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Investigation of insulation and thermal protection systems for reusable cryogenic stages

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Abstract

Reusable launch vehicle stages encounter large heat fluxes during their mission, especially during reentry. For winged stages decelerating through aerodynamic forces this means, large areas of the of the vehicle have to be covered with a thermal protection system (TPS). For reusable systems with integral cryogenic tanks the TPS is exposed to the cryogenic temperatures of the propellants within. If the propellant tanks are covered in cryogenic insulation, required for hydrogen-fueled stages, the TPS and cryogenic insulation cannot be treated as separate technical domains but have to be designed and integrated jointly, considering the boundary conditions of each other. Additional complexity is introduced by the fact that no operational experience for orbital stages exist for the reuse of cryogenic insulation.

Within the DLR this topic was first explored in the AKIRA project, and the work is being continued within the currently ongoing project TRANSIENT. The design of the combined subsystem from AKIRA is further refined and applied to both metallic and composite tank materials. In addition to the thermal loads previously considered, the mechanical loads acting on the vehicle throughout the mission are assessed and incorporated into the design of the experimental devices. For both cases segments meant to represent a slice of an RLV propellant tank are being manufactured and equipped with the combined cryogenic insulation and thermal protection systems and will be tested under representative loads for up to 50 cycles. In addition to the thermal loads, mechanical loads will also be applied to the test objects. The current status of the integration and preparation of the test objects is shown and the planned experiments discussed.

Keywords: RLV, TPS, Cryogenic insulation, cryogenic propellant

Nomenclature

AOA	Angle of Attack	LOX	Liquid Oxygen
CAD	Computer Aided Design	MECO	Main Engine Cut Off
CMC	Ceramic Matrix Composite	RLV	Reusable Launch Vehicle
DIC	Digital Image Correlation	RP-1	Rocket Propellant (Kerosene)
DLR	German Aerospace Center	RTD	Resistance Temperature Detectors
ELV	Expendable Launch Vehicle	SLB	SpaceLiner Booster
GLOW	Gross Lift-Off Mass	Ti	Titanium
ITO	Integrated Test Object	TPS	Thermal Protection System
LFBB	Liquid Fly-Back Booster	TRL	Technology Readiness Level
LH2	Liquid Hydrogen	TSTO	Two-Stage-To-Orbit
LN2	Liquid Nitrogen		

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. 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 vehicles, the use within RLV's comes with new challenges. As one critical technology for future hydrogen-fueled 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 [6]. For a winged system the cryogenic insulation has to be integrated with the thermal protection system (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][2], with a more in depth-discussion of the reference mission and the mechanical loads experienced by the reference configurations, which are the basis for the more detailed design at subsystem level. In order to test the derived designs three Integrated Test Objects (ITO) are being designed, manufactured and integrated, the current status of the test objects and the planned experimental campaign are also discussed.

1.1. Technical challenge

The understanding of the behavior 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, 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 [1] - [5].

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 will be put through dozens of cycles of thermal and mechanical loads representative of a first stage RLV mission.

2.1. System aspects

In support of the experimental campaigns at the core of the project, system aspects are also being evaluated in order to assure a better understanding of the full-sized vehicle and provide representative boundary conditions for the sizing of the relevant subsystems.

2.1.1. 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 were chosen, the ENTRAIN 2 HL [7] stage and the SpaceLiner 7 Booster [8]. 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 [6] 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-fueled vehicles.

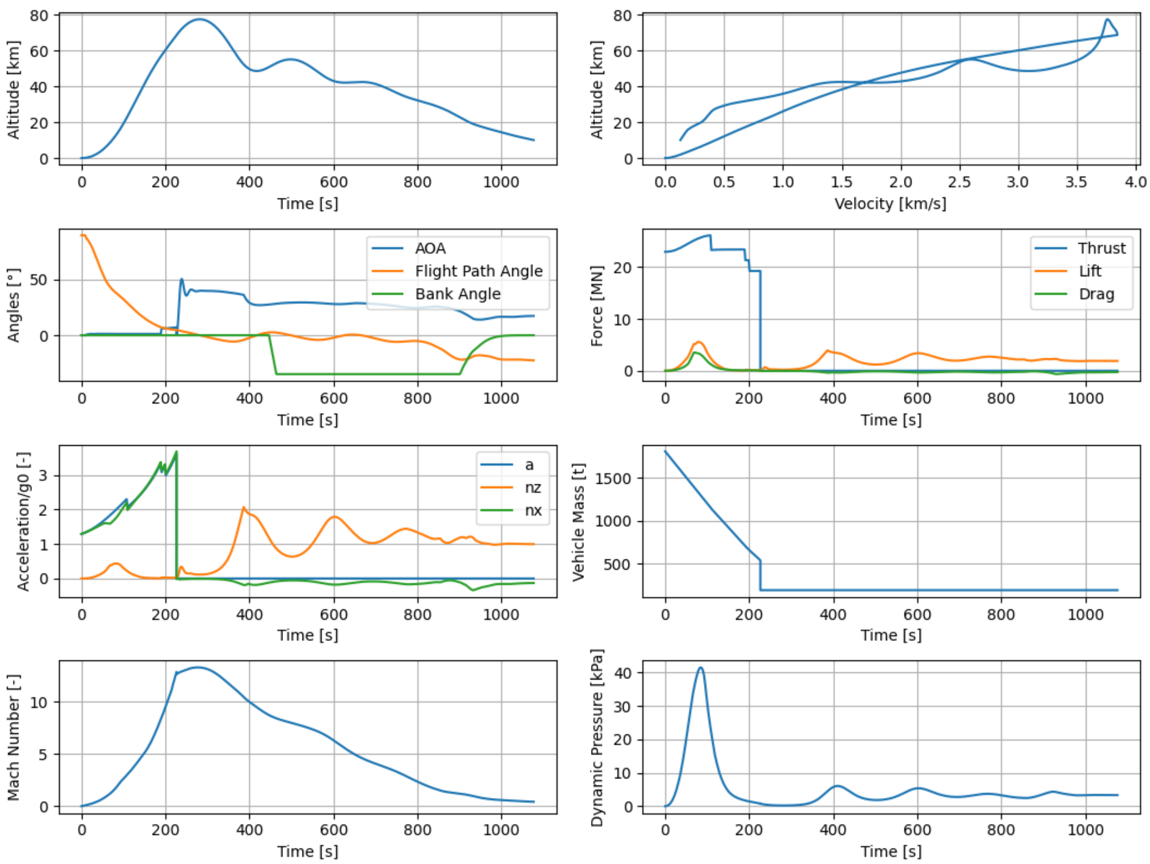

Figure 1: Ascent and descent trajectory of SpaceLiner 7 Booster

The ascent and descent trajectory of the SLB7 is shown in Figure 1. The different phases of the mission can be seen:

1. Ascent, initially with full throttle and then gradual throttling
2. MECO and separation from the upper stage (at ca. 240s)
3. Initial reentry with maximal trimmable angle of attack to reduce heat loads
4. Reduction of angle of attack in order to reduce peak nz acceleration
5. Banking maneuver in order to reorient the stage and quasi-stationary gliding flight.

The flight profile is typical for a winged first stage, albeit the MECO Mach number can be considered on the upper range of possible separation conditions.

In addition to the thermal loads, mechanical loads for a number of reference points had to be generated. These points are situated at the front and back of each tank, with an additional reference point being placed at the middle of the large hydrogen tank (5 points in total) where bending moments are expected to be highest. In contrast to standard structural launcher design, the loads are not only analyzed at the critical trajectory points but instead over the whole flight. The structural analysis is performed with the in-house tool *lsap* which simplifies the rocket to a bending beam. While this methodology does not deliver the degree of detail of, for example, a FEM-tool, it enables the efficient generation of hundreds of computations along a trajectory and delivers useful upper and lower boundaries for the expected global mechanical loads.

The mechanical loads shown and discussed in this section have been generated based on the trajectory shown in Figure 1. Wind loads including possible wind gusts were considered in the following results, so that they reflect the highest possible loads at every moment.

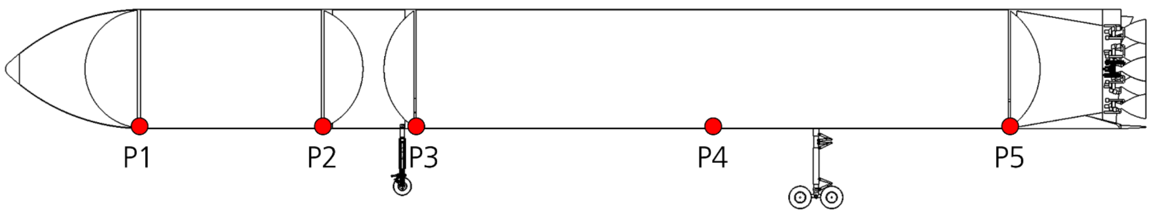

Figure 2: Reference points for analysis of thermal and mechanical loads of SpaceLiner 7 Booster

Figure 2 shows the aforementioned reference points along the underside of the SLB7 vehicle. Based on the aforementioned structure model Figure 3 and Figure 4 show the global loads acting at the reference points and their evolution over the mission. The shown parameters are the axial force along the stage and the bending moment lateral to the stage.

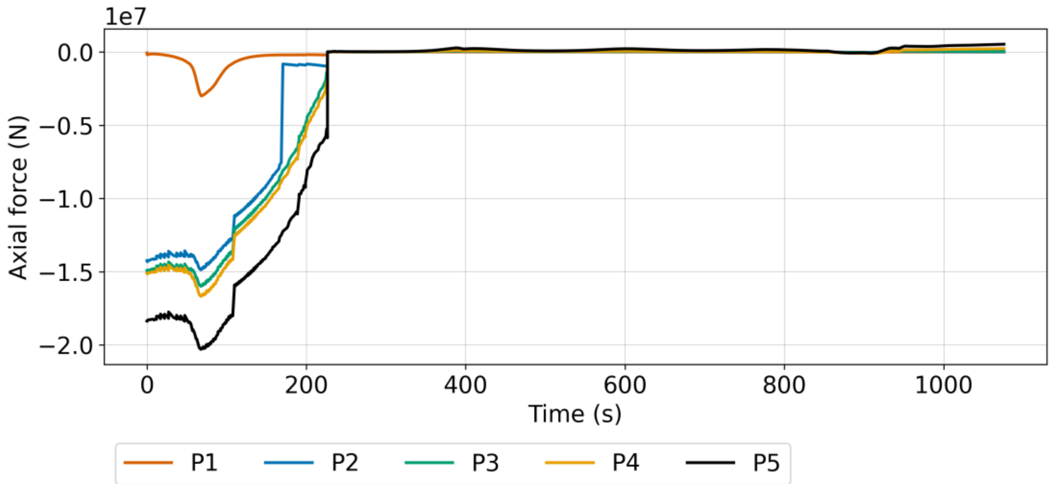

Figure 3: Global axial force along the stage for the reference points of the entire mission timeline

As the axial force is essentially caused by the thrust from the engines being transferred to the rest of the rocket, especially the propellants initially, it is consistent that these forces are the highest during the initial part of the ascent. During the course of the flight, the axial force significantly decreases, since less force has to be transferred to the upper parts of the stage. The main cause of this shifting of the thrust distribution is the draining of the LOX tank, which is at the top of the stage and, initially, contains more then 2/3 of the stages mass. After MECO no thrust is generated and while the small contribution of the drag forces during descent can be seen, they are comparably minor.

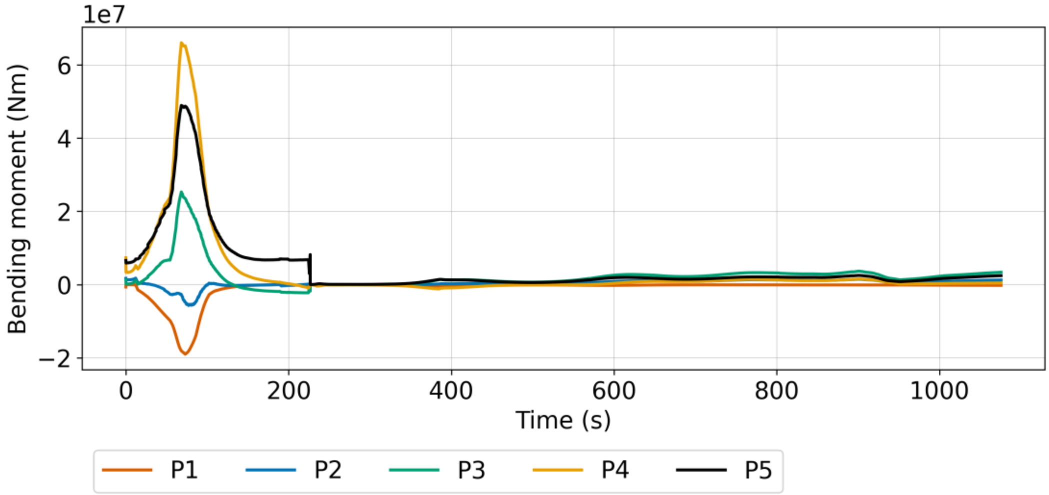

Figure 4: Global bending moment lateral to the stage for the reference points of the entire mission timeline

The bending moment lateral to the length of the stage is shown in Figure 4. In nominal flight the produced lift and the resulting bending moment would be much smaller, since the angle of attack is nominally zero during the flight of the first stage. However, for the estimation of the maximum loads possible wind loads have to be considered, including gusts. Typically, the stage has a velocity of roughly Mach 1-2 when it passes through the maximum dynamic pressure regime during ascent and at those velocities the wind can change the direction of the incoming air sufficiently to induce significant angles of attack and subsequently create substantial lift and thus bending loads. The bending loads are mostly caused by the moment arm between the main lift source, the wing, and the main mass element, the LOX in the forward tank. Thus, the largest bending moments are found in the aft section with the wing.

As with the previously discussed axial force, the bending loads during the ascent are significantly higher during the ascent. However, as can be seen in Figure 1, the nominal lift is of similar magnitude during ascent and descent. This discrepancy can be explained with two factors: First, the impact of the wind is much larger during ascent. The vehicle speed is lower at the high dynamic pressure phases of ascent than for the equivalent phase of the descent (Mach 1-2 vs Mach 10), so the ability of wind gusts to change the effective angle of attack is much higher during ascent. Second, the stage is much lighter during descent and the mass is much more evenly distributed along the vehicle length, with the main mass points no longer being the LOX in the front but instead the wings and the propulsion in the rear of the vehicle.

Figure 5 and Figure 6 show the same data from a different perspective: The axial force and bending moment along the vehicle x-axis for significant time points during the mission. As expected the axial force shown in Figure 5 is largest close to the engines and is continually reduced along the length, essentially being slowly cancelled out by the inertia forces needed for the acceleration of the point masses with which the system is modelled. It can be seen that almost half the axial force is needed for the acceleration of the LOX tank and its contents.

For the case with maximum acceleration the thrust and thus axial force are significantly reduced in comparison to the earlier snapshots. This is partially caused by the throttling during the mission: At this point the SL7 system has shut off 6 of the 11 engines operating during the ascent (9 on the booster and 2 in parallel on the upper stage). This only leaves 3 engines of the booster still operating until MECO. A noticeable part of the thrust generated by the engines is cancelled by the inertia force of the engine mass itself, thus leading to the comparably small axial force experienced by the rest of the stage at this point in the mission.

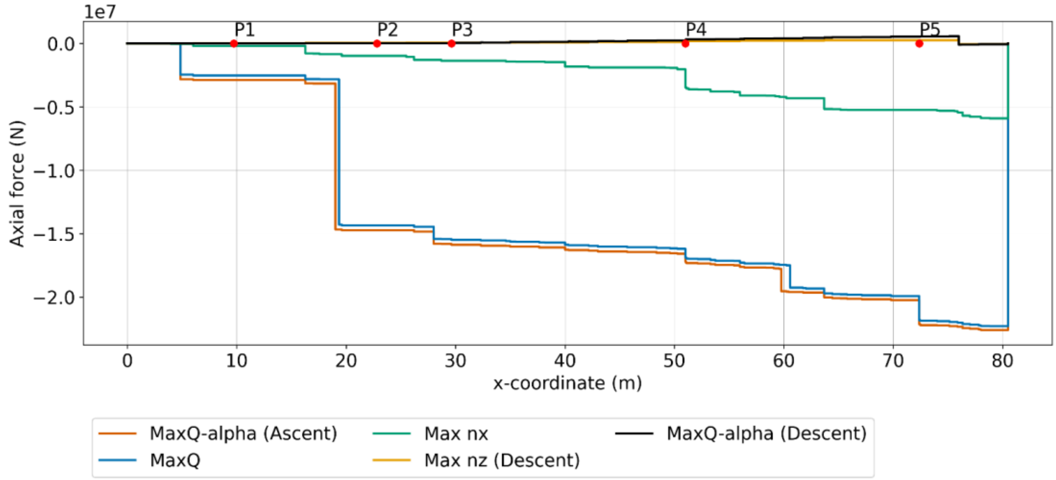

Figure 5: Global axial force along x-axis of SLB7 stage for significant moments throughout the mission

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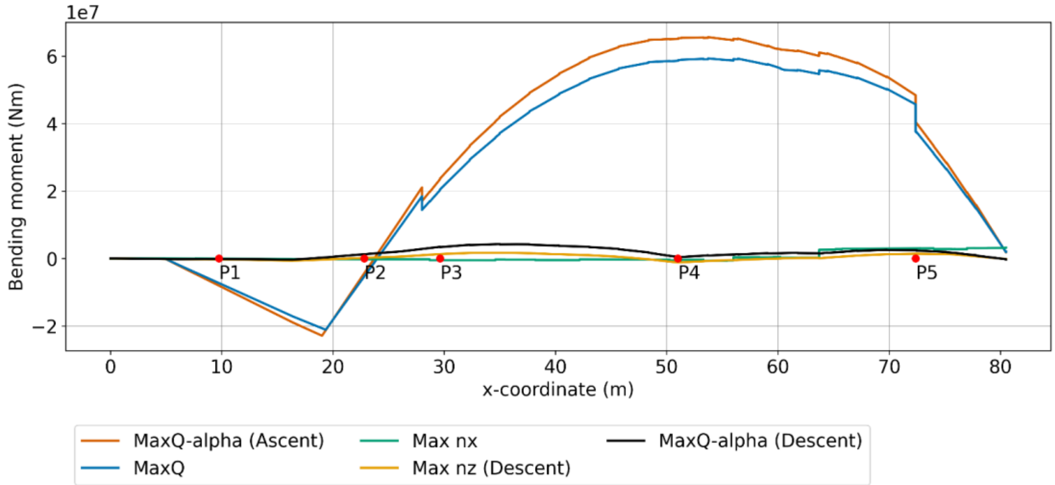

Figure 6: Global bending moment around y-axis of SLB7 stage for significant moments throughout the mission

Finally, Figure 6 shows the global bending loads, induced by the lift mostly generated by the wings and the nose of the vehicle. Again, the impact of the LOX tank at ~20 m can be seen. The discontinuities at 28 and 76 m are introduced by the attachment of the upper stage and the forces acting on the connection. Since these connections are not on the central axis, they introduce moments at these specific points. For the reasons discussed previously for Figure 4 the bending loads are much larger during ascent. From this perspective the reason for the opposite direction of the global bending loads at the front and the rear of the vehicle become apparent: The heavy LOX tank essentially hangs between the two main sources of lift: The nose and the wings, causing moments with opposite sign.

The stresses caused by these loads have been shown and discussed in [1]. In general, the largest stress within the structure is the circumferential stress created by the internal tank pressure which is present throughout the whole flight. While this is the largest stress, it is not necessarily critical in sizing, as the internal pressure actually stabilizes the hull with regard to potential buckling causes by compressive loads.

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 will investigate composite base structures in addition to the aluminium base structures, which have already been considered in the previous AKIRA project. For both material selections a combined thermal system is designed and will be investigated in experimental campaigns under thermal and mechanical loads. Flat plate samples are manufactured for the experimental investigation in a geometrical size that allows a transition of the expected thermo-mechanical loads from the reference configuration (see section 2.1) to the experiment setup in the available test facilities.

2.2.1. *Aluminium tank structure*

Based on the findings of the AKIRA study a refined design was derived for a metallic tank structure. A main target of the current study is to investigate the behaviour of the cryogenic insulation at similar strain conditions as expected in a reference configuration. Main focus is the combination of mechanical stress in addition to the thermal loads. In contrast to the AKIRA study a dedicated purge gap is omitted in the experimental apparatus. If needed, a purge system can be added to the design by milling channels into the cryogenic insulation.

For the experiment campaign aluminium AW 6085 will be used as base structure material, representing the wall structure of a propellant tank. For the cryogenic insulation a closed-cell, thermoplastic polymer foam is considered. For the hot thermal protection, a combination of aluminium silicate wool and CMC plates will be used, which is a configuration similar to other DLR re-entry projects. A cross sectional sketch of the test article is shown in Figure 7.

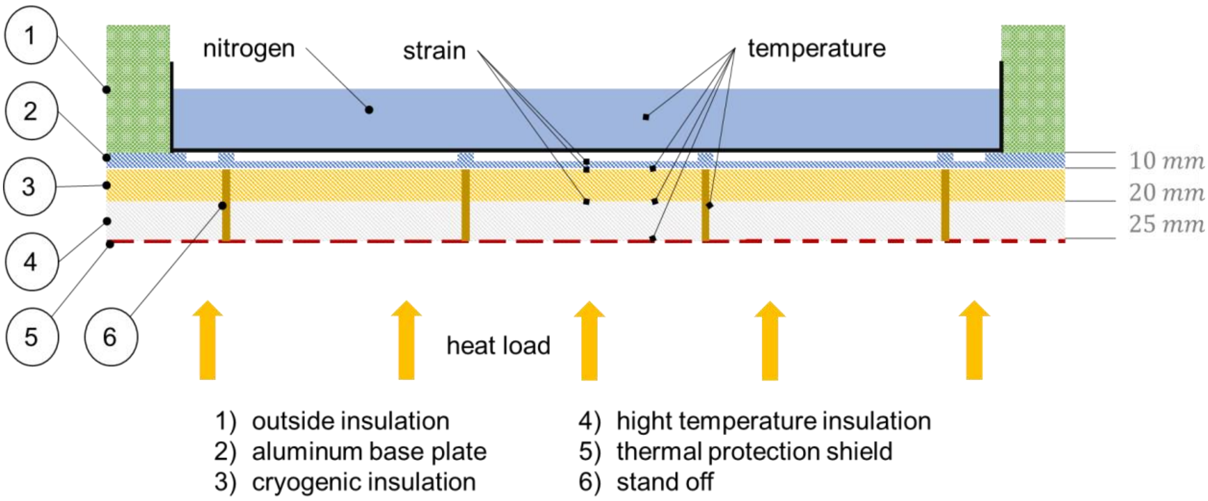

Figure 7: Sketch of cross section of the ITO representing metallic tank structures

Liquid nitrogen (LN_2) is used as a substitute for the cryogenic propellant. 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 the stand-offs, which carry the thermal protection plates. In Figure 8, a CAD model of the planned metallic ITO configuration is shown.

Temperature sensors will be integrated between the insulation layers to measure the temperature distribution throughout the layer structure. Several temperature profiles will be measured at distributed points in the area to get a temperature field of the whole ITO. Resistance Temperature Detectors (RTD) sensors will be used mainly for cold and warm temperatures, thermocouples will be used where high temperatures are expected. Strain gauge measurement is planned at the surfaces of the aluminium plate and the cryogenic foam insulation. In addition, the measurement of strain and temperature with fibre optical sensors within the cryogenic foam insulation is considered as well.

The high temperature insulation is a loose wool material for thermal protection, but will not be carrying mechanical loads. The applied TPS consists of six individual plates with spacing to compensate for thermal expansion of the various components.

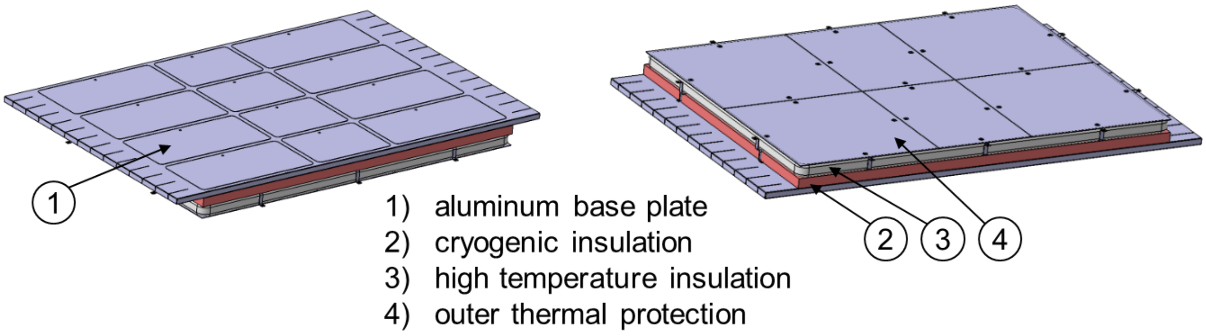

Figure 8: CAD model of the metallic ITO

2.2.2. Carbon fibre tank structure

For the CFRP tank structure, a design concept was developed based on the fluted core skirt structure built and tested during the Composite Cryotank Technology and Demonstration (CCTD) project of Boeing and NASA [11]. The design comprises of a sandwich consisting of two skins connected with longitudinal stiffeners with a trapezoidal cross-section. This design inherently creates channels in the tank structure wall that can be conveniently used for purging. The CFRP structure was made of the epoxy resin prepreg system CYCOM®5320-1/IM7, which is designed for out-of-autoclave manufacturing, offering low temperature curing capability with low resulting void content [12].

The detailed ITO design was supported by numerical simulations and is shown in Figure 9. CMC panels form the outer surface which will be exposed to thermal loads during the transient heating phase of the experiment campaign. A fibrous high-temperature insulation protects the underlying structure from exceeding the material's temperature limit. In the same time, no condensation or freezing of humid ambient air was tolerated in the high-temperature insulation in order to maintain the designed insulation performance and to prevent mass-increase. This was defined as a governing requirement for the steady-state phase of the experiments, where the CFRP tank structure of the ITO will be subjected to cryogenic temperatures, representing the pre-launch tank filling phase of the RLV. Hence, a dedicated cryogenic closed-cell foam insulation was added and will be adhered to the composite structure.

Each CMC surface panel is attached directly to the CFRP structure by four multi-part fasteners. Connecting the hot outer surface with the cold tank structure, the fasteners must provide sufficient strength and flexibility to compensate the thermal expansion mismatch between TPS surface and cold tank wall. In the same time, it is crucial to manage the thermal bridge effect of the fastener in order to maintain the required limit temperatures within the insulation materials. 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 fasteners can be effectively utilized to dissipate thermal energy into the cold structure without exceeding the cryogenic foam's or the composite's limit temperature.

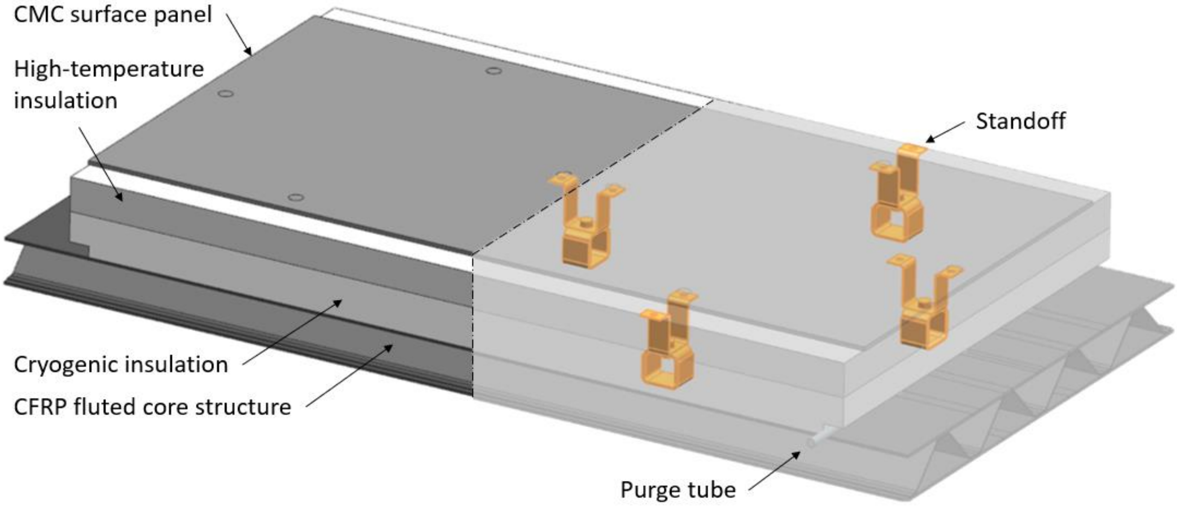

Figure 9: Concept of the CFRP base-structure ITO for the thermo-mechanical test campaign

To satisfy the requirement for the steady-state case, however, it was decided to build on the positive results of the AKIRA purge gap experiments [25] and adapt the case to the fluted core structure. Detailed thermal and fluid simulations were carried out to investigate the effect of applying a purge gas flow in the channel structure on the required insulation thicknesses. For the parameter study, different heat transfer values resulting from purge gas temperature and flow velocity were assessed as well as the required number of purged channels. The design challenge was to find the gas parameter combination that would meet the thermal requirements for the insulation while at the same time keeping the heat input into the tank within acceptable limits. As a result, every second channel will be purged during the steady-state phase as this has proven to be the most efficient method with regard to the heat transfer into the cryogenic fuel. In Figure 10 it is displayed that as a result of the purge flow in the fluted core structure, a temperature level in the high-temperature insulation above zero degree Celsius can be maintained in steady-state pre-launch conditions.

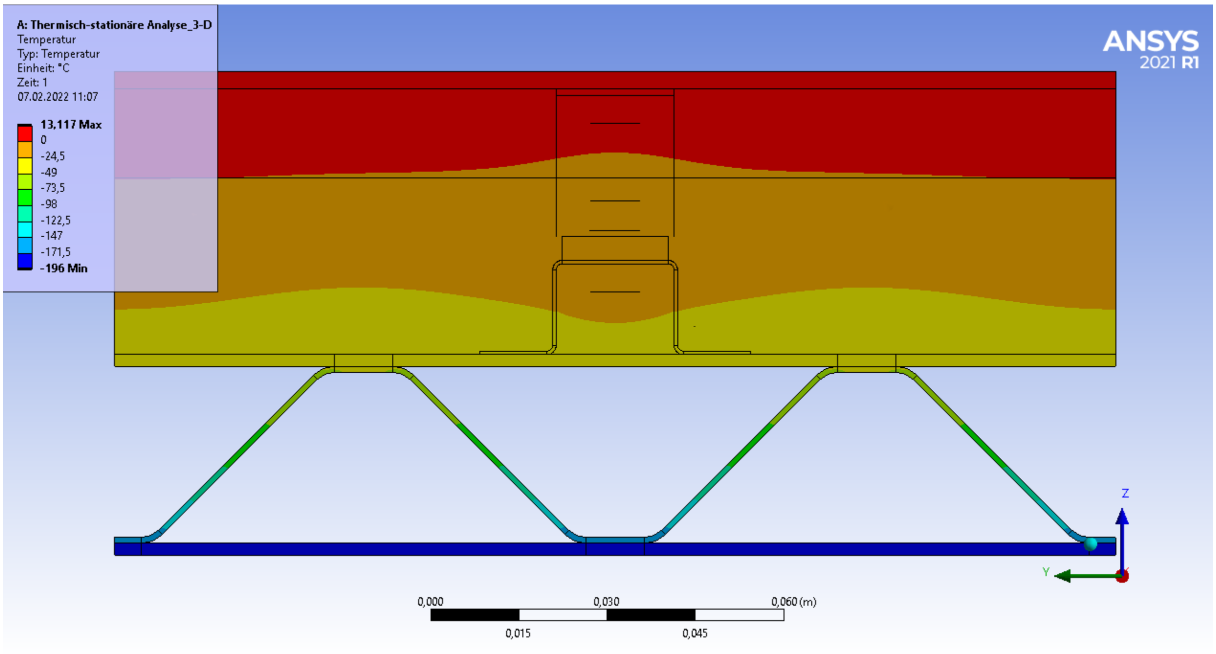

Figure 10: Temperature contours within the ITO under thermal steady-state conditions with liquid nitrogen as cryogenic propellant substitute.

2.3. *Outlook on thermo-mechanical experiments*

The updated designs for both possible base structures will be integrated into ITOs meant to represent slices of an RLV propellant tank. In total, three test campaigns with three different ITOs are planned for the second half of 2022.

2.3.1. *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. The test objects can reach a maximum dimension of 1000x800 mm and are thermally loaded by one-sided radiant heating up to 190 kW and 400 kN of axial force. It has been used in the past for similar investigations [21] of TPS systems. The investigation of stiffened CFRP panels has been part of past studies [22] and has recently become of interest again [23][24]. Here, the research focus is to elevate service temperatures by novel material solutions and to investigate the mechanical loading capacity up to glass transition temperature. The facility is shown in Figure 11.

Common test programs investigate the structural behaviour of a load carrying base structure under various thermomechanical load conditions. Within the TRANSIENT project, the focus is on 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.

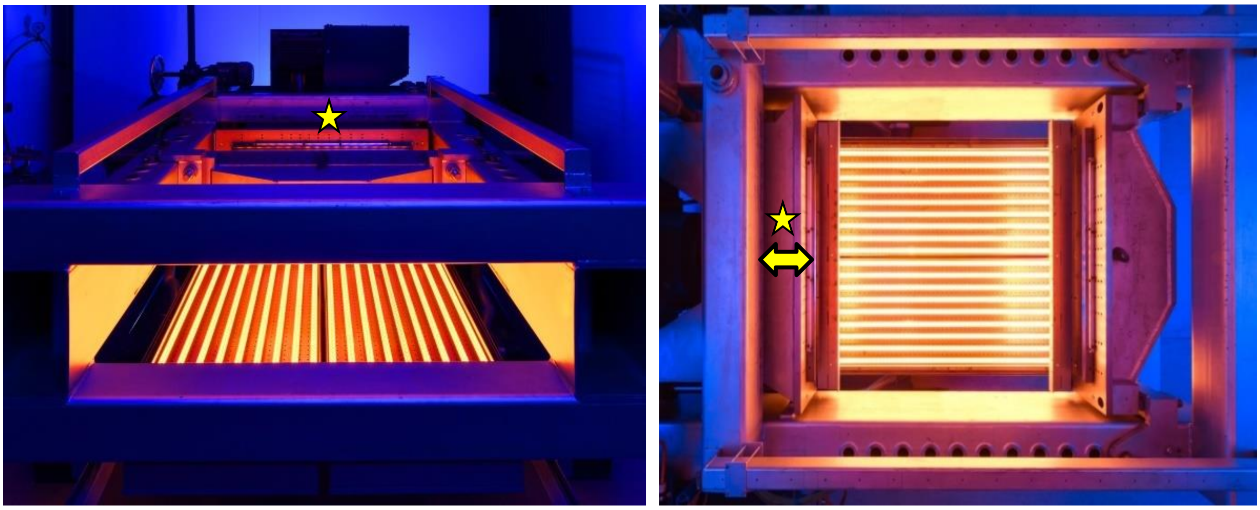

Figure 11: Front view (left) and top view (right) of the THERMEX facility. The structure is placed above the infrared heating unit. The star denotes the clamped side of the structure that applies axial forces.

Planned tests

The two ITOs, one with metallic base structure and one with carbon fibre composite material base structure will be integrated into the THERMEX facility and subjected to representative thermal and mechanical loads. The ITOs will be installed upside down, whereas the heat loads are imposed from underneath to the TPS protected ITO side and an open LN2 bath will be used to impose cryogenic temperatures to the base structure, that represents the inner tank wall (see Figure 7). The mechanical loads are applied in axial direction of the ITO. Mechanical and thermal (heat) loads are adjusted and allow the investigation of several load conditions. Thermal response and mechanical strain behaviour of the ITO are carefully monitored, especially for the cryogenic insulation.

While damage in the outer layers can be assessed by inspection, cracks within the cryogenic insulation might not be immediately visible. However, monitoring the thermal response over numerous load cycles allows the observation of changing thermal behaviour implying local damages. Although the use of spray-on foam is common for cryogenic applications, the combination of strong thermal gradients with external mechanical loads is not well reported but important for the development of a reusable launch vehicle with cryogenic propellants.

The goal of the test campaign is to apply up to 50 representative load cycles to investigate functionality and structural integrity of the system. Possible degradations in performance are monitored and investigated in order to allow for designs that retain their functionality throughout a large number of missions without needing extensive refurbishment.

2.3.2. Arc-Heated Wind Tunnel L3K

A smaller ITO with a metallic tank structure will be tested in the arc-heated wind tunnel L3K at DLR Cologne (Figure 12, see also [13] 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 will be conducted in addition to temperature measurements inside the wind tunnel model (see [14] for an example of the DIC system at the L3K facility).

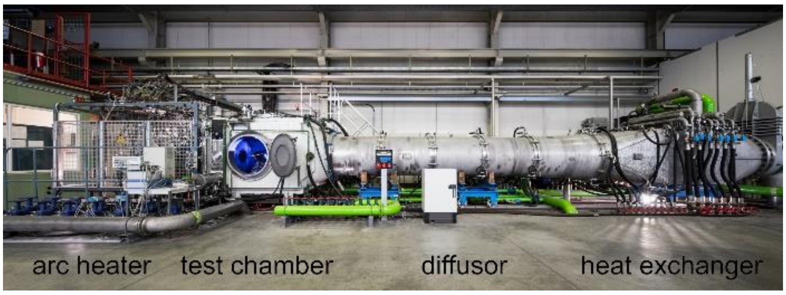

Figure 12: Arc-Heated Wind Tunnel L3K [14]

Planned tests

In the planned tests, an ITO with the same TPS and insulation design as in the THERMEX facility will be used, including an internal tank filled with liquid nitrogen. However, the wind tunnel model will be adapted in size to the requirements of the L3K facility. Figure 13 shows a wind tunnel run in the arc-heated wind tunnel L2K conducted in preparation of the final model design and an example of the obtained temperatures of the TPS surface.

The main objectives of the wind tunnel experiments are:

- 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 thermal control system
- Observation of potential deformations of the TPS surface

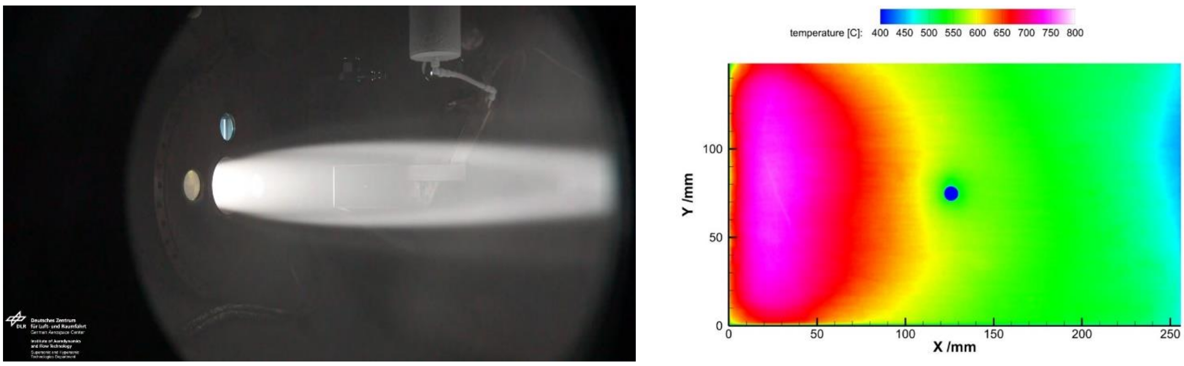

Figure 13: Wind tunnel model during preparatory test run in the arc-heated wind tunnel L2K and example of obtained TPS surface temperatures

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 [14][15][16][17][18]. Regarding actual vehicle structures, such behaviour was for example investigated regarding X-33 TPS panels [19] or observed on the SR-71 [20]. In the present case, it would thus both be useful to show the absence of such effects or to observe to what extend they occur.

Wind Tunnel Model

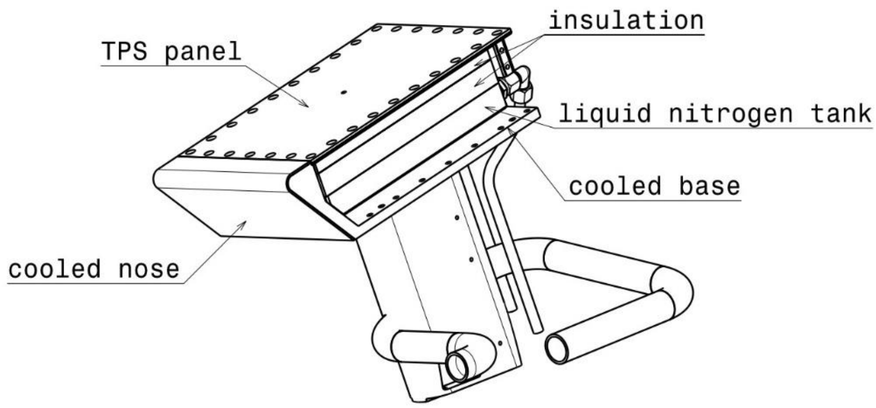

Figure 14: Sketch of L3K wind tunnel model (without side wall)

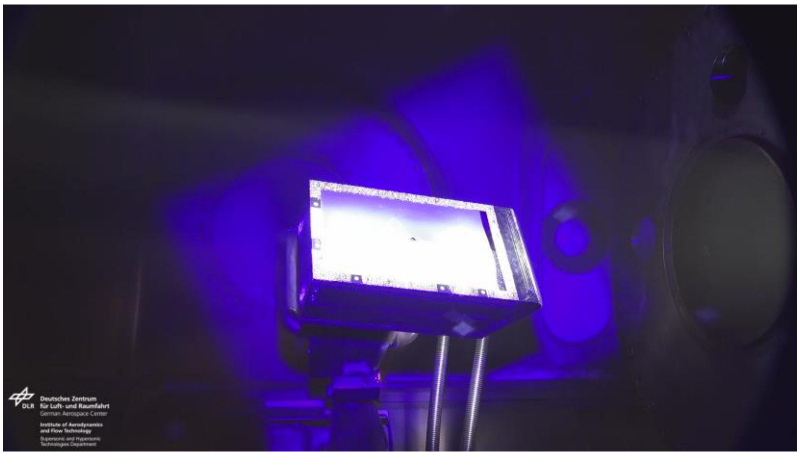

Figure 15: Wind tunnel run in L3K

Figure 14 shows a sketch of the wind tunnel model for the planned tests in the wind tunnel L3K. Nose, base, and side walls of the model holder are water-cooled. On top, Inconel and ceramic TPS panels can be inserted. The setup enables to either allow or prevent thermal expansion of the TPS panels to investigate the influence of panel mounting on deformation of the structure. The configuration of the insulation layers will be the same as in the ITOs used in the THERMEX facility. Figure 15 shows the model during the first run in the experiments currently being conducted in the L3K facility.

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 thermal functionality of the derived designs has been verified in a first set of experiments within the AKIRA project. Within the subsequent TRANSIENT project experimental campaigns are currently being prepared where thermal and mechanical loads will be applied for up to 50 representative load cycles.

The current mechanical loads experienced by the reference configuration SLB7 were assessed and discussed. Finally, the current status of the experimental design and integration was shown. The work is progressing and it is expected the experiments will be completed by the end of the first quarter of 2023. The work done within the TRANSIENT project does not cover experiments with LH2 instead of the surrogate LN2, since 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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