DOI: 10.13009/EUCASS2019-738

Concept Development of a Cryogenic Tank Insulation for Reusable Launch Vehicle

Nicolas Darkow, Alexander Fischer*, Henning Scheufler*, Harald Hellmann*, Jens Gerstmann**
** German Aerospace Center (DLR) Institute of Space Systems, Bremen, Germany*
nicolas.darkow@dlr.de

Abstract

The development of insulation is of crucial importance for spacecraft with cryogenic tank systems. During the fueling procedure with cryogenic liquids the outer tank shell is cooled down with the rise of icing. In case of the hydrogen tanks the condensation of liquid oxygen is likely to occur, which is a great hazard to the spacecraft. The presented work is part of the AKIRA project performed by the German Aerospace Center (DLR). Reference configuration for the insulation concept uses a reusable booster stage with a liquid hydrogen/oxygen engine. This study aims to contribute in the development of a reusable insulation system for both, the liquid hydrogen and liquid oxygen tank. For the design of the insulation system, different common insulations types are investigated about their applicability for a RLV. Due to the booster flight trajectory, surface temperatures higher than 1000 K are expected to occur while spacecraft re-entry, which requires a proper Thermal Protection System (TPS). To achieve these temperature requirements, the thickness of the insulation increases and leads into a higher structural mass. To tackle this problem, a 'Purge Gap' between the cryogenic insulation and the TPS is investigated. Purging a gap between the insulation and the TPS with a dry gas provides a small excess pressure that prevents humid air from entering into the system. Thus the total thickness of the insulation system and consequently the structural mass can be reduced. In order to support the design process, 1D-tools were developed for the calculation of transient heat conduction and the temperature profile evolution in the insulation system during the whole flight trajectory. Experimental investigations have been carried out to observe the long-term stability for different types of insulation materials. An experimental setup was developed and serval insulation samples were tested A cold head system is used which is able to cool down the samples to a temperature of about 20 K. Commercial 'of the shelf' insulation foams look promising in withstanding typical lifecycles of a RLV, such like the booster reference configuration.

1. Introduction

For the economic operation of a reusable spacecraft the isolation of cryogenic storage tank is an important and significant prerequisite. In order to prevent evaporation of cryogenic fluids and condensation of humidity on outer parts of the tank the isolation is required to fulfil certain specifications. An additional challenge is the application of a reusable isolation for cryogenic tanks. Additionally high boil-off rates and propellant losses during the mission are the consequences. To prevent such effects it is essential to design a satisfactory cryogenic insulation. Usually, for expendable launch vehicles (ELV) the requirements for the insulation are mainly driven by low structure masses and no icing on the launch pad. However, for reusable launch vehicles (RLV) further considerations in long-term stability and maintainability are needed. Especially for lifting body RLV, the insulation has to withstand very high temperatures during the re-entry phase. Therefore a thermal protection system (TPS) is needed in addition to cover high temperature loads and has to be combined with the insulation to an insulation system. Considering the whole mission, the pre-flight fueling phase and the spacecraft re-entry phase turned out to be design driving points.

Main goal of the presented investigations are the concept design and test of a reusable cryogenic insulation under laboratory conditions. These measurements are carried out with special samples to determine the thermal properties and to validate the isolation concept. Special considerations are the operational temperature cycles of a reference configuration spacecraft.

DOI: 10.13009/EUCASS2019-738

Today and in the past, the primary driver for the development of a cryogenic isolation for a reusable space vehicle is a low mass of the launch vehicle. Additionally the insulation should have little or no preparation before the flight and should be as maintenance-free as possible. Further it is essential that the insulation withstand the numerous missions and therefore must be reusable itself. For this purpose, experimental investigations are essential to qualify the insulation material with cyclic loads for reusability. Information of failures which occur during the experiments is important as parameters for the SHM to monitor the isolation with non-destructive methods and to reduce the maintenance activities. Experiments with different isolation materials have been performed at the DLR Institute of Space Systems in Bremen.

2. State of the Art

2.1 Experimental Investigations

The motivation for a reusable cryogenic storage tank with a good isolation is more than 40 years old. First Investigations were carried out for an airplane which should use hydrogen as fuel. Experiments which are designed to determine several material properties: heat conduction, mechanical strength and the permeability of the isolation were carried out. Beside these measurements results were used to verify mathematical models. Special for the investigation of the heat conduction a facility was used which allows testing of large isolation samples (76 cm diameter) with liquid hydrogen (LH2) for cooling. Tungsten halogen quartz lamps with 100 kW were used for heating the sample outside to a maximum temperature of 1366 K [1] [2].

Especially for cryogenic storage tanks with liquid hydrogen (LH2) it is necessary to carry out thermal cyclic tests with the isolation probe [3]. Therefore laboratory tests were made with different isolation thickness to test the thermal stress of the isolation for the airplane. Significant reductions of the thermal stress at smaller probes due to edge effects were investigated. The test panel was made of aluminium to investigate isolation specimen with LH2. The heat through the insulation was estimated from boil-off experiments. Therefore the fill level was measured with thermocouples. Other investigations were carried out in which the samples were additionally blown with hot air. Different isolation samples for instance were made of polyurethane foams (PU) and polymethacrylimid foam (PMI). Former aviation applications with PU-foams already demonstrated structural stability and durability over more than thousand cycles. Also a very low degradation of the PU-foams during the thermal cycles was investigated. The PU foams were already used during early space applications or for LNG tankers and road tank cars. The boil-off rates were measured during 4000 temperature cycles. The result is always a degradation of the isolation material. Especially one type of PU foam falls off in quality after about 800 cycles. Ice was detected near originated cracks together with white steam. This reason is so called „cryo-pumping“. The results of the study demonstrate that the number of thermal cycles has a significant effect on the properties of the isolation. Therefore this correlation is necessary to investigate in detail. The investigations with PMI foam samples show worse isolation properties than the PU foam and failed after few cycles when cracks occurred in the foam. Additionally polyisocyanurat (PIR) foams were tested which later were used for isolation of the Space Shuttles booster. PIR had also worse isolation properties than the PU foam and during the cycles delamination occurred. Later all these results were summarised in a report [4].

In the 1980’s NASA set Lockheed-California Company in charge for the development of advanced thermal structures for a spacecraft. Part of the structure was a reusable isolation of the cryogenic LH2 and LOX tanks. Five different levels must be done for the development of the isolation stating from the design process up to scaled laboratory experiments with real environment conditions [5]. Isolation panel specimen with a base area of about 25 cm x 25 cm and a thickness of about 2.5 cm were used for the experiments. The used material was a PMI-foam (Rohacell 110WF) which was mounted on an aluminium substrate (2219-T87) of 0.3 mm thickness. For the mounting a glass fabric was soaked with FM400 glue. For the panel specimen a small chamber was produced. Within the chamber the panel specimen were cooled with LN2 or LHe from one side. From the other side the panel specimen could be heated with a controlled resistance heater. 8 Cycles with LHe and 5 cycles with LN2 were carried out within 30 minutes. After these experiments no anomalies were detected with x-ray inspection. Additionally visual inspections with 10-fold magnification have shown small cracks in the isolation or detachment from the substrate. For more complex experiments the test facility was redesigned. With this new facility it was possible to measure mechanical loads with a tension apparatus. LN2 was used for cooling so that the mechanical and thermal loads of a LOX tank could be determined. A total of 100 cycles were carried out for each panel specimen. Always after 5 cycles the panel specimen was inspected. After 40 cycles again a detachment of the isolation from the substrate was occurred at the edge of the specimen.

For the Atlas-programme a new test facility was constructed, with the aim to perform thermo-mechanical experiments on LH2-insulation of the Centaur upper stage. Stainless steel substrate and PVC-foam insulation were

DOI: 10.13009/EUCASS2019-738

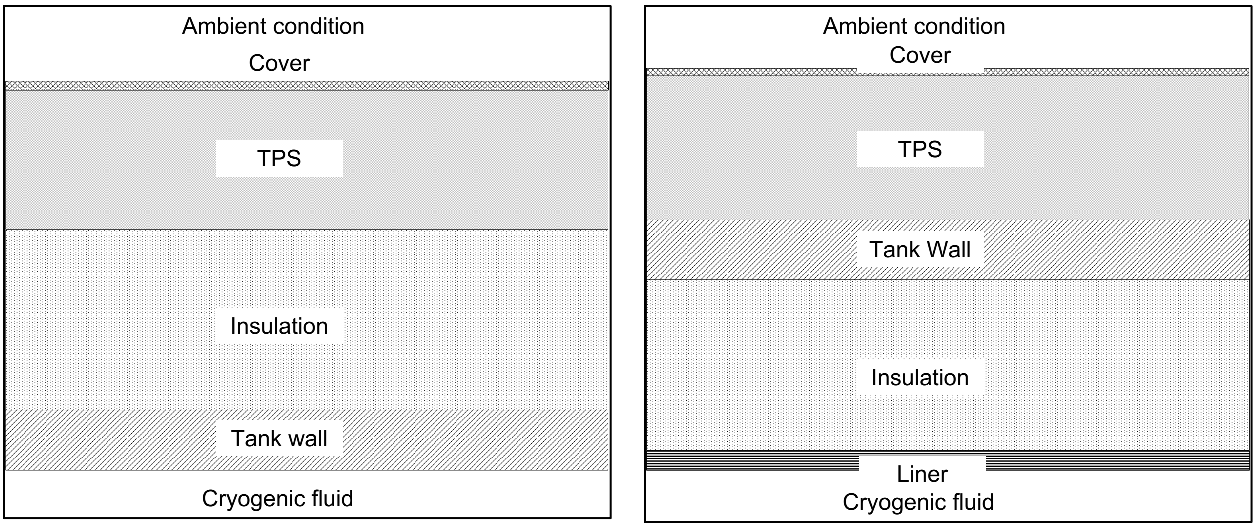
glued with epoxide. The base area of the samples was 56 cm x 40 cm and the isolation thickness was 15 mm. The samples were tested with a cycled thermal and mechanical load. Also the presence of cryo-pumping was investigated. Beside the experiments methods to repair isolation were tested. The test facility consists of two chambers. The lower chamber was used to cool the sample with LN2. The upper chamber was used to house the sample. A large acryl glass window was used for visual inspection. As there were no problems the isolation was qualified for the upper stage fuel tank. [6]

During the 1990's, American as well as European engineers investigated the technology of reusable space vehicles with cryogenic tanks. For instance NASA's Venture Star programme as a follow on programme of the Space Shuttle. The goal was a reusable single-stage to orbit space vehicle (SSTO) with LH2 und LOX tanks. The technology demonstrator was called X-33. Detailed investigations were conducted for different aspect of reusability, with a special focus on the investigation of the tank isolation properties during several cycles [7]. PI-foam (TEEK) insulation was qualified with 50 cycles [8] [9]. The isolation samples consisted of flat tank wall panels with a base area of 0.6 m x 0.3 m. Sample cooling was performed with LN2 and LHe. The temperature was measured with fibre optical sensors [10]. To reduce the complexity of the tests the experiments were carried out without the TPS. Thermal mechanical experiments with a complete mission cycle were made to get a representative result for a RLV. To simulate the fuel tank load, the sample was uniaxial loaded. The LOX tank panels were made of an aluminum lithium alloy 2195 as substrate with a spray-foam (SOFI SS-1171) and a PEI-foam (Airex). Problems with the Airex-foam have been occurred after 50 cycles. For the SS-1171-foam a contraction was detected without leading to a bad isolation. The LH2 tank material is graphite fiber with epoxy. A second tank consists of a titan sandwich structure. For the isolation external PEI-foam and internal PMI-foam (inside the sandwich) were used. Different glues were investigated for mounting the isolation on the tank panels. With mounting Airex on the graphite fiber panel with the glue EA 9394 there was a failure after 42 cycles. During an additional experiment with the same combination no problems appeared [11].

2.2 Insulation Concepts

For high velocity, re-entry RLV-systems, the cryo tanks need a TPS in addition to the insulation. It is important to regard the whole system of tankwall, thermal protection system and insulation. Even the interfaces between the different layers are important for investigation. Different generic configuration concepts were considered for reusable insulation [12].

For instance a compact configuration can be used. For compact insulation configuration the cover is usually glued to the TPS. Further the cryogenic insulation can be mounted internal or external to the tank wall (Figure 1). Figure 1 (a) shows a schematic layer for a compact external insulation. Here the insulation is between the TPS and the tank wall. Figure 1 (b) shows a schematic layer for a compact internal insulation. For internal, the insulation is between the tank wall and the fluid. For an internal insulation usually a liner is considered for use to avoid contamination of the propellant. For very high temperatures also a cover on the TPS is used.



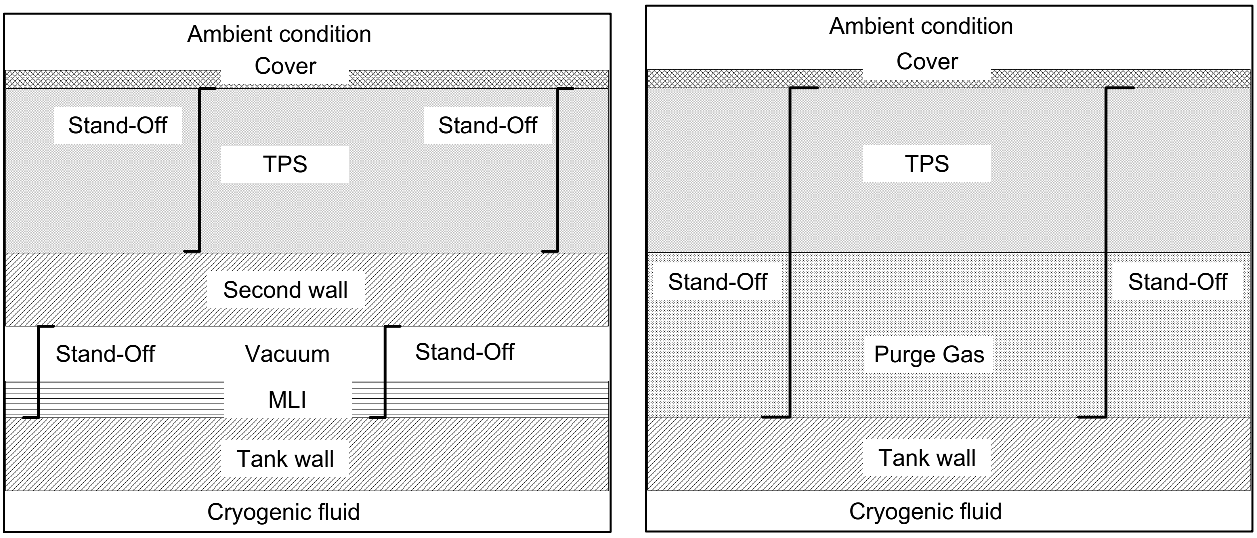
a) external compact insulation b) internal compact insulation

Figure 1: Schematic layer build-up of a) an external compact insulation and b) internal compact insulation with either tank wall, insulation, TPS and cover. The internal insulation is shown with liner.

DOI: 10.13009/EUCASS2019-738

Further without gluing the cover to the TPS, stand-offs can be used to bear the cover to the tank wall. The separate layer insulation configuration is indicated with two tank walls, connected with stand-offs. For high temperature protection a TPS and coating is used. For high performance insulation the space between the tank walls is evacuated to provide a vacuum insulation. Due to the vacuum, heat transfer is only given through the thermal radiation and a small amount of thermal conduction through the stand-offs, without any thermal convection. Usually multi-layer-insulation (MLI) is applied at the cold tank wall in the evacuated layer to decrease the thermal radiation. Figure 2 (a) shows a schematic view of the different separate insulation layers.

Aeroshell insulation configuration is close to the separate layer insulation configuration, but consists purge gas to insulate a spacecraft. Especially when using nitrogen (N2) as purge gas for LH2 tanks, a small insulation layer is also needed, to prevent condensation of the purge gas on the cold tank wall. Figure 2 (b) shows a build-up without additional insulation, which is for instance used for helium (He) purge.



a) separate layer insulation a) aeroshell insulation

Figure 2: Schematic layer build-up of a) separate layer insulation with two tank walls, stand-offs, TPS and cover and b) aeroshell insulation with purge gas layer and cover.

2.3 Insulation material

In former ELV applications foam was used for insulation. But especially for reusable systems not only low conductivity of the material is important, further the material has to tackle lots of temperature cycles without losing the insulation properties. In Figure 3 the thermal conductivity for different solid materials and gases are shown. Due to the temperature dependence of thermal conductivity, for some materials different values are given in different bars. The best possible insulation would be granted with a high vacuum with multi-layer-insulation (MLI). For aerogel bead, also a high vacuum in needed. Especially for cold temperatures the foams (PU and PMI) have small differences in their insulation properties. It is also shown, that gas is a good insulator.

DOI: 10.13009/EUCASS2019-738

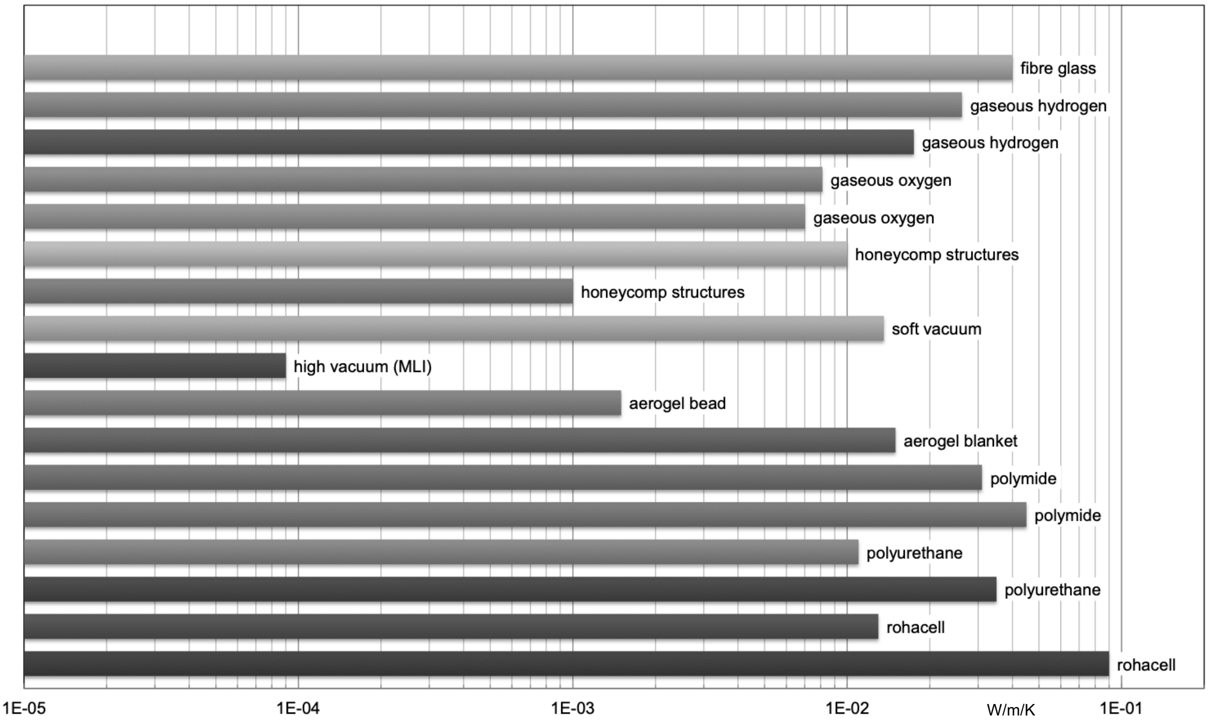


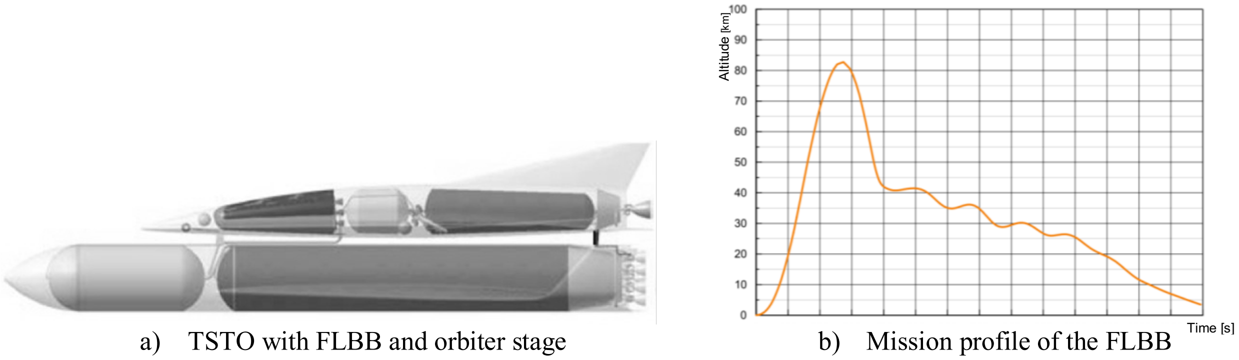
Figure 3: Thermal conductivity of common gases and insulation materials [13] [14] [15] [16]

PMI foam usually is an open-pore and therefore prone to cryo-pumping. But, the PMI foam type “Rohacell” is close-pored hard foam, especially developed for lightweight construction. Rohacell has very good mechanical qualities and low thermal conductivity for low temperatures. Rohacell is already used in commercial applications for noise insulation. PI foam also has some applications in noise insulation, but was former not used for thermal insulation in spacecraft. PU foam has a long history for space craft insulation. PU foam is usually close-cell foam with good insulation properties. The PU foam mechanical properties are usually lower than for PMI ($3\,MPa > 1.1\,MPa$). Also the highest temperature is lower than for PMI ($450\,K > 400\,K$).

It is also possible to use loose fillings, like bubbles, spheres or perlite instead of a homogeneous, closed material as insulation material. Loose fillings show small thermal conductions due to the small contact areas of the filling material. Whereas the launch of a space craft causes a lot of vibrations, the density of the filling increases [17] [18].

3. Reference Configuration

As reference configuration the fly-back-booster (FLBB) stage of a two-stage-to-orbit (TSTO) is chosen. The FLBB is a cryogenic stage with LOX and LH2 as propellant. Each tank system is double-domed aluminium tank with a diameter of $8.5\,m$. Length of LH2 tank is $60\,m$ and of the LOX tank is $30\,m$. Both tanks used as integral tanks, therefore they not only have to withstand the pressure loads, but also the mechanical loads of the stage. With the given flight trajectory, also a TPS is needed to protect the tank structure and the insulation against the high re-entry temperatures. A reusability of 10 times of the FLBB is designated. Figure 4 (a) shows the FLBB reference configuration with both, tank systems and the orbiter stage on top. Due to the mission profile a maximal FLBB altitude of $90\,km$ is given. Figure 4 (a) shows the mission profile of the FLBB with the altitude given as function of time. The duration of the FLBB ascent phase is less than 5minutes, decent with re-entry takes 20 minutes. For both, the LH2 and the LOX tank a concept for insulation was made. Because of the different liquid temperatures and the different temperature loads due to the re-entry, at least two different insulation systems have to be developed. The design driving thermal load for the design of the insulation is below and on top of the FLBB. Below the FLBB very high adiabatic radiant temperatures from $1200\,K$ are expected. On top the booster the adiabatic radiant assumption is below $450\,K$. The static pressure is expected below $10\,kPa$ [19] [20] [21].



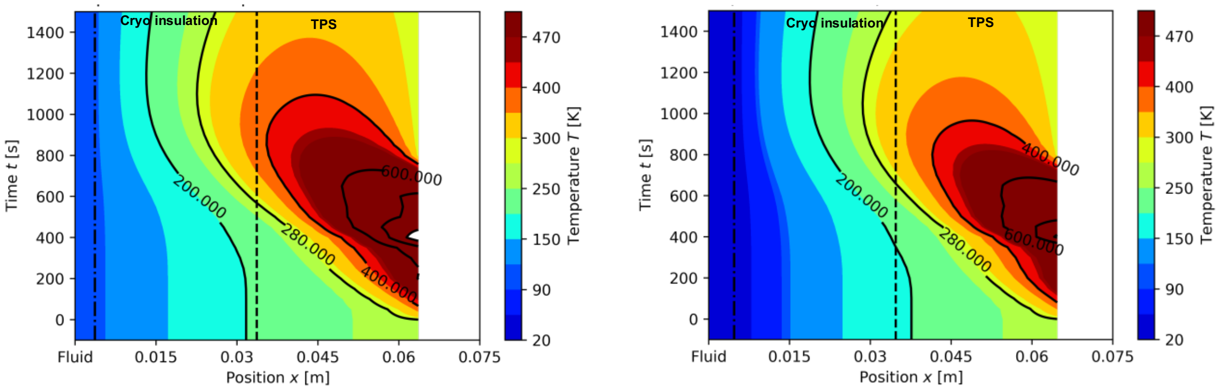
a) TSTO with FLBB and orbiter stage b) Mission profile of the FLBB

Figure 4: TSTO reference configuration with (a) FLBB and orbiter stage and (b) altitude versus mission time (mission profile) of the FLBB [19] [20]

4. Insulation system design

For both, the LH2 and the LOX tank system, a proper insulation system is needed to tackle the given specifications from the FLBB reference configuration. For the FLBB lower part, a TPS is mandatory to protect the insulation and the tank structure against high temperatures. As insulation material the PMI foam Rohacell was chosen. Rohacell grants close-cell foam structure, has good mechanical properties and was successfully used in former studies as LH2 insulation material. As TPS a high mullite alumina silica fibre mat (Altra Mat) is chosen with an Inconel plate as cover [21]. The Inconel plates need to be mechanical fixed to the tank structure. Therefore, a stand-off from the cover to the tank wall is necessary and is also a thermal bridge through the insulation material. As boundary condition for the insulation foam, as well as the Altra Mat, no icing is required. Icing in the insulation can lead to cryo-pumping. Temperatures inside the insulation and Altra Mat above at least $275\ K$ are necessary.

For the design process of the needed insulation system, unsteady numerical analyses were made to fulfil the given requirements. Figure 5 shows transient temperature calculation on the lower part of the FLBB for the LOX tank and the LH2 tank for the whole mission, below the FLBB (point 2 and 5). Here both, the insulation and the Altra Mat have a thickness of $30\ mm$. Due to the thin layer and high thermal conductivity of metallic tank wall and cover, these haven't been considered for the numerical investigations. The temperature assumption shows that it is not possible to bring the temperature inside the Altra Mat over $275\ K$. Especially for the filling at the start ramp, very low temperatures are expected. To investigate this problem, a parameter study was made with different thicknesses for the Altra Mat and Rohacell. As result insulation with a thickness above $150\ mm$ is required to achieve the specifications. Otherwise 150 mm cryogenic insulation results into high structure masses and is therefore not sustainable.



c) LOX tank d) LH2 tank

Figure 5: Temperature development for a) the LOX tank and b) the LH2 tank during FLBB mission on the upper side, with tank wall, 30 mm insulation and 30 mm Altra Mat

To tackle this problem, a purge gap between the Rohacell and the Altra Mat was developed. During the filling procedure a dry purge gas like nitrogen is brought into the purge gap to bring in some heat and protect the Altra Mat for the cold temperatures. On the other hand, due to an additional piping system for the purge gas, the purge gap increases the complexity of the insulation system and the whole FLBB. But here, only small pipes are needed to bring in the hot gas. Because of the well packed insulation system with Rohacell, Altra Mat and Inconel cover, a spacer material between the Altra Mat and the Rohacell is needed to bring in the purge gas. The stand-offs for the Inconel cover is used to bear the piping system. Additionally, due to the low overpressure, humid air from the outside is prevented to get inside the insulation system. Figure 6 shows a schematic view of the whole insulation system with the purge gap. The stand-offs are designed with an s-profile. Due to the fact, that the filling is an important sizing point for the insulation, it is sufficient to provide the purge gas only on the start ramp. First numerical estimations show that 30 mm Rohacell and 30 mm Altra Mat will perform well for the given boundary conditions.

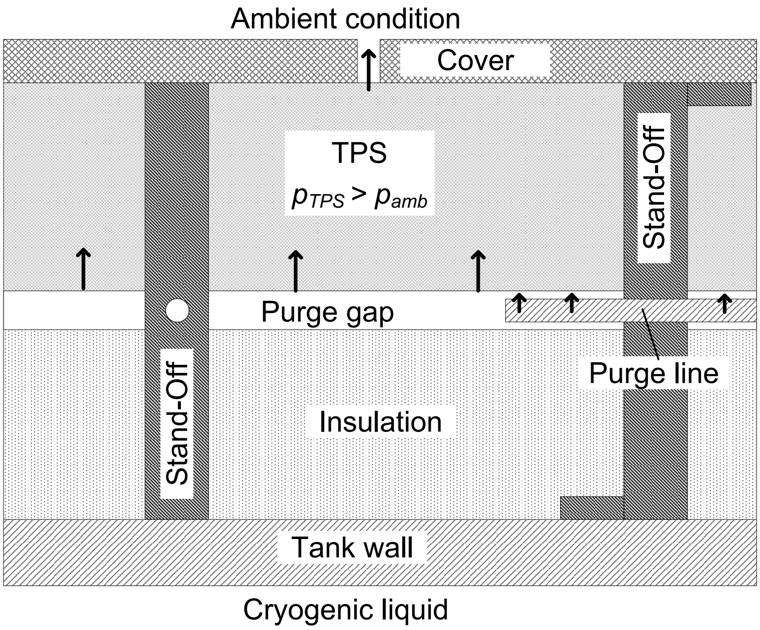
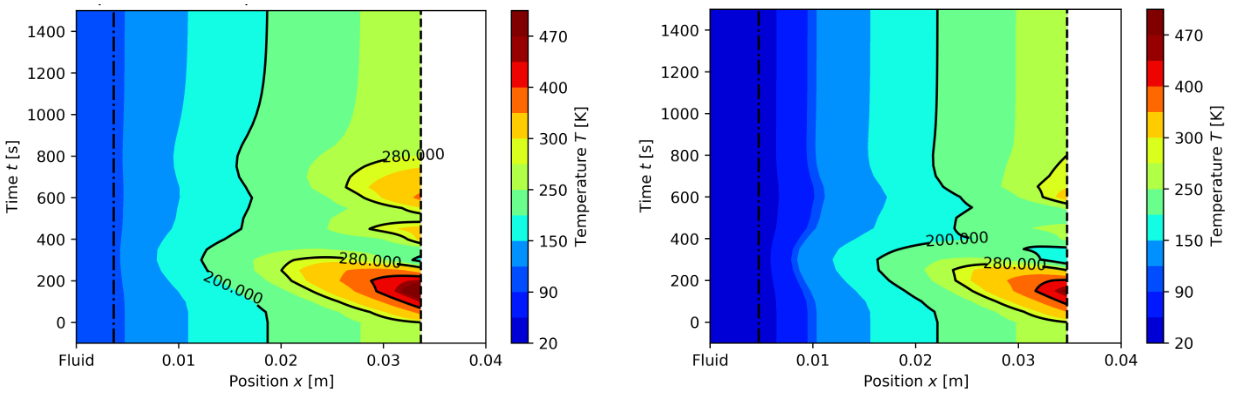


Figure 6: Schematic layer build-up of insulation system design with tank wall, insulation, purge gap, stand-offs, TPS and cover

Due to the temperature assumption of the FLBB, the TPS is not needed for the upper part. Again, Rohacell insulation with 30 mm thickness was designed to fulfil the reference configuration needs. Figure 7 shows the transient temperature development for the whole mission profile for the LOX and the LH2 tank. Rohacell WF provides a heat deflection temperature of at least 475 K and withstands the temperature loads.



a) LOX tank b) LH2 tank

Figure 7: Temperature development for a) the LOX tank and b) the LH2 tank during FLBB mission on the lower side with tank wall and 30 mm insulation

DOI: 10.13009/EUCASS2019-738

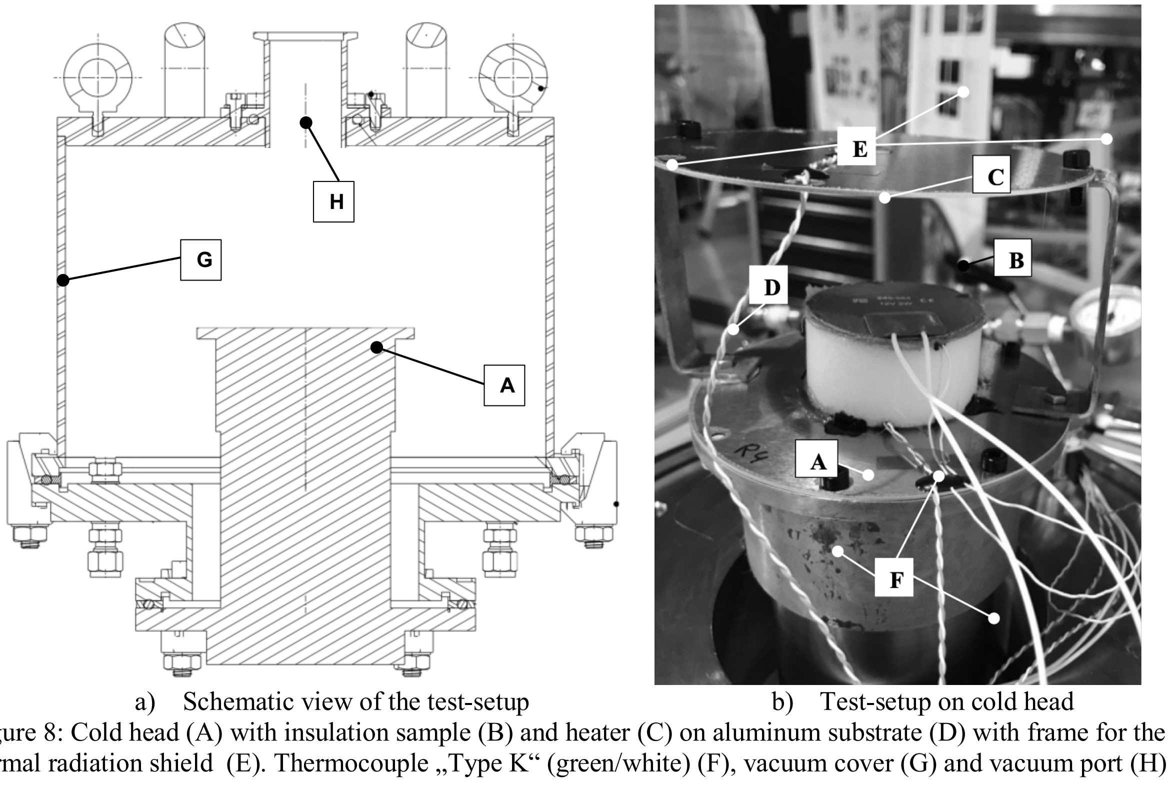
5. Experimental Investigations

To support the design of an insulation for the given reference configuration, experimental test are necessary to have a better understanding how the whole insulation system performs under temperature cycles. Therefore an experimental testbed was developed. This testbed allows temperature cycles for insulation samples from ambient temperature ($293\ K$) to liquid hydrogen temperature ($20\ K$). The samples are small cylinders with an height between $25\ mm$ and $30\ mm$ and a diameter of $54\ mm$. As indicator for the quality of the insulation, the measured change of the thermal conductivity is used.

5.1 Experimental Testbed

As experimental testbed which allows a chill down of the insulation sample to cryogenic temperatures was needed. Therefore a set-up was developed with a cold head. The cold head operates with a closed helium cycle as Gifford-McMahon refrigerator. The helium is compressed in a compressor and relaxed on the cold head to afford temperatures of $20\ K$ without payload on top. Also to provide steady conditions for the insulation samples a vacuum shield is needed. Figure 8 (a) shows a schematic view of the cold head (A) and the vacuum cover (G), with the vacuum port (H). Flanged to the vacuum port is a vacuum pump evacuating the vacuum shield.

As insulation samples first a PI-foam (AC 530) are used as payload on the cold head. The sample was cut out of plates, both with a diameter of $54\ mm$, with a height of $30\ mm$. To apply a thermal load on the insulation sample, a silicon heater with a maximum power of $2\ W$ is chosen. As substrate an aluminium plate is used as interface between the insulation sample and the cold head. To have a well performing thermal connection between insulation and substrate, vacuum grease (Apiezon N) is used. Mechanical stability was granted by punctually gluing the insulation sample to the substrate with epoxy Stycast 2850 and Catalyst 23 LV as hardener. Also between sample and heater, a small aluminium plate is fixed with punctual glue and vacuum grease as thermal connection. Figure 8 (b) shows the test-setup, with heater (C) and insulation sample (B) on the substrate (D) on the cold head (A). To lower the thermal radiation on the system, thermal radiation shield of thin aluminium foil is wrapped around the insulation sample. Copper rods and an upper aluminium plate (E) are used to keep the cover in shape and not to touch the insulation sample. Measurement of the temperatures is performed with Type-K (F) thermocouple and a silicon diode. Due to the only thermal connection of the heater to the sample, the heat flow is equal to the measured electrical power of the heater.



a) Schematic view of the test-setup b) Test-setup on cold head

Figure 8: Cold head (A) with insulation sample (B) and heater (C) on aluminum substrate (D) with frame for the thermal radiation shield (E). Thermocouple „Type K“ (green/white) (F), vacuum cover (G) and vacuum port (H).

5.2 Experimental procedure

Each temperature cycle follows the same procedure, from first the evacuation of the vacuum cover, second the chill down of the insulation sample, third the electrical heater heat up and closing the cycle with warm up the system to ambient conditions. A typical procedure with the temperature development is shown in Figure 9. After an hour, it appears that the temperature below the insulation, on the cold head (T2), is close to 20 K. After a long chill down (> 12 h) the temperature difference (dT) reaches steady state (state 0). Next heater is turned on to heat up the sample, where the temperature difference (dT) rises, until reaching next steady state (state 1).

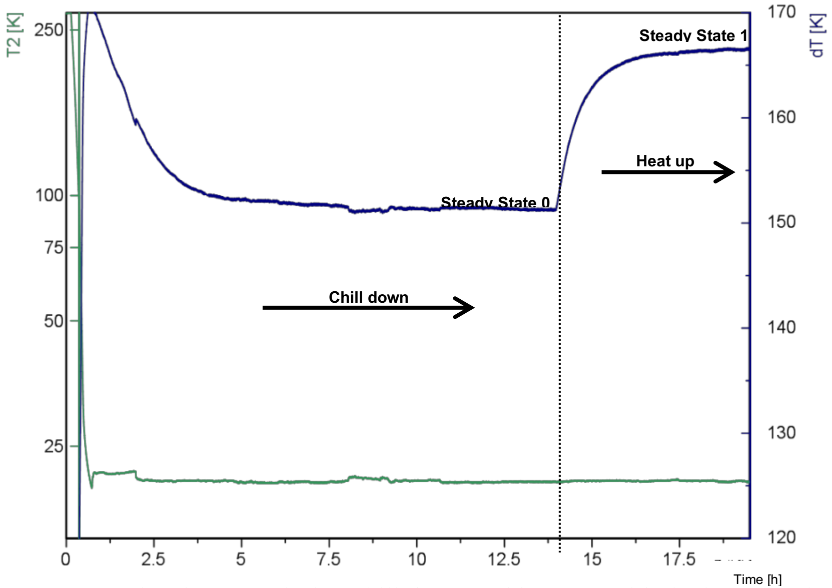


Figure 9: Typical temperature development during chill down and heat up, with the logarithmic temperature on the cold head (T2) and the temperature difference over the insulation (dT)

5.3 Experimental results

For PI-foam AC530 9 cycles (runs) were performed, with the described procedure. Figure 10 shows the temperature development between state 0 and state 1, after turning on the heater. For each cycle the electrical power of the heater is 100 mW. It occurs that the first two runs reaching different, higher temperature differences. Afterwards for run three to ten, only minor changes in the final temperature appear. As result, the thermal conductivity of the AC530 is degraded after 9 cycle only by 30% from 55 $W/m/K$ to 72 $W/m/K$.

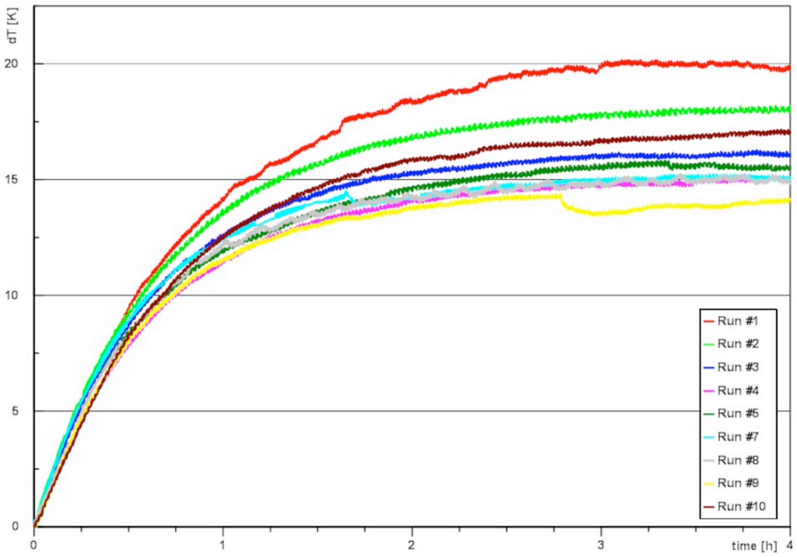


Figure 10: Normalized temperature developments for 9 cycles (runs) with PI-foam AC530 during heat up

DOI: 10.13009/EUCASS2019-738

6. Conclusion

For a given reference configuration FLBB a proper reusable insulation system need to be designed. The FLBB is a re-entry lift body and consists of cryogenic LH2 and LOX tank. Due to this given constraints, the insulation system must contain either, a cryogenic insulation and a TPS. For very high temperatures, also a cover for the TPS is needed. After reviewing the state of the art of insulation system for ELV and RLV, a couple of insulation concepts in combination with different insulation materials tackle the specifications of the reference configuration. The design process was supported with unsteady numerical thermal calculations for the whole mission profile. To fulfil the given requirements, a purge-gap between cryogenic insulation and TPS is needs to be designed. The purge gap prevents infiltration of ambient humid air from and prevents icing by bringing heat into the system. The purging especially is needed during the filling procedure and can be provided by ground service.

Also experimental investigations were carried out to analyse the behaviour of insulation materials for numerous temperature cycles. Therefore a testbed was designed, to chill down insulation samples to cryogenic temperatures. Measurements were performed to determine the thermal conductivity of the samples. The change of thermal conductivity is an indicator for the temperature cycle resistance. It is shown, that AC530 only degrades by 30% and reaching an asymptotic state after 9 cycles. Further tests need to be performed to analyse the behaviour of Rohacell for various temperature cycle.

Next, for prove of concept a demonstrator as integrated test object (ITO) is developed and needs to be tested. The ITO consists of the in this study presented insulation design concept. Aim of the coming test is to show the functionality of each insulation sub-system, with focus on the purge gap.

References

[1] R. G. Helenbrook and J. Z. Colt, *Development and Validation of Purged Thermal Protection Systems for Liquid Hydrogen Fuel Tanks of Hypersonic Vehicles,* 1977.

[2] G. D. Brewer, *Advanced Supersonic Technology Concept Study - Hydrogen Fueled Configuration,* 1984, p. 304.

[3] E. L. Sharpe, "External insulaton for liquid hydrogen tanks," vol. 1978, 1978.

[4] F. M. Anthony, J. Z. Colt and R. G. Helenbrook, "Development and validation of cryogenic foam insulation for LH2 subsonic transports," 1981.

[5] P. S. McAuliffe, R. C. Davis and A. H. Taylor, "Development of a reusable, flight-weight cryogenic foam insulation system," 1986.

[6] M. Gruszczynski, R. Wronski, V. Thorp and T. Walters, "Development of a foam insulation system for pressure stabilized liquid hydrogen propellant tanks," Reston, Virigina, American Institute of Aeronautics and Astronautics, 1988.

[7] H. K. Rivers, *Cyclic Cryogenic Thermal-Mechanical Testing of an X-33/RLV Liquid Oxygen Tank Concept,* NASA, Ed., 1999.

[8] T. F. Johnson, H. K. Rivers and R. Natividad, "Thermal structures technology development for reusable launch vehicle cryogenic propellant tanks," 1998.

[9] E. S. Weiser, T. F. Johnson, L. St. Clair and Echigo, "Polyimide foams for aerospace vehicles," *High Perform. Polym.,* vol. 12, pp. Introduction/page i-Introduction/page ii, 1999.

[10] L. Melvin, B. Childers, R. Rogowski and W. Prosser, "Integrated Vehicle Health Monitoring (IVHM) for Aerospace Vehicles," in *Structural health monitoring*, Lancaster, Pa., Technomic Publ, 1997, p. 705–714.

[11] J. E. Fesmire and S. D. Augustynowicz, "Insulation Testing Using Cryostat Apparatus with Sleeve," in *Advances in Cryogenic Engineering*, Boston, MA; s.l., Springer US, 2000, p. 1683–1690.

[12] Sumin and Prel, "Study of insulated and equipped cryogenic tanks for RLV," in *IAC*, 2006.

[13] Augustynowicz and Fesmire, "Cryogenic Insulation System for Soft Vacuum," 2000.

[14] Blackmon and Wessling, "Insulation system having vacuum encased honeycomb offset panels". 2005.

[15] S. K. Mital, J. Z. Gyekenyesi and S. M. Arnold, "Review of Current State of the Art and Key Design Issues With Potential Solutions for Liquid Hydrogen Cryogenic Storage Tank Structures for Aircraft Applications," 2006.

[16] Fesmire and Augustynowicz, "Cryogenic Thermal Insulation Systems," 2005.

[17] M. S. Allen, R. G. Baumgartner, J. Fesmire and S. D. Augustynowicz, "ADVANCES IN MICROSPHERE INSULATION SYSTEMS," in *Cryogenic Engineering Conference*, 2003.

DOI: 10.13009/EUCASS2019-738

[18] R. J. Werlink, J. Fesmire and J. P. Sass, "Vibration considerations for cryogenic tanks using glass bubbles insulation," 2011.

[19] M. Sippel, "Focused research on RLV-technologies: the DLR project AKIRA," *EUCASS,* 2019.

[20] Bussler, Sippel and Kopp, "Referenzkonfigurationen AKIRA SL 7-3 Booster," 2017.

[21] T. Reimer, E. Arce and C. Rauh, "Interface Designs between TPS and Cryogenic Propellant Tank of an RLV Booster Stage," *EUCASS,* 2019.