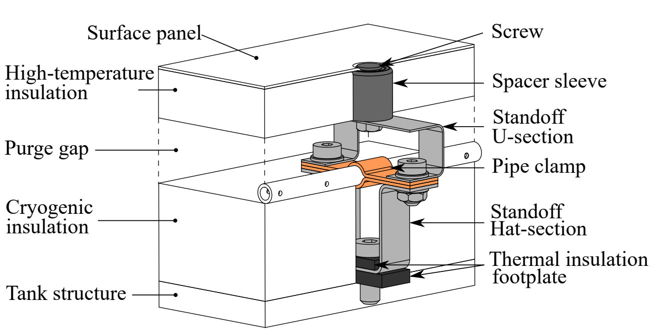

Fig. 2. Section of the AKIRA ITO including standoff element.

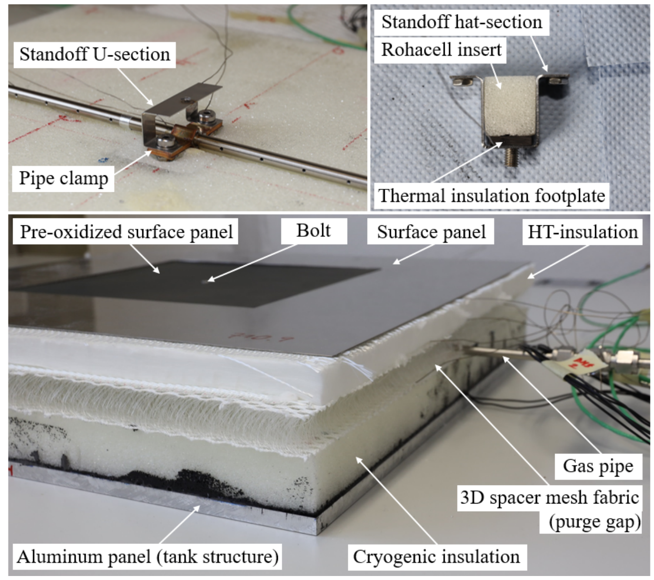

Fig. 3. Standoff details and fully assembled AKIRA ITO.

In conclusion, the critical function of the temperature control by the integrated concept of cryogenic insulation, purge gap, and TPS insulation was successfully verified. No performance degradation was observed throughout the test cycles. However, the inherent complexity of the purge gap necessitates further investigation into gas management, system simplification, and the potential size effects associated with operational vehicle purge lines spanning several meters.

3. TRANSIENT – PURGED INSULATION SYSTEM FOR COMPOSITE CRYOGENIC TANK

To further proceed the investigations of reusable insulation and thermal protection systems for RLV cryogenic tanks, the follow-on DLR project TRANSIENT (translated to: thermal control system for reusable launcher) was initiated in 2020 [13]. One of the key aspects was the transfer of the AKIRA experimental results to a composite cryogenic tank, aiming at maximizing the weight-saving potential of the purge concept.

To do so, the purge system was integrated into a CFRP corrugated core sandwich structure, which simultaneously served as the tank structure. The corrugated core provides a high stiffness-to-mass ratio and internal channels for purging for both thermal control and removal of leaked propellant gases. Consequently, it eliminates the weight penalty of a separate purge system, unlike the AKIRA concept. The new tank insulation concept was again realized as ITO, featuring an external cryogenic insulation and a TPS including a CMC surface panel and a modified TPS attachment system. The ITO design process was accompanied by a comprehensive numerical parametric study to assess the insulation layer thicknesses and material choices for the TPS attachments,

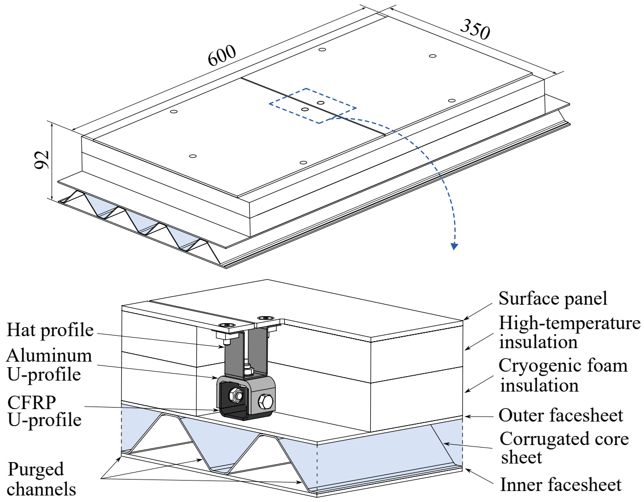

Fig. 4. Section of the TRANSIENT ITO.

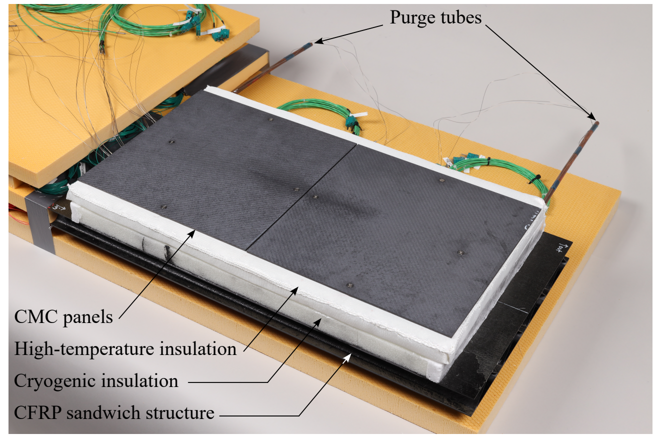

Fig. 5. Fully assembled TRANSIENT ITO.

which are detailed in [14]. Again, the SL7 booster stage with its corresponding thermal requirements R1 and R2 was the design's reference configuration.

The final ITO design including the TPS attachment element is illustrated in Fig. 4. To minimize heat input into the cryogenic propellant, only alternating channels of the corrugated core were purged with preheated gas, as highlighted blue. A $30\,\mathrm{mm}$ thick Rohacell® cryogenic insulation layer was bonded to the outer CFRP facesheet. The TPS configuration consisted of a $25\,\mathrm{mm}$ thick HT-insulation layer and an in-house fabricated carbon fiber reinforced silicon carbide (C/C-SiC) matrix composite surface panel [15]. The TPS panel was mechanically attached to the tank structure using a multi-component attachment system designed with varying thermal conductivites. A CFRP U-profile, selected for its thermal compliance, was bonded to the tank structure as base component. An inverted aluminum U-profile was then mechanically fastened to the base, followed by a stainless steel hat profile bolted to the aluminum part. Finally, the surface panels were bolted to the flexible flanges of the hat profile, which were designed to accommodate thermal expansion.

Subsequently, the ITO was manufactured and extensively instrumented with a total of 55 thermocouples, allocated at each interface layer and within the central TPS attachment element, to evaluate the effectiveness of the purge and insulation concept. Purge gas temperatures and pressures were continuously monitored at each purge channel inlet and outlet. Additionally, a thermal imaging system was used to monitor the surface temperatures of the TPS panels. Detailed information regarding the manufacturing process and instrumentation can be found in [16]. The fully assembled ITO is depicted in Fig. 5.

The ITO was successfully tested in the DLR thermomechanical test facility THERMEX [17]. A total of 36 test runs were conducted, including 23 full thermal cycles simulating pre-launch and reentry conditions. For these tests, the ITO was installed upside down in the test facility, with the TPS panels oriented towards the infrared heating unit. An LN2 filled basin was placed atop the ITO to provide the thermal boundary condition representing the propellant.

Each thermal cycle included two phases, the first being a steady-state tank filling load case. This involved LN2 filling and maintaining a constant level while purging with preheated gas at $45\,^{\circ}\mathrm{C}$ and a mass flow rate of $2\,\mathrm{g\,s^{-1}}$ for most cycles. Once all ITO temperatures reached steady-state, the LN2 was allowed to evaporate, immediately followed by the reentry transient load case. To simulate reentry conditions, infrared heaters applied a predefined heat load of $46\,\mathrm{kW\,m^{-2}}$ to the CMC panel surface for approximately 140 seconds, resulting in TPS surface peak temperatures of $690\,^{\circ}\mathrm{C}$. A thermal cycle was considered complete when the ITO temperatures returned to ambient room temperature. The complete testing procedure is described in [16].

The results of the tests are detailed in [18], the following sections will give a brief overview over the most important results.

The steady-state test phase aimed to validate the efficacy of internal purging in preventing condensation within the HT-insulation, thereby ensuring that temperatures within the HT-insulation layer remained above $0\,^{\circ}\mathrm{C}$. Figure 6 presents interpolated temperature distributions at the interface between the cryogenic insulation and the HT-insulation for both unpurged (a) and purged (b) test runs. In the unpurged test, a uniform temperature distribution of approximately $-50\,^{\circ}\mathrm{C}$ was observed across the entire interfacial area, serving as a baseline. Conversely, the purged test exhibited a distinct temperature gradient along the x-direction, with elevated temperatures at the centerline (y = 175 mm) and lower temperatures towards the long edges. The initial temperature increase is attributed to the preheated purge flow entering the corrugated core channels at x = 0 mm. Then, a significant thermal gradient was observed along the longitudinal axis (x-direction). Specifically,

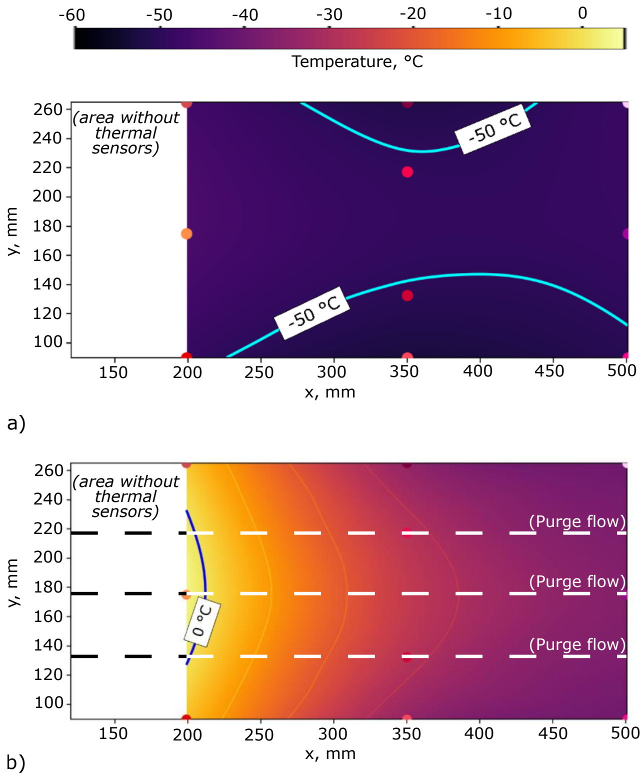

Fig. 6. Interpolated temperature distribution of the steady-state temperatures at the interface between cryogenic and HT-insulation of an unpurged (a) and a purged (b) test run. The red dots indicate thermocouple positions.

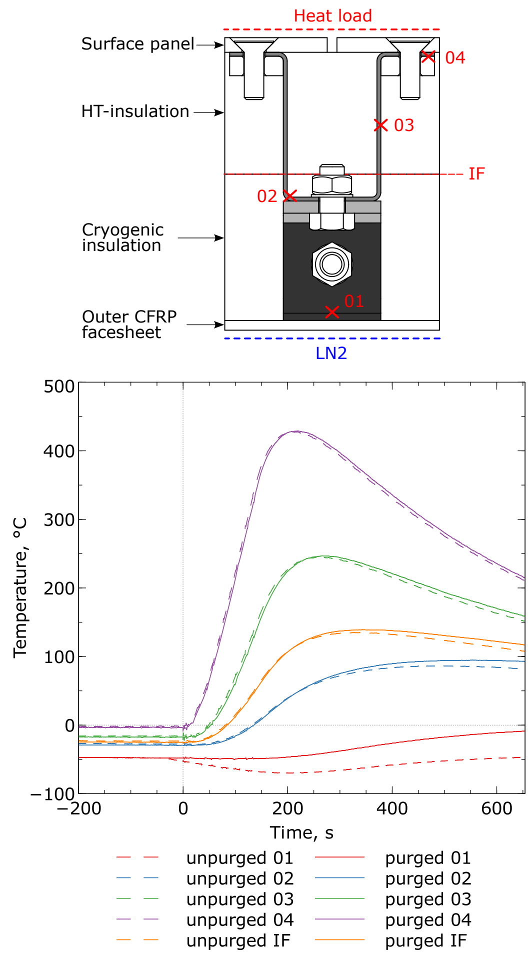

Fig. 7. Attachment element temperature profiles for a purged (solid lines) and unpurged (dashed lines) test run. Thermocouple position 01-04 of the central attachment element tagged in the image above.

temperatures began at approximately 0 °C at the initial thermocouple location (x = 200 mm) and progressively decreased to approximately -40 °C at the outlet (x = 500 mm) along the purge flow path. This temperature decline indicates insufficient purge flow to maintain the desired temperature profile. The temperature gradient in y-direction suggests potential edge effects caused by the fixturing method applied to the corrugated core's short edges within the test facility, enabling an increased heat transfer into the ITO. Additionally, a non-uniform purge flow distribution into the three channels could amplify this temperature gradient. Although purging demonstrably influenced the temperature distribution at the insulation interface compared to the unpurged test, the thermal requirement R1, specifying temperatures above 0 °C, was not achieved.

To evaluate the TPS requirement R2 during the transient heating test phase, the central attachment element temperatures were analyzed in addition to the layer interface temperatures. The metallic components, due to their higher thermal conductivity, pose a risk of overheating the surrounding cryogenic insulation. Figure 7 compares attachment element temperature profiles for a purged test with those of a test where purging was deactivated prior to heating, simulating flight conditions where purging is limited to pre-launch operations. A marginal effect of purging was observed at thermocouple position 02, 03 and 04. At thermocouple position 01, located at the base bonded to the cold tank structure, a maximum temperature difference of 40 °C was measured between the two tests. To validate thermal requirement R2, the interface temperature between the cryogenic and HT-insulation was interpolated using temperature signals 02 and 03 located at the attachment element. The resulting temperature profile IF is presented in 7. Across all test runs, the resulting interface temperature remained below the maximum allowable temperature of 170 °C, thus confirming compliance with R2.

While the purge system did not prevent widespread temperature drops within the HT-insulation, the results indicated that strict temperature requirements on the HT-insulation might be relaxed without significant insulation performance degradation. The reusability of the overall concept consisting of CFRP cryogenic tank, insulation and CMC TPS including attachment system was thermally proven. A comprehensive presentation and discussion of the TRANSIENT experimental results are provided in [18].

4. TWEAK – RLV TPS ATTACHMENT SYSTEM

Building upon the thermally validated integrated cryogenic insulation and thermal protection system, the follow-on project TWEAK (thermal protection for reusable cryogenic tanks), initiated in 2025, will advance multidisciplinary concepts from AKIRA and TRANSIENT. A key focus is the development and testing of a cost-effective, rapid-assembly fastening system for TPS integration on cryogenic tanks, minimizing bolt connections. A test demonstrator will be subjected to relevant loads. The project will also expand research on bonding procedures for cryogenic insulation, addressing maintenance and sustainability considerations.

5. CONCLUSION

The development of a robust insulation and thermal protection system (TPS) for reusable launch vehicle (RLV) cryogenic propellant tanks is crucial. The German Aerospace Center (DLR e.V.) addressed this challenge by developing and testing an integrated purged insulation system, including TPS attachment elements, initially for metallic RLV tanks and subsequently adapted for composite tanks. Thermal design requirements were derived from the conceptual SpaceLiner7 RLV booster stage mission cycle, representing the launch preparation and tank filling thermal load case and the reentry thermal load case.

To validate temperature control ability and reusability, integrated test objects (ITO) were designed and built for each of the concepts and subjected to thermal testing. Cyclic tests, simulating the steady-state pre-launch phase using liquid nitrogen at $-189\,^{\circ}\mathrm{C}$ as cryogenic propellant substitute, and the reentry phase with peak temperatures reaching $690\,^{\circ}\mathrm{C}$, were conducted in DLR high-temperature test facilities. Results demonstrated the concepts' reusability, showing no significant degradation after repeated cycles in both cases.

In the case of the carbon fiber reinforced polymer (CFRP) tank structure, where purge flow was integrated within the CFRP corrugated core sandwich structure, maintaining the high-temperature insulation above freezing point, as intended, was not successful. However, despite potential condensation within the high-temperature insulation, no negative impact on insulation performance was observed. Notably, the TPS effectively protected the underlying insulation and structure from extreme temperatures in both the metallic and composite tank configurations across all cycles. With regard to the composite ITO test results, further investigations are targeted regarding the effects of condensation and icing inside of the HT-insulation and its consequences on insulation and mechanical properties, mass accumulation and safety issues.

Current research efforts are dedicated to the development of new TPS fastening systems applicable to both metallic and composite tank structures. The goal is to design and validate a rapid, cost-effective mechanical attachment system that reduces or replaces bolted interfaces, considering the operational requirements of a full-scale vehicle.

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