Enhancing Critical RLV-technologies: Testing Reusable Cryo-Tank Insulations

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At DLR a multidisciplinary research project called AKIRA (in English: specific critical technologies and integrated system investigations for RLV applications) is ongoing. Reusable cryo-tank insulation is one of the key-challenges and is in focus of AKIRA.

A preferred reusable insulation concept is defined which subsequently is assembled as an Integrated Test Object (ITO) to be tested in DLR's facilities under relevant conditions. This ITO, to be built at various sizes, is combining a cryogenic fluid compartment, reusable insulation, external thermal insulation as well as sensors for data acquisition and health monitoring.

The paper provides an overview of the ongoing activities in enhancing RLV tank insulation and summarizes major research results available. The ITO concept is described and the impact of this design on a full scale reusable launcher stage is discussed.

Keywords: LOX-LH2-propulsion, cryogenic tank technology, RLV, insulation, TPS

Subscripts, Abbreviations

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

1 INTRODUCTION

Implementing reusable systems in cost-effective European space transportation requires not only hypersonic flight testing. The development of all critical technologies and their demonstration in ground testing is a sine-qua-non for the successful realization of an RLV.

In 2017, a multidisciplinary research project called AKIRA (***A****usgewählte* ***K****ritische Technologien und* ***I****ntegrierte System-untersuchungen für* ***R****LV* ***A****nwendungen* or in English specific critical technologies and integrated system investigations for RLV applications) was launched in DLR. In AKIRA some technologies critical for the successful development of reusable space transportation systems are theoretically and experimentally investigated [1], following launcher system requirements.

The AKIRA project covers a range of RLV relevant topics. Due to limited resources, not every important aspect can be addressed in detail. However, the main benefit of the project is the bundling and tight integration of the various activities, and the orientation of the technology work on RLV reference configurations and reference missions. AKIRA is planned for a duration of 3 years and total funding amounts to around €6.2 million.

Reusable cryo-tank insulation is one of the key-challenges because today's thermal insulations on ELV cryo-tanks are not designed for multiple flights. A suitable combination with the external TPS protecting the vehicle from reentry loads is another aspect only relevant for RLV. The formation of ice, due to climatic conditions at the launch site, on either the external surfaces or within internal layers of the insulation is to be avoided. In AKIRA several insulation concepts have been traded and investigated by numerical and experimental methods.

2 PAST INVESTIGATIONS IN AEROSPACE

2.1 Technical challenges

The understanding of the behavior of reusable tank insulation is of crucial importance for a RLV with cryogenic propellants. While the spacecraft is fueled, its outer tank shell is cooled down to very low temperatures, when not insulated properly. It is not only that the propellant loss is reduced by tank insulation, but there are safety issues as well. If icing occurs at the outside of the launcher it can cause serious damage to the vehicle structure or the thermal protection system (TPS).

As a winged RLV is subject to elevated temperatures during re-entry, the tank insulation 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 to less than 200°C acceptable 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.

2.2 Historic examples of reusable cryogenic insulation concepts

The number of reusable launch vehicles (RLV) ever been operational in the history of spaceflight is very much limited. Interestingly, none of them (Space Shuttle, Energia Buran, Falcon 9 booster stage) had made use of a cryogenic tank insulation on their reusable parts. The US Space Shuttle and the Soviet Buran were orbital stages without any large cryogenic tanks integrated into the RLV-vehicle. The Falcon 9 is a typical booster stage with integral tanks, however, using the propellant combination LOX-RP-1 which has a heritage of flown on rockets without cryo-insulation (e.g. Atlas, Saturn V, Soyuz). Therefore, any practical experience with an operational RLV implementing reusable cryogenic tank insulation does not exist.

An application of reusable cryotank insulation related to RLV is the operation of hydrogen propelled aircraft. Although such planes have not yet been developed, several studies on their technical realization have been performed in the past (e.g. [2]). Actually, the requirements for a commercial transport aircraft using LH 2 fuel tanks are probably more demanding than for RLV-stages. These include minimum operating costs and the achievement of a very high level of safety throughout the aircraft lifetime. In order to realize cost goals, the system must combine lightweight construction with low heat transfer characteristics which are consistent with in-flight tank pressurization requirements; have a high reliability, low maintenance, long life cycle; and have development and fabrication cost commensurate with commercial aircraft practice [2]. The goals of RLV are not much different to those listed for aircraft but the number of intended reuses and the safety and turnaround requirements of passenger airplanes are significantly more challenging.

Multiple layer designs, either purged or cryo-pumped or filled with gaseous hydrogen have been investigated as potential technical solutions. Systematic screening of material options as well as preliminary structural sizing of the tank and interface structures was part of a NASA contract study. Great care was taken to assure that consistent calculation methods were used for all candidates so that the weight comparisons would be as representative as possible [2]. Two examples of tank-insulation cross sections for nonintegral tank and integral tank designs are shown in Figure 1. Overall system mass of the N2-purged systems were found below vacuum designs and finally achieving better score in the overall assessment including safety and reliability criteria.

NASA's Langley Research Center (LaRC) has later also performed analytical and experimental studies for investigating integrated cryogenic propellant tank systems for an RLV. The cryogenic tanks have been investigated as an integrated tank system including the tank wall, cryogenic insulation, TPS attachment sub-structure, and TPS [3].

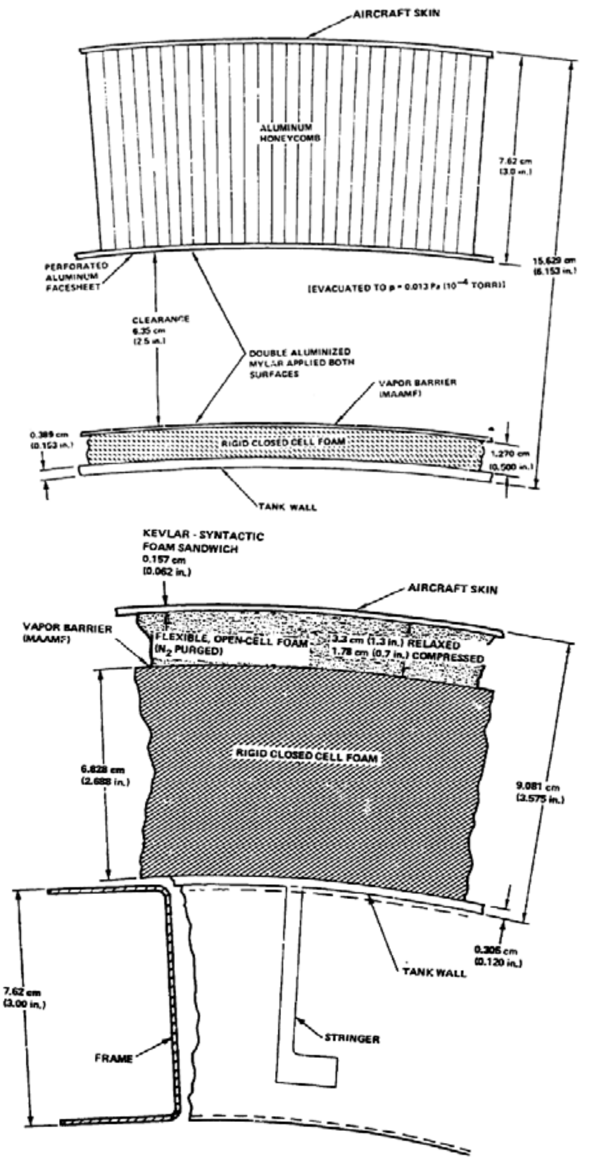


Figure 1: Examples of tank-insulation cross sections for nonintegral tank (top) and integral tank with external foam (bottom) [2]

The NASA testing at cryogenic and high-temperatures was planned to verify the integrity of materials, design concepts, manufacturing processes, and thermal/structural analyses. Test specimens ranging from the element level to the subcomponent level have been subjected to operational mechanical loads and temperatures of generic RLV concepts [3].

Several combinations of LH2 tank walls and TPS have been analyzed at LaRC to identify lightweight and thermally efficient concepts. An example of an integrated tank system design of [3] is displayed in Figure 2. The titanium (Ti) sandwich wall acts as a pressure vessel, cryogenic insulation, primary structure, and TPS support. The external foam concepts are based upon a forward-located, IM7/977-2 graphite-epoxy ring and stringer stiffened tank concept from the X-33 Phase I Rockwell vehicle of the mid 1990s.

A series of tests and test facilities have been developed during Phase I and Phase II of the NASA X-33/RLV Program to further evaluate potential reusable cryogenic tank designs for RLVs.

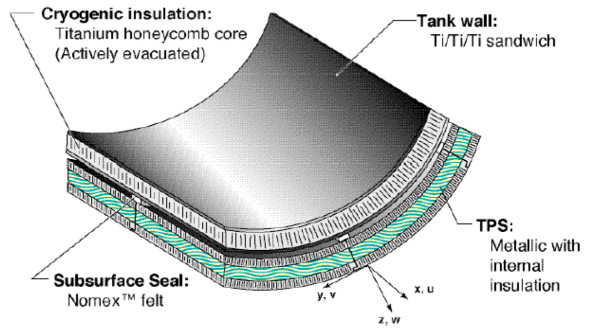


Figure 2: Example of an all-metallic Ti/Ti/Ti sandwich cryogenic tank with metallic TPS as integrated tank system concept for RLV [3]

The compressive load capability of a tank wall concept under simulated structural and inertial loads was tested using representative flat specimens in the cryogenic/high temperature compression test fixture as shown here in Figure 3 as one example of the performed work at LaRC.

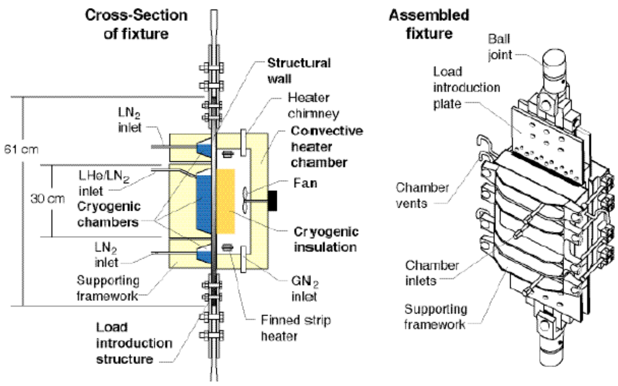


Figure 3: Schematic and assembled view of the test fixture for the uniaxial tension test at NASA Langley [3]

3 AKIRA REUSABLE CRYOGENIC TANK INSULATION INVESTIGATIONS

3.1 Material properties characterization

Experimental investigations of common cryogenic insulation materials are carried out to study the long-term behavior of their thermal properties. A cold head experimental system is used for thermal cycle tests between ambient temperature and about 20 K. The cold head operates with a closed helium cycle as "Gifford-McMahon" refrigerator. [4] The helium is compressed in a compressor and expanded on the cold head to reach temperatures of 20 K without test specimen on top. In order to provide steady test conditions for the insulation samples, a vacuum shield around the test setup is needed. Figure 4 shows a schematic view of the assembly with cold head (A), the vacuum cover (G), and the vacuum port (H). A pump for evacuating the test volume (not shown) is flanged to the vacuum port [4].

To apply a thermal load on the insulation sample, a silicon heater with a maximum power of 2 W is chosen. As substrate an aluminum plate is used as interface between the insulation sample and the cold head. A vacuum grease (Apiezon N) is used to achieve a sufficiently good thermal connection between insulation and substrate. Mechanical stability is attained by gluing the insulation sample to the substrate with epoxy Stycast 2850 and Catalyst 23 LV as hardener. Further, between sample and heater a small aluminum plate is fixed with spotty glue and vacuum grease as thermal connection [4].

The photo in Figure 5 shows the test-setup, with heater (C) and insulation sample (B) on the substrate (D) and on the cold head (A). Copper rods and an upper aluminum plate (E) are used to keep the cover in shape. Measurement of the temperatures is performed with Type-K thermocouple and a silicon diode (F). The heat flow is equal to the measured electrical power of the heater [4].

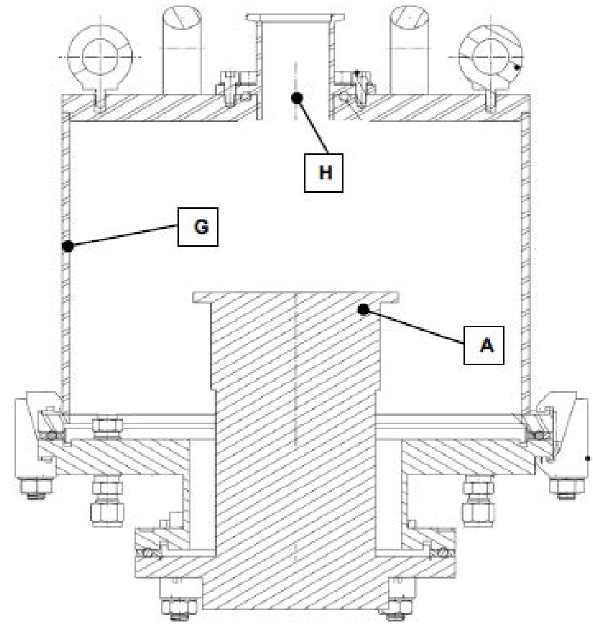


Figure 4: Schematic view of the test-setup used in AKIRA [4]

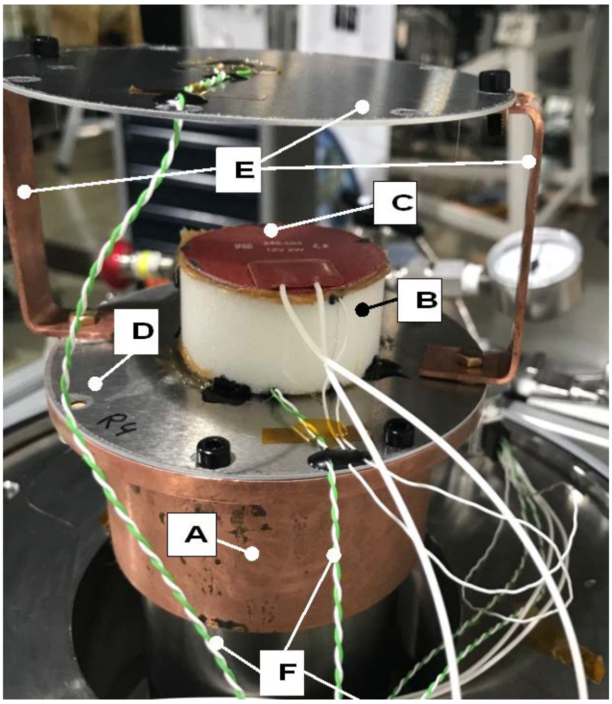


Figure 5: Complex test arrangement for determination of insulation foam heat conductivity (material probe is shown at B)

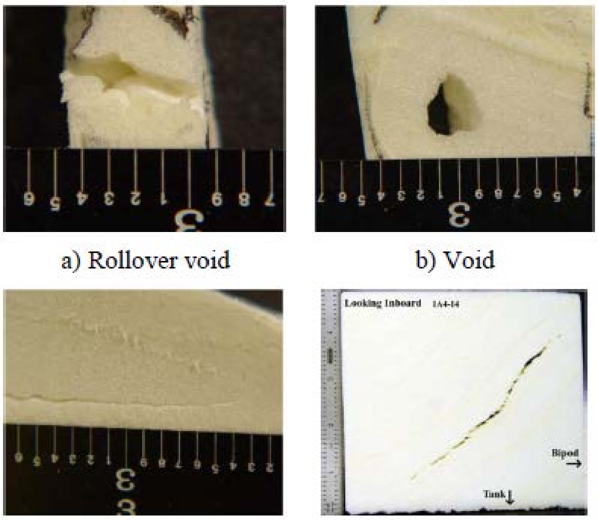
Each temperature test cycle follows the same procedure, starting with the evacuation, second the chill-down of the insulation sample, third the electrical heater heating up and finishing with returning the system to ambient conditions. A typical procedure with the temperature development is shown in [4]. After a long chill down (>12 h) the temperature difference reaches steady state and the heater is turned on to heat up the sample, that the temperature difference rises until reaching a new steady state [4].

Investigation performed in AKIRA show that PMI foam and PI foam withstand at least 10 cycles and only a small decrease of the insulation properties has been observed [4].

3.2 Health-Monitoring of insulation integrity

Although several insulation concepts have been investigated in the AKIRA-project, the health monitoring is focused on foam insulation which is a promising concept. Foam insulations are commonly used for launch vehicles with cryogenic propellants (e.g. Ariane 6 upper stage or the Space Shuttle external tank). The materials used for the hydrogen tank of the Space Shuttle were Polyisocyanurate and Polyurethan [5].

Especially when the foam application is performed manually, defects can already occur during the spraying process. Typical defects are entrapped air, so-called “rollover voids” (see Figure 6 a) or voids (see Figure 6 b), cracks caused by stresses in the foam material (see Figure 6 c) and delamination of inhomogeneous layers inside the foam insulation (see Figure 6 d). However, defects occurring during the manufacturing process can be minimized by machine application of the foam material [5].



a) Rollover void b) Void

c) Crack d) Delamination

Figure 6: Different types of defects in foam insulation materials [5, 6]

In addition to the defects already occurring during production, damages can also arise during tank operation, e.g. detachment of the foam material from the tank wall and cracks in the foam insulation itself. These damages can, for example, be caused by aerodynamic and thermal loads during flight, vacuum effects, vibrations and mechanical stresses. Obviously, such damages are a major challenge for RLV-booster stages and thus are in focus here. Other well-known damage mechanisms are so-called "cryopumping" and "cryoingestion". Cryopumping occurs when a crack in the foam material leads to a void directly at or near the tank wall of the cryogenic tank. Due to the extremely low temperatures of the tank, the air in the void can liquefy and the resulting vacuum can draw-in even more air. During take-off and flight the temperatures in the insulation rise due to aerodynamic heating. This causes the air to evaporate again and pressure builds-up inside the void which can lead to spalling of foam insulation parts [7].

Cryoingestion follows the same principle as cryopumping. However, instead of air, nitrogen leaks from the inert gas tank into a void near the hydrogen tank and liquefies or freezes.

Several potential approaches for health monitoring of foam insulations exist [5]:

- Damages can be visualized using imaging techniques (cameras).
- With acoustic methods (ultrasound) damages can be detected and localized.
- Analogous to the acoustic method, X-ray backscatter and electromagnetic waves in the terahertz range can be used for damage localization.
- Defects in the insulation lead to temperature changes. Therefore, damages can also be inferred from temperature measurements.

The detection by imaging techniques is limited to larger defects that are visible from the outside. A delamination of the insulation from the tank structure, which in itself is not necessarily a critical damage but could later lead to larger defects like spalling of insulation parts, cannot be detected [5]. Ultrasonic measurements are frequently used in structural health monitoring systems but in materials with high porosity like foam insulations large acoustic attenuation and scattering occurs [5]. In the same manner imaging techniques like backscatter X-ray, terahertz and shearography systems have been used for the inspection of the Space Shuttle ET insulation. These techniques are not suitable for in-situ measurements but can be used during maintenance for a more detailed inspection of areas where an integrated health monitoring system detected an anomaly [5].

This approach follows the HM-logic for application in RLV-insulation and thermal protection of RLV. The amount of maintenance between two succeeding flights should be minimized and unnecessary inspection should be avoided to reduce operations costs. Therefore, the health-monitoring sensors have the task of early identification of large scale damage critical for further operation of the RLV but not in exact localization of e.g. spalling of insulation parts.

Different kinds of sensors were investigated for the application as health monitoring sensors in the foam insulation at cryogenic temperatures that can directly indicate possible defects. Finally, temperature sensors were chosen to detect possible damages in the insulation via changes in the temperature distribution caused e.g. by delaminations. Several types of available temperature sensors like thermocouples or fiber optical sensors are available. Standard thermocouples were used for sample instrumentation because of easier integration and signal processing. However, as the temperature measurement method is not crucial for the actual health monitoring, also fiber optic sensors could be used for later tests, larger demonstrators or the final application [5].

A test facility consisting of a small vacuum chamber with integrated sample holder was built to perform tests on foam samples. The holder was cooled using liquid nitrogen to create the necessary cryogenic temperatures. The foam samples were instrumented with several thermocouples to monitor the temperature distribution inside the insulation [5]. To simulate a foam delamination from the tank structure, a gap between insulation and liquid nitrogen tank was created manually during sample manufacturing. Comparing measurements with and without damage indicates the temperature change due to the delamination.

For the tests in the thermal vacuum facility several different samples were manufactured. One objective of the tests was the verification of the general applicability of temperature measurements inside the foam insulation for health monitoring purposes. In addition the measurements were used to validate a numerical model, especially the used material parameters. Using thermal simulations, further test cases were computed varying parameters like the delamination area to create a numerical database for various damage cases. This database was used to train an artificial neural network for damage detection, localization and classification. By applying the network on the experimental data from the foam samples, the general feasibility of the damage detection could be shown [5].

In order to simulate the effect of an insulation detachment from the tank structure, a small defect was integrated in the test. A detachment of the insulation would interrupt the heat conduction between insulation and tank wall. Since the actual bonding between insulation and aluminum plate was no longer accessible, the delamination was simulated by the removal of a circular piece of the aluminum plate with a diameter of 15 mm (in the middle of the plate). This artificial damage also interrupts the heat conduction similar to an insulation detachment.

Based on a measurement accuracy of ± 1.5°C for the thermocouples, the defect could be detected with thermocouples. Small insulation detachments are only detectable with a high number of temperature sensors because their influence on the temperature distribution is small. Extrapolated to a full-scale propellant tank of an RLV this would result in an unrealistic number of sensors. However, small detachments are not critical and can be tolerated by the launcher system. Therefore, the damage detection can be limited to larger scale defects which eventually lead to critical failures (e.g. spalling of insulation parts). Hence, temperature measurement points can be significantly reduced. The exact number is to be determined by demonstrator testing. In addition, instead of providing health monitoring for the complete tank, it can probably be reduced to the highly stressed areas.

3.3 Integration of insulation and external thermal protection

The design of an integrated system comprising the cryogenic fuel tank with added thermal insulation and a thermal protection system protecting against hypersonic heat loads is a key engineering challenge for RLV. The design challenge arises due to the combination of the super-cold tank and its cryogenic insulation with the TPS that relies on a fibrous, open-pore, high-temperature insulation. Typical cryogenic insulations of closed-cell foams are usually limited to around 100°C acceptable temperature. On the other hand, fibrous high-temperature insulations should be kept above the dew point of air during ground operations to prevent internal moisture condensation or even icing [8]. For one, the tank shall be insulated as good as possible to keep the fuel at low temperature and prevent fuel loss from evaporation calling for an ideal layer of cryogenic insulation. On the other hand, a TPS is required to protect the structure and insulation from re-entry heat loads. The baseline design chosen for the TPS was to attach rigid surface panels to the underlying structure via dedicated structure fixations penetrating through the insulation, thus disturbing the temperature field in the cryogenic insulation [8].

The driving thermal load cases are the pre-launch tank filling with cryogenic fuel and the re-entry loads. Requirements driving the design were identified to be the maximum limit temperature of 100° C for the cryogenic insulation and a temperature of more than 0° C in the TPS insulation before launch.

One basic possible design solution was suggested with a stack of two layers of cryogenic respectively high-temperature insulation. However, the overall thickness adds up to approximately 130 mm [8]. In addition this does not take into account local thermal disturbances due to thermal shortage effects caused by structural connections between TPS panels and the tank structure. Another option was the inclusion of a so-called purge gap in the design to reduce thickness as visible in Figure 7.

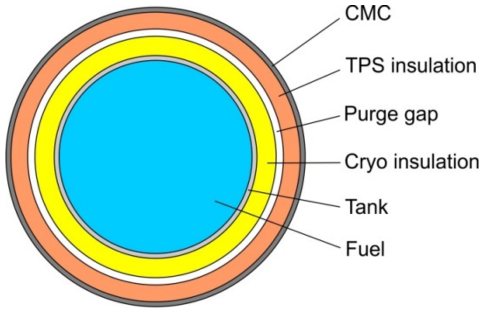


Figure 7: Schematic of promising purge gap option [8]

The purge gap is a design feature creating a distinct gap between the insulation of the cryogenic tank and the one of the thermal protection system, which has to be resistant to high temperatures. In the gap a forced flow of pre-heated dry gas is created, providing a controlled boundary condition at the outer interface of the cryogenic insulation. Thus, the thickness of said insulation can be reduced to a large extent, at the cost of somehow increased fuel evaporation in the tank. Thermal analyses show that the purge gap solution is feasible with a cryogenic insulation of drastically reduced 30 mm thickness.

Simplified numerical trade-offs have been performed to assess the feasibility of a purge gap system including insulation layer thickness, gas mass flow, velocity, and inlet temperature. Analyses showed that it should be possible to design a purge gap system and come up with feasible values for gas temperatures, mass and volume flows [8].

Based on the results of the 1D analysis without any fixation elements and the findings from the analytical purge gap considerations, a model was set up for the purpose of combining the effects of a purge gap with structural fixation elements going right through all the insulation layers. In order to be able to determine the effects of changes of different materials easily, the 3D-model was simplified considerably with respect to the geometry (Figure 8).

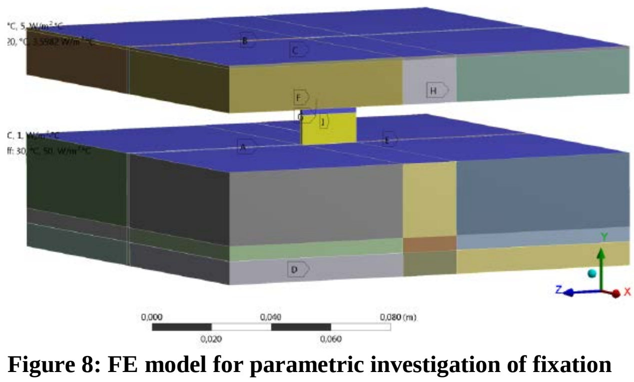


Figure 8: FE model for parametric investigation of fixation element materials and purge gap convection [8]

The fixation element was modelled as a very simple straight connection between tank and surface panel with rectangular cross section.

In Figure 9 a cross section through the model is shown along with the explanation of the individual geometric items which were used for parametric studies. It shows also the surfaces on which convection was applied.

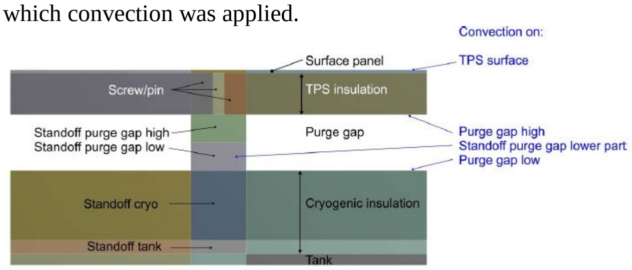


Figure 9: Elements of the structural connection between surface panel and tank [8]

The simulation methodology was to carry out a steady-state simulation of the temperature field representing the pre-launch situation and to check if the requirement of temperatures in the TPS insulation above 0° C was satisfied. In case of realization, that result was used as the starting condition for a transient simulation representing the ascent and re-entry of the vehicle for which obtained data were checked if the requirement of maximum cryogenic insulation temperature of 100° C was satisfied. In case of any non-compliance, parameters were changed and the simulation process started again.

Several iterative design steps with different material choice and thickness have been investigated before a feasible configuration was found [8]. Quantitative results of FEM analyses (Figure 10) show that the temperature requirements at the interface of more than 0°C on ground and less than 100°C during RLV-reentry can be satisfied. A detailed design suggestion was made for the structural fixation elements of the TPS panels to the underlying tank structure.

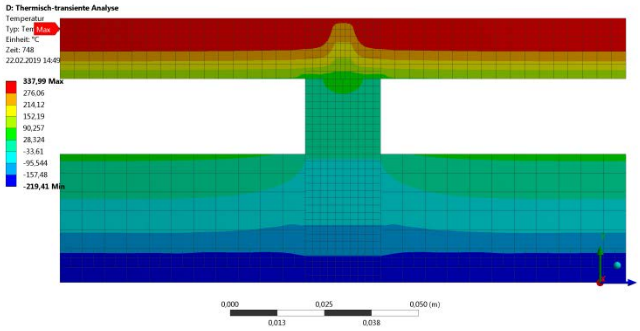


Figure 10: Transient simulation result at time when maximum temperature is reached on cryo-insulation (approx. 90°C below 100°C) [8]

4 INTEGRATED TEST OBJECT (ITO)

The project's insulation concept will be investigated by developing an integrated test objects (ITO), which include the cryogenic insulation, the TPS and system health monitoring (SHM). Similar devices, which combine different layers of structure and insulation material and are beyond sample probes but are less complex than a tank demonstrator, allow for fast cyclic testing. In a similar approach NASA LaRC had extensively tested such probes for RLV cryo-tank structures and insulation [3] (see also section 2.2 and Figure 3!).

DLR builds in AKIRA three ITOs of similar lay-out and layer thickness but different planar size which will be tested in three different test facilities. The design requirements of the insulation are derived from a reference concept of a winged RLV-first stage with separation Mach-number of around 12: the SLB7-3 booster stage. Thermal profiles along the flight trajectory have been calculated for several missions and provide realistic input data for the tank insulation sizing. The heatfluxes acting on the LOX-tank at three characteristic points (lower position, side wall, upper position) are shown in Figure 11. Although the heatflow with a peak of less than 80 kW/m^2 is relatively moderate, radiation equilibrium temperatures are beyond 1100 K which is more than a reusable cryo-insulation can endure.

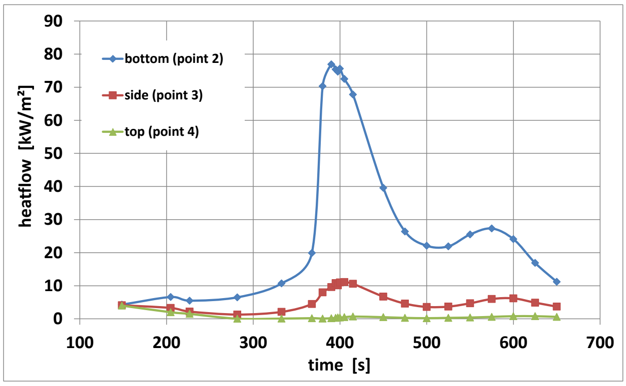


Figure 11: Heatflux history at different positions on SLB7-3 LOX-tank

Thermal cycling test with LN2 will be performed to investigate the complex behavior of the developed insulation concept. Analysis in temperature distributions and possible material damages is done with combined experimental and numerical investigation. Further test objectives are:

- Cryogenic insulation properties
- Purge gap functionality
- Thermal properties of the structural standoff assembly
- Standoff and purge gap thermal control via the gas feed line
- health monitoring observation due to deliberately introduced damages

The three ITOs are to be tested under different conditions:

- tank filling and ground hold phase with respect to different climatic conditions
- full thermal cycle in DLR's induction-heated Indutherm facility with radiative heatload
- thermal cycle with convective heatload in DLR's arc-heated windtunnel L2K

4.1 ITO architecture

Therefore, a relatively complex combination of external TPS and cryogenic insulation is to be selected which avoids icing even in humid and relatively cold environment. A schematic drawing of the tank insulation and thermal protection cross section is given in Figure 12. The TPS is made of a thermal protection material and a covering metal plate. The ITO is built up of an aluminum wall plate covered with cryogenic foam insulation. A spacer construction is used, granting a gap for purging and placing the TPS above the insulation material.

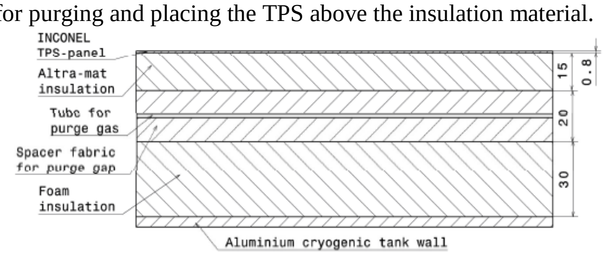


Figure 12: Schematic cross section of the AKIRA ITOs [5]

The foam insulation with a thickness of 30 mm is glued to the aluminum 6061 tank structure. Above the insulation a purge gap with a thickness of 20 mm is used which is filled with a spacer fabric made of a fine gas-permeable mesh structure. The nitrogen purge gas is lead through metallic tubes with several holes, so that the gap is homogenously purged by the gaseous nitrogen. Above the spacer fabric a 15 mm thick alumina fiber mat insulation (Altra) is used with an application temperature up to 1600°C.

The mat is covered by 0.8 mm metallic cover-panel made of high-temperature resistant INCONEL. This is a deviation from the earlier assumption of an external side CMC cover (Figure 7). The change is justified by the operational advantages of metallic protection on the outside (e.g. less sensitive to humid and rainy environment) and is feasible due to the relatively modest peak temperatures expected on the lower side of the tank. Overall subsystem weight increases with the metallic plates and the impact is discussed below. The 0.8 mm thickness of INCONEL is a preliminary choice for the ITO, not necessarily maintained in an RLV application.

All three ITOs have the same cross-section layout shown in Figure 12 and use liquid nitrogen to generate the cryogenic temperatures on the tank side.

4.2 Design of Standoff elements

As described in the previous section 3.3, a suitable design of the connecting elements between cryo-insulation and TPS is critical for the feasibility of the overall concept.

A design suggestion is made which is shown in Figure 13.

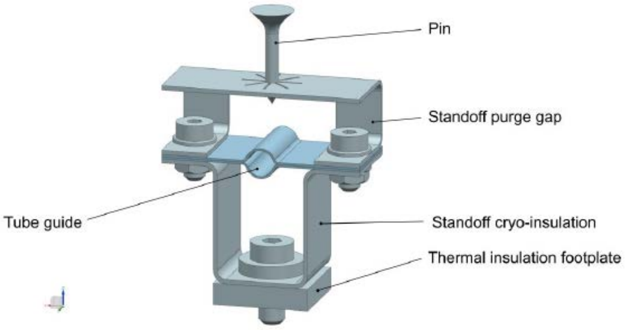


Figure 13: CAD model of standoff component [8]

The connection between surface panel and the standoff is suggested to be made with just a pin, thereby relying on the elastic properties of the TPS insulation. The realized design of the standoffs in all Integrated Test Objects (ITO) to be tested is shown in Figure 14.

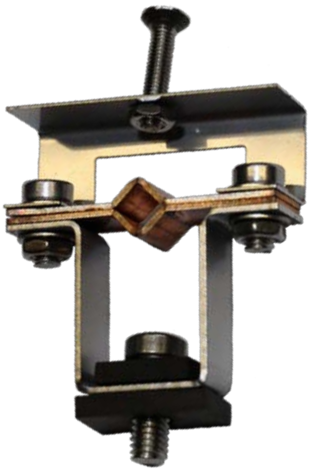


Figure 14: Realized standoff component

4.3 ITO type description

The largest of the three ITOs is flat and 800 mm by 800 mm in size and its CAD-geometry is depicted in Figure 15. It consists of three full cover panels and two half panels with shifts in the intersecting lines. Each of the full size quadratic panels is supported by four standoffs. Thermal expansion and contraction of the materials due to the significant change in temperatures during thermal cycling has been taken into account in the design. In order to reduce the disturbance by heat transfer from the sidewalls, a thermal insulation is foreseen on the boundaries of the test object.

The ITO used for tests in the arc-heated wind tunnel L2K of DLR-Cologne is shown in Figure 16. It incorporates the complete insulation setup presented in Figure 12 with one stand-off in the middle of the model. The insulation is glued to the liquid nitrogen tank and intentionally contains one small void with an area of 44 x 44 mm and a depth of 3 mm at the lower side of the insulation (at the LN2-container) to simulate a partial detachment of the insulation.

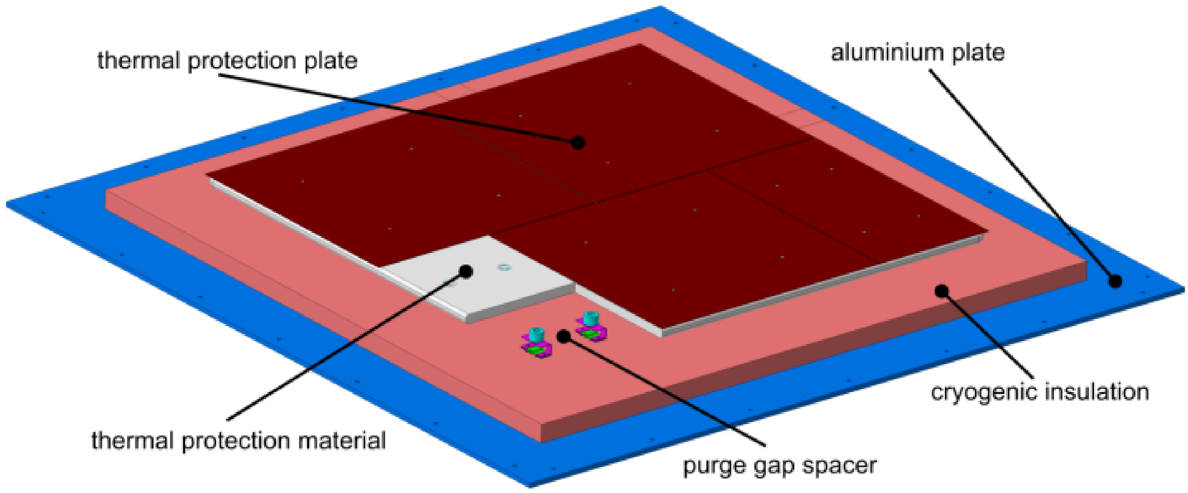


Figure 15: CAD Model of the largest Integrated Test Object (ITO) of AKIRA

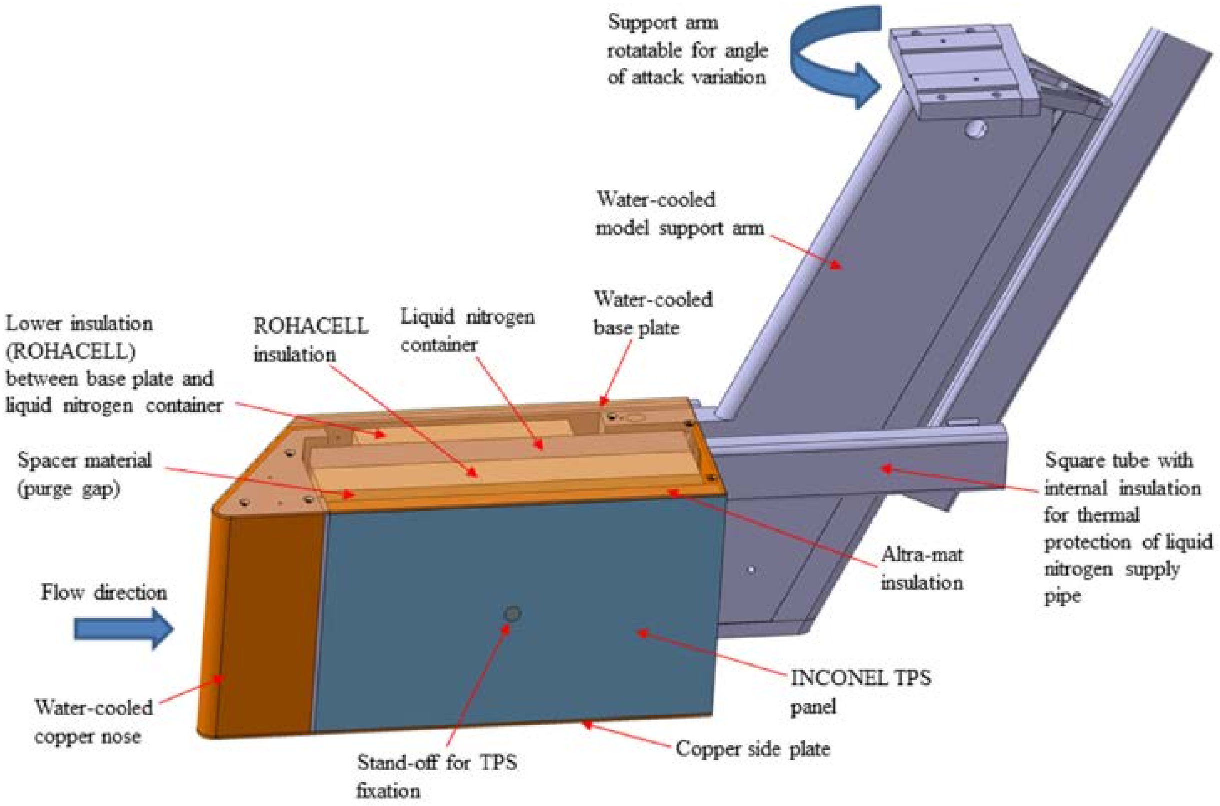


Figure 16: Integrated Test Object (ITO) for tests in arc-heated wind tunnel as CAD-model [5]

The INCONEL TPS panel leading edge is fixed with a small clamping device to ensure a smooth transition between the copper nose part and the TPS panel and for additional panel fixation. As the L2K-tests simulate the flight conditions, no purge gas is used because purging is only performed during the ground phase. The model has a length of 327 mm including the water-cooled nose and a width of 160 mm.

The model support structures including nose, base plate and support arm are water-cooled because of the high gas temperatures in the arc-heated wind tunnel. At the lower side of the liquid nitrogen container a second insulation with thickness of 21 mm is used to thermally isolate the cryogenic tank from the comparably warm water-cooled base plate and avoid disturbance of the test results. Two metallic tubes are used for the LN2, one for supplying the container and the other to allow for evaporation of the nitrogen gas. Both tubes are fed through a stainless steel square tube for protection against the hot gas flow.

The model support arm is rotatable as indicated in Figure 16, so that the model angle of attack can be varied to increase the heat load on the TPS. In addition to the angle of attack several other parameters like model distance to the wind tunnel nozzle or wind tunnel heater power can be adjusted to increase or decrease the heat load on the model.

The model is instrumented with 38 thermocouples (TC) to monitor the temperatures of the different model parts. Type K thermocouples are used either in a sheathed version with 0.5 mm diameter or in a version build of twisted PTFE insulated thermocouple wire.

In addition to the thermocouples an infrared camera is used to monitor the upper side temperature of the TPS panel.

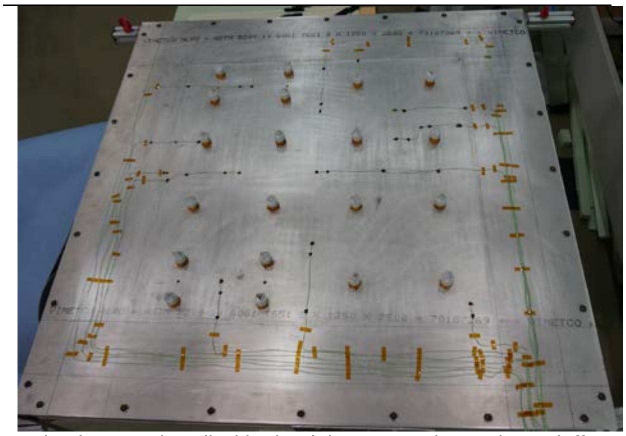
Table 1: ITO instrumentation for L2K wind tunnel tests

Sensor position	Number of TC
Liquid nitrogen container	2
Lower side of insulation (between insulation and container)	3
Inside void	1
Inside insulation (with distance of 10 mm to the liquid nitrogen container)	8
On top of the insulation (between insulation and spacer material)	8
At the sides of the insulation	4
Between spacer material and Altra-mat insulation	4
At the standoff-parts	4
Internal side of INCONEL TPS panel	4

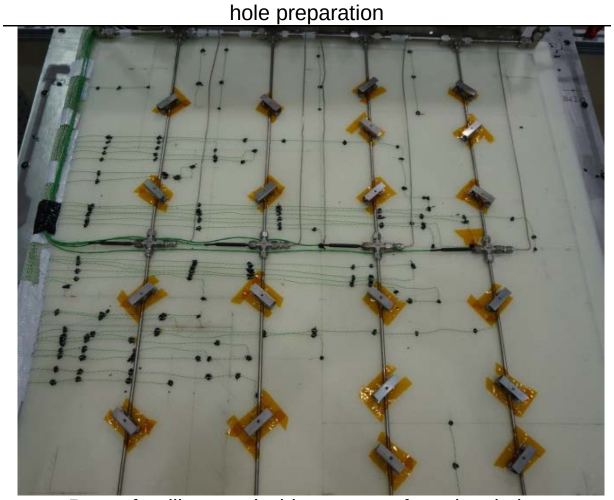
The third ITO is of medium size compared to the other two and has the planar dimensions 400 mm x 400 mm. This test object will see the full cycle from ground filling and hold to ascent and the following atmospheric reentry profile. While the large ITO has its LN2 reservoir at the bottom, the medium size ITO has the exact opposite arrangement and puts the LN2 basin at the top. The latter arrangement is closest to the real situation as the ITOs investigate the conditions on the lower side of the LOX-tank which sees the maximum heat loads. However, it is currently believed that the orientation of the ITOs wrt. the gravity vector has a minor impact on the intended investigations in AKIRA.

4.4 ITO integration and test status

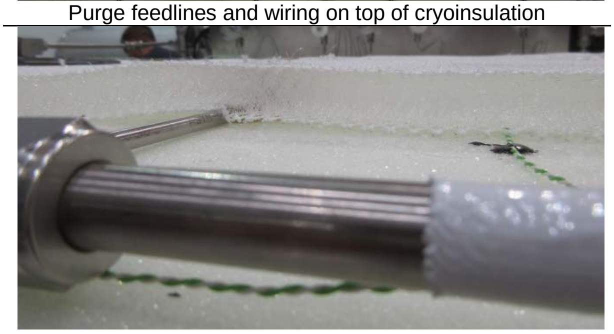
All three test objects are now almost completely integrated and are either in test check-outs or are ready for testing. A few photo impressions are summarizing the status of the integration progress. Figure 17 shows the plates, purge feedlines and some of the wiring for the thermocouples of the largest ITO.



Aluminum tank wall with glued thermocouples and standoff hole preparation



Purge feedlines and wiring on top of cryoinsulation

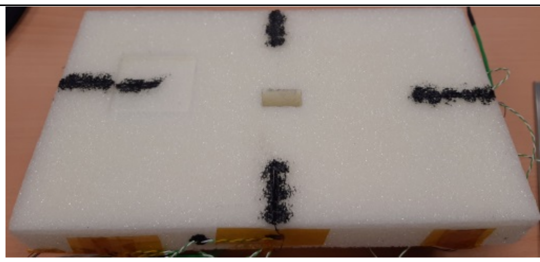


Purge feedlines going through gas permeable spacer fabric

Figure 17: Parts and integration steps of the largest ITO

Images of the different ITO parts during assembly of the windtunnel ITO are presented in Figure 18. The ITO intended for the tests in the Indutherm facility in Stuttgart is almost fully integrated as visible in Figure 19. Fluid simulations were carried out to assess the basic settings for the pressure and temperature boundary conditions of this ITO [9].

A special test environment for testing the ITO under dry and humid tank filling ground hold conditions is under preparation at the DLR Bremen site (Figure 20). Environmental conditions are to be varied in a wide range of outside wall temperature and levels of humidity. As convective heat transfer processes play an important role in potential ice formation, also wind speeds can be simulated. Characteristics of the purge gas and of the flow scheme are modified to find suitable combinations for operation. DLR's Indutherm facility will simulate the full thermal cycle with heatloads radiatively transferred into the metallic cover via coupling plate (Figure 21) following the reference profile.

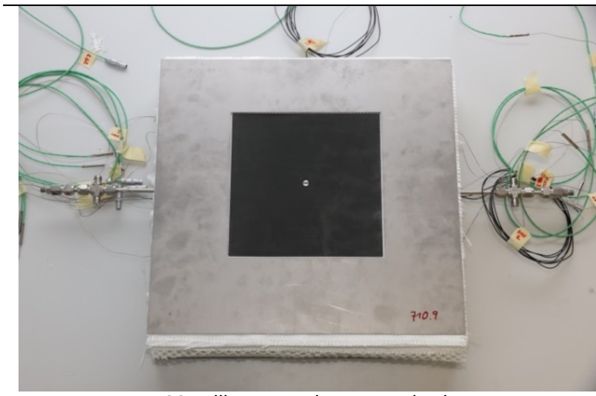


Bottom of insulation with glued thermocouples, void and hole for standoff

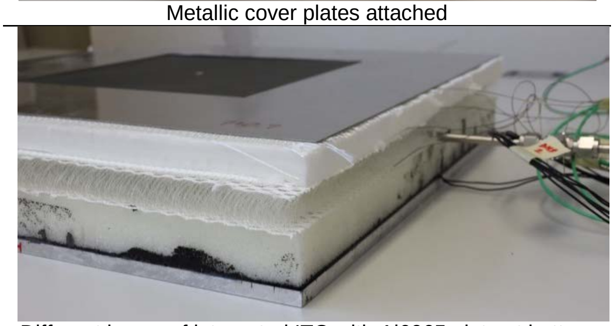
Top side of aluminum liquid nitrogen container

Bottom of Inconel TPS panel with welded thermocouples

Figure 18: Parts of the ITO for L2K wind tunnel prior to final integration



Metallic cover plates attached



Different layers of integrated ITO with Al6065 plate at bottom and INCONEL cover plates on top

Figure 19: TPS cover and side view of the medium size ITO after final integration

Figure 20: Climatic chamber in preparation and control unit for ITO tests at DLR cryogenic lab Bremen

Figure 21: Open chamber of Indutherm facility and integrated sidewall insulation at DLR Stuttgart

A heatload profile similar to that of point 2 (blue curve in Figure 11) will also be in the Indutherm and in the arc heated windtunnel tests. For the latter at small scale but realistic convective heat transfer conditions, a maximum TPS outside panel temperature of 1100 K should be reached.

5 CONCLUSION AND EVALUATION

The DLR-internal project AKIRA is addressing some of the most critical technologies to be matured before the realization of any successful European RLV development. Not only flight experiments at high speed are necessary but also ground demonstration of integrated hardware objects supported by a wide range of system studies.

Based on the system requirements of a reference vehicle, the assessment of suitable reusable cryo insulation for tanks in combination with thermal protection for external heat fluxes is systematically investigated.

An integrated concept of cryogenic tank wall insulation, purge gap with inert gas supply system and external TPS with metallic cover is defined for the application on the lower side of RLV-booster stage integral tanks. A peak heatflux of 80 kW/m^2 and external temperatures up to 1100 K are expected as load conditions. The concept is numerically analyzed and three Integrated Test Objects (ITO) have been prepared which will be subjected to cyclic testing in three of DLR's facilities.

The INCONEL-covered TPS and the purge feedlines have an impact on the overall system mass exceeding the mass of the preliminary reference design. Still it is too early for a final assessment, as the sizing has been merely performed for the maximum loaded areas. Further, the feasibility of the concept will be critically evaluated after the experiments and improvements are to be implemented in a follow-on project already under preparation.

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