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Focused research on RLV-technologies: the DLR project AKIRA

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DLR has organized a multidisciplinary research project on technologies critical for the realization of RLV-stages called AKIRA. The research topics are efficient RLV-stage return, reusable cryogenic tank insulation technologies, and structural technologies in RLV-stages and reusable engines.

The paper provides an overview of all ongoing activities and summarizes major research results achieved over the successful mid-term review of November 2018 up to early 2019.

Abbreviations

CAD	Computer Aided Design
CFRP	Carbon Fiber Reinforced Plastic
CMC	Ceramic Matrix Composites
DRL	Down Range Landing
GLOW	Gross Lift-Off Mass
GTO	Geostationary Transfer Orbit
IAC	In Air Capturing
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
TPS	Thermal Protection System
TSTO	Two-Stage-To-Orbit
TVC	Thrust Vector Control
UAV	Unmanned Aerial Vehicle

1 Introduction

In 2017, a multidisciplinary research project called AKIRA (**A**usgewählte **K**ritische Technologien und **I**ntegrierte Systemuntersuchungen für **R**LV **A**nwendungen or in English specific critical technologies and integrated system investigations for RLV applications) was launched in DLR [1]. In AKIRA technologies critical for the success of reusable space transportation system development are theoretically and experimentally investigated following launcher system requirements. AKIRA is planned for a duration of 3 years and total funding amounts to around €6.2 million. Thus, the project is scheduled to be finished at the end of 2019.

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 advantage of the project is the bundling and tight integration of the various activities, and the orientation of the technology work on two RLV reference configurations and reference missions.

Three main research topics are addressed which are described in more detail in the following sections:
- Technologies for efficient RLV-stage return
- Reusable cryogenic tank insulation technologies
- Structural technologies in RLV-stages and reusable engines

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1.1 Reference RLV-concepts

The two RLV reference concepts chosen in AKIRA for system studies are following different approaches. The main differences are characterized by the data in Table 1. The reusable first stages are in focus of the AKIRA-project and therefore are briefly described in the following sections.

Table 1: Key characteristics of AKIRA RLV reference concepts

	SpaceLiner 7 TSTO	Aurora-R2
primary mission	GTO, > 8200 kg	LEO 250 km, 7000 kg
lift-off / landing - mode	Vertical/Horizontal	Horizontal/Horizontal
propellants	LOX/LH2	LOX/Kerosene
GLOW	1807 t	454.6 t
total number of launcher stages	3	2

1.1.1 Reference RLV-Booster SL 7-3

The SL 7-3 Booster is the first stage of the fully reusable TSTO launcher SpaceLiner [2, 3]. The GTO-mission requires an expendable, storable upper stage to be released from the internal cargo bay of the orbiter. Achievable payload mass in GTO is more than 8.2 t [3]. The geometry of the Booster SLB 7-3 is shown in Figure 1 and key-characteristics are provided in Table 1.

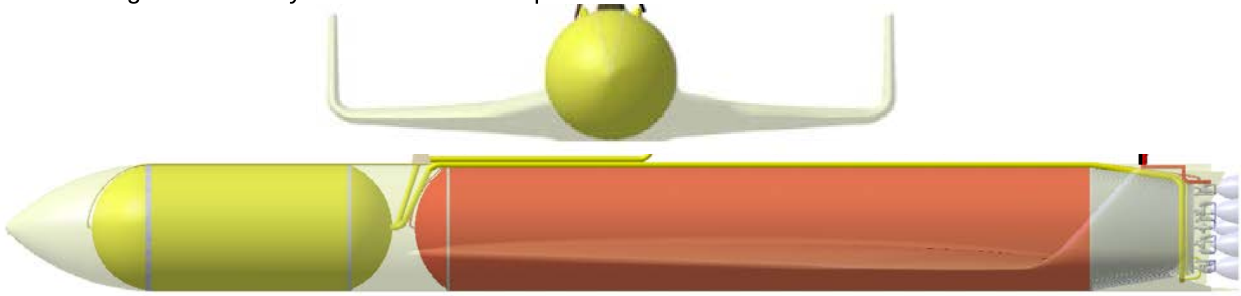

Figure 1: SL 7-3 Booster Geometry [2]

The SLB 7-3 performs a typical winged RLV mission with vertical ascent, stage separation around Mach 13 at 60 km followed by a benign reentry flight due to the vehicle's low flight path angle. Maximum thermal and mechanical reentry loads are expected at around Mach 10. The estimated maximum stagnation point heatflux remains below 300 kW/m^2. In AKIRA the heatfluxes at the LOX- and LH2-tank interfaces have been calculated to reach peak values on the lower side of 78 and 55 kW/m^2 respectively.

Within the AKIRA project the SLB7 Booster stage serves as the reference for full-scale "in-air-capturing"-simulation, integration of cryogenic insulation and combination of TPS as well as investigation of the structural connection between integral tank and wing.

1.1.2 Reference concept Aurora-R2

The second reference concept Aurora-R2 is based on a delta-winged, two-stage-to-orbit (TSTO) launch vehicle configuration providing sufficient lift for horizontal take-off and horizontal landing (HTHL) [4]. The R2 configuration utilizes a reusable lower stage and an expendable upper stage. The preliminary vehicle geometry resembles a flying wing design, but with a "bump" on the vehicle back [4]. This concept has been iteratively investigated in terms of mass budget, propulsion, aerodynamics and structural optimization. The vehicle design is shown in Figure 2, and its key characteristics are given in Table 1.

The LOX/Kerosene propellant combination allows the placement of the kerosene tanks into the wing structure [4]. As for the ascent, the rocket engines are partially combined with air-breathing military turbofan engines up until Mach 1 [4], while for ferry flights from the landing site back to the launch site the launch vehicle should be operated using the air-breathing engines only. For the re-entry and descent phase, the launch vehicle remains unpowered. The upper stage is located inside the delta-winged main stage and is released at separation time for further ascent.

Within the AKIRA project the Aurora first stage serves as the reference for controllability analyses and for the potential application of thin-ply laminates (compare also [4]!).

For the AKIRA trajectory controllability studies, a polar orbit with an apogee altitude of 1200 km and an inclination of 90° is targeted. For controlling the descent phase, a reaction control system (RCS) and aerodynamic control surfaces are used whenever possible.

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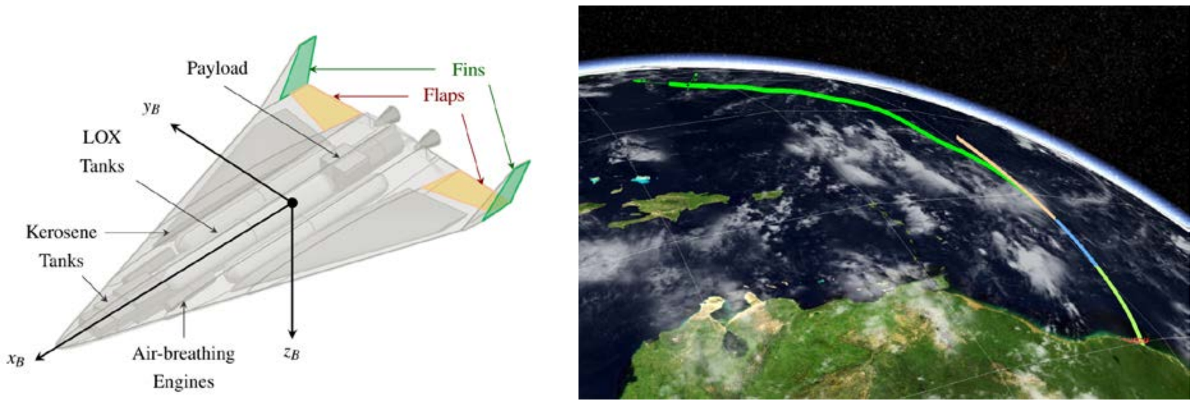

Figure 2: Overview of the reference concept Aurora-R2 and its optimized trajectory

The Aurora-R2 concept is analysed with the newly developed multibody modelling and simulation framework for system dynamics and control studies, providing flight dynamics models with appropriate level of detail for each corresponding analysis. For instance, 3-DOF flight dynamics models are generated using the object-oriented and equation-based modelling language MODELICA. These models are translated into *Functional Mock-up Units* (FMU) and then integrated into the Matlab-based multi-phase and multi-objective trajectory optimization package *MOPS trajOpt*. The overall modelling concept and trajectory optimization results are discussed in [5], [6] and [7].

The resulting reference trajectory in combination with consistently derived nonlinear 6-DOF models are subsequently used for controllability studies considering control allocation methods. The nonlinear inverse modelling approach to obtain the required RCS moments for specified flight manoeuvres as shown in Figure 3, as well as the double-loop Nonlinear Dynamic Inversion (NDI) based attitude control system are discussed further in [8] and [9].

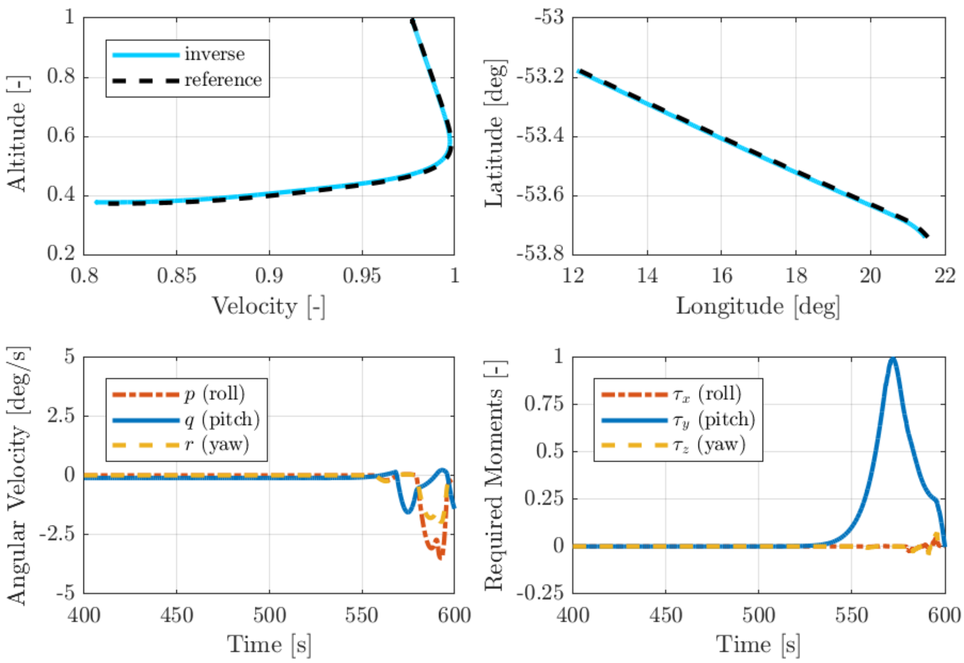

Figure 3: Aurora-R2 descent flight parameters obtained by nonlinear inverse modeling

Further improvements in terms of the angular impulse budget, using a combined RCS with aerodynamic surface controls for instance, can lead to improvements in terms of the launch vehicle preliminary design since the dimensioning and location of the RCS thrusters can also have a considerable impact on the vehicle configuration. This scenario considering a combination of RCS thrusters with aerodynamic surface controls is shown in Figure 4. The nonlinear control system, simulated for the descent phase including the re-entry flight and covering a wide flying envelope demonstrates the controllability of the launch vehicle as well as the budgeting of the angular impulse required during re-entry in terms of RCS thrusting moments.

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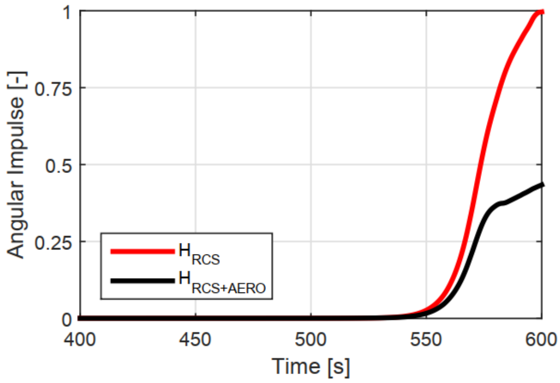

Figure 4: Impact on the resulting angular impulse required for RCS when using with and without aerodynamic controls

2 Topic 1: RLV-return technologies

Returning reusable stages into the atmosphere and back to their launch site is a key-technology only required by RLV. Several technical options exist; however, none of them is without impact on launcher performance. How far the payload mass or vehicle size will be affected is depending on the procedure, its propulsion system and the mission.

2.1 Systematic comparison of different RLV return modes

The goal of the AKIRA project is to investigate a broad range of return options and systematically compare them to each other. The return options investigated in AKIRA focus on first stage full or partial recovery. Hence, several landing and return options are not investigated in detail, since they do not work well for high dry masses (e.g. parachute landings).

The potential RLV stage return modes strongly vary from pure ballistic to using aerodynamic lift-forces, gliding flight or captured towing. In case of propelled return, the options stretch from using the rocket engines or separate air-breathing turbo-fan or even propeller for efficient low-speed flight. A schematic of the available options is presented in Figure 5 which considers also the possibility of returning only some key-components of the first stage while discarding other elements. Recovery of merely the propulsion bay with the main rocket engines has been proposed recently for ULA Vulcan and another concept under the name Adeline.

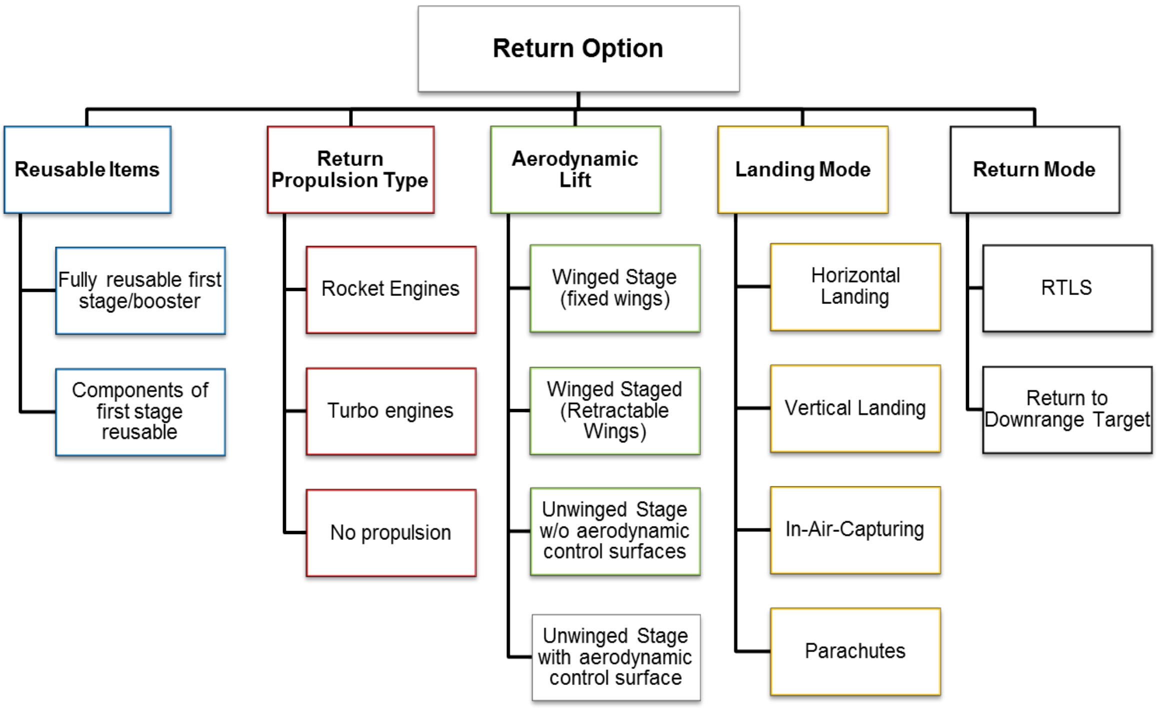

Figure 5: Potential RLV stage return modes

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A return option investigated in AKIRA is the VTVL method with retropropulsion as used by SpaceX (Falcon 9 and Falcon Heavy) and Blue Origin (New Shephard and in the future New Glenn). This method is based on the idea to use the rocket engines to decelerate the first stage after MECO to land it either on a barge downrange or to return it to its launch site (RTLS). Another method extensively studied in the past at DLR is the VTHL (Vertical Take-Off, Horizontal Landing) method, either in turbojet flyback mode or using the innovative "in-air-capturing" (see section 2.2 below and [12 - 18]!).

Figure 6 shows the return modes considered for full first stage recovery in AKIRA. A first stage equipped with no wings has to do a vertical landing with the two options of either a downrange landing (DRL) or a landing at the launch site (RTLS). A first stage equipped with wings or wing-like devices creating sufficient lift can either land horizontally like a conventional aircraft or land vertically using its own engines. In the case of a horizontal landing, two different options are considered within AKIRA: the LFBB method (Liquid Flyback Booster) using turboengines for a propelled flyback and the In-Air-Capturing (IAC) method using a capturing and towing aircraft.

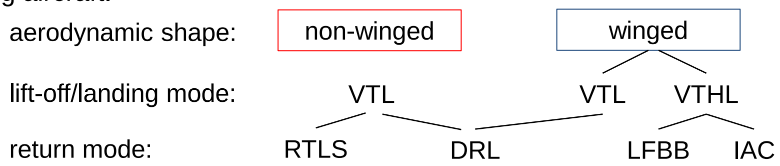

Figure 6: Investigated RLV return modes of complete first stages

Any RLV-mode is degrading the launcher's performance compared to ELV due to additional stage inert mass or required descent propellant. However, the amount of performance degradation is spreading over a significant range depending on the mode or separation conditions. A comparison of the different performances is of strong interest because these are related to stage size and hence cost. As a reliable and sufficiently precise estimation of RLV costs is almost impossible today, the performance impact comparison gives a first sound indication of how promising the modes are.

The performance impact of an RLV is directly related to its (ascent) inert mass ratio or net-mass fraction, reasonably assuming that the engine Isp is not considerably affected. Inert masses of the stage during ascent flight are its dry mass and its total residual propellants including all those needed for controlled re-entry, landing, and potentially fly-back. A specific inert mass ratio is then defined as:

$$\text{inert mass ratio}_i = \frac{m_{i,inert}}{GLOW_{stage}}$$

The higher the inert mass ratio of a stage, the lower is its acceleration performance if propellant type and engine performance are unchanged. Figure 7 presents a comparison of the inert mass ratio for generic TSTO-launchers and different return modes of the reusable first stage. All launchers have been sized for 7.5 tons GTO payload with a variation in separation Mach-number of the RLV [18]. As mission and stage number are identical, the inert mass ratio can be presented as function of the total ascent propellant loading. RTLS for GTO is excessively high in its stage size and inert mass ratio and has hence been excluded.

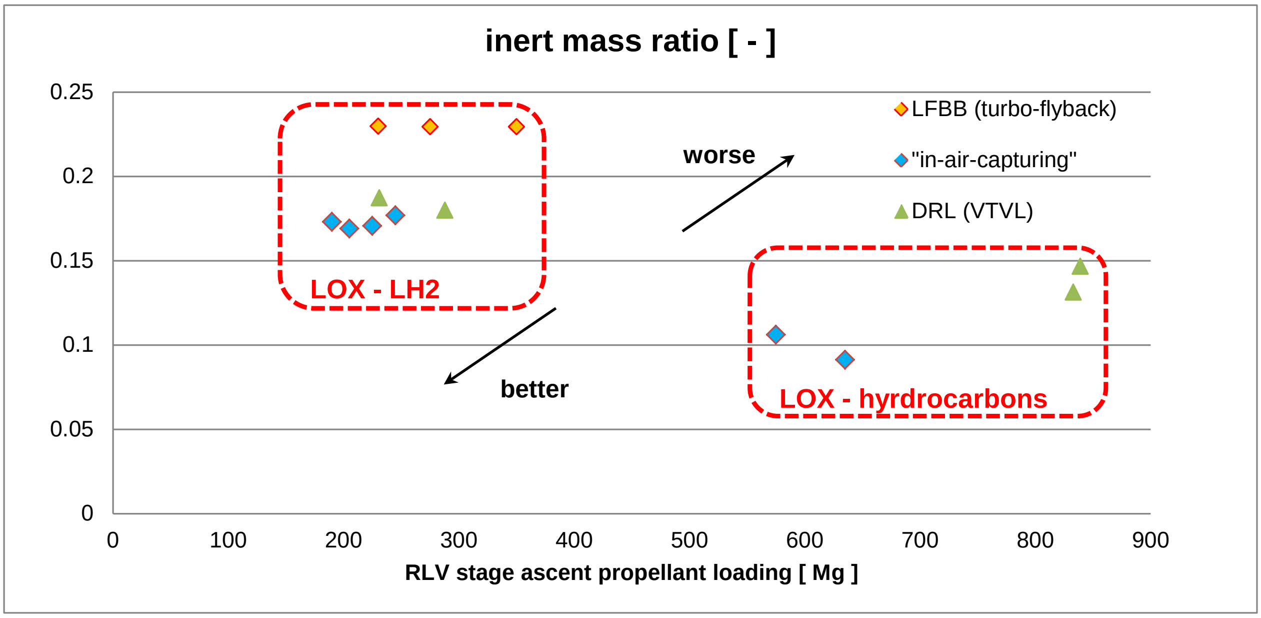

Figure 7: Inert mass ratios of different RLV-return modes (all same GTO mission)

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In all presented cases the IAC-stages have a performance advantage not only when compared to the LFBB with turbojet flyback (as already claimed in the past, see [12, 14, 17]) but also in comparison to the DRL-mode used by SpaceX for GTO-missions.

In [11] the inert mass ratios have been distinguished into the stage's dry mass and its total residual propellants at ascent MECO. Striking differences in relative distribution depending on the return modes are revealed. For RTLS-stages the residual fuel is strongly dominating the inert mass with up to 70% of the total mass. Further, RTLS' inert mass ratios are approximately 30% above all other modes using the same propellant. The "antipodal" mode is in-air-capturing with a small amount of residual propellants left in the tank and a relatively tiny quantity of re-entry RCS-fuel bringing dry mass well beyond 90% of inert mass. DRL-mode stages have approximately 50% on fuel and 50% on dry mass while the LFBB-types require an increased amount of fuel compared to IAC-mode but still are clearly dominated by its dry weight inert mass ratio [11].

2.1.1 Cost Assessment

The above mentioned inert mass ratio is somehow related to launch costs. However, the relationship is non-linear and potentially a certain return mode could be more costly than another. Within AKIRA, the estimation of the impact of different RLV methods on the launch service costs is under investigation. Recently, a detailed study on operational scenarios of various RLV concept recovery methods has been concluded. This investigation includes the autonomous return flight options LFBB and RTLS as well as the downrange recovery on a sea-going platform (DRL) and "in-air-capturing" by large towing aircraft. All direct costs including personnel, port- or air-traffic-control-fees, and depreciation of the drone ship or the aircraft have been taken into account and have been estimated based on publicly available data of similar vehicles. The preliminary results of the study indicate that both recovery modes DRL and IAC have similar operation expenses of approximately 500 k€ per flight [19]. Refurbishment costs are more difficult to assess at the early development phase of first-stage RLV. A comparison of the mechanical and thermal loads acting on the stages as presented in [11, 19] will support a more precise estimation of the maintenance costs in the future.

2.2 Flight demonstration of "in-air-capturing" in subscale

As has been shown in the previous section 2.1, the innovative approach for the return of RLV-stages "In-air-capturing" (IAC) systematically offers better performance than other RLV-return options. This is a good reason to raise its previously low TRL of not better than 3 by extensive lab-scale flight testing.

AKIRA is moving on IAC from pure simulations to lab-scale flight experiments aiming for a TRL between 3 and 4. Establishing connection between the RLV-stage and the large carrier aircraft requires formation flight of both vehicles during the approach maneuver. Actual coupling is best achieved by a highly agile connecting device or coupling unit with onboard actuators. The build and controlled device was tested for its functionality in ground runs and in flight tests towed by an aircraft (Figure 8) but without connecting to the 2nd UAV.

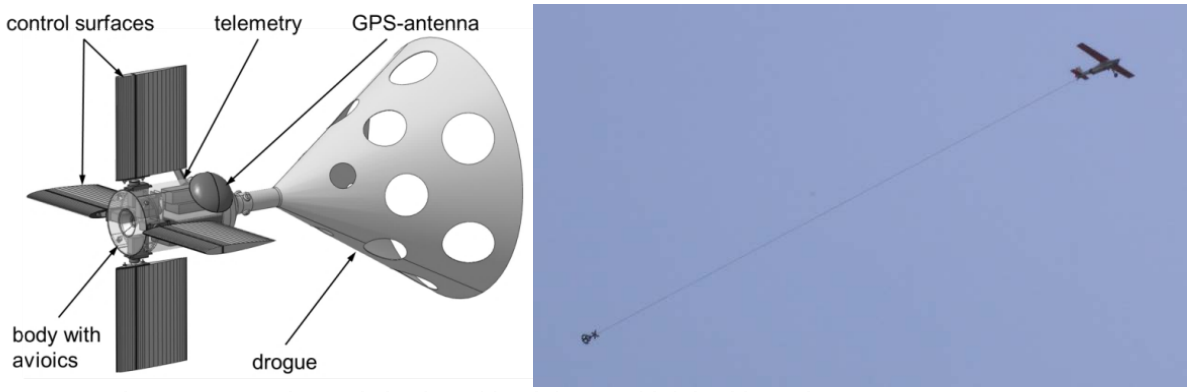

Figure 8: Coupling unit (left) and in flight test (right) with towing UAV "MAL" of DLR

The next step for performing the in-air capturing demonstration is to set-up a GNSS based formation between the two vehicles which is based on a communication link. The resulting error from the GNSS data is expected to be within the positioning capabilities of the coupling device. Two commercial autopilots are used which are modified for the formation flights. One is set to be the 'master' system which sends waypoint and speed commands to the 'slave' system. These waypoints contain a relative position based on the navigation data of the master system. Flights have been performed using two very lightweight test vehicles

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(takeoff mass <3 kg, Figure 9) to keep the risk and effort at a minimum. These planes are nevertheless fully equipped to perform automatic missions and capture video data.

Figure 9: Test vehicles for automated formation flight testing

In parallel work the detection of the position from the device with respect to the reusable stage demonstrator is done. This is realized by camera and laser based environment perception at the RLV-stage demonstrator. The reason for equipping the sensors on this vehicle is simply due to the weight limitation of the device. In a real scenario it would probably be feasible to directly equip the coupling device.

2.3 Continuation of “in-air-capturing” demonstrations in H2020

In order to accelerate development of the promising “in-air-capturing”-technology”, a new project with the name **FALCon** (**F**ormation flight for in-**A**ir **L**auncher 1st stage **C**apturing dem**on**stration) is funded by the Horizon 2020 program. Based on the AKIRA-accomplishments, the TRL will be further raised to 4 to 5 by extended flight tests with capturing and towing of relevant UAV with typical aerodynamic shape of RLV [18]. Seven European partners from six countries are involved in FALCon which is coordinated by DLR.

The project kick-off was in March 2019, scheduled duration is 36 months and with total funding of 2.6 M€ the FALCon project will address three key areas:

- “in-air-capturing”-Development Roadmap and economic benefit assessment
- “in-air-capturing”-Experimental Flight Demonstration
- “in-air-capturing”-Simulation (subscale and full-scale)

The development roadmap for “in-air-capturing” is to be defined in workshops in cooperation with the European stakeholders from agencies and research (e.g. ESA, CNES, ONERA, CIRA, VKI), and industrial primes.

3 Topic 2: Reusable cryogenic tank insulation technologies

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. In AKIRA an insulation concept is defined and investigated by numerical and experimental methods.

3.1 Technical challenges and design solutions

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 spacecraft 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. To tackle the problem of the high temperature gradients, a configuration with ‘purge gap’ between the cryogenic insulation and the TPS is investigated (see section 3.3!) as a promising solution. Purging this gap with a dry gas during ground fueling prevents humid air to enter into the system and reduces the needed insulation thickness, but increases the system complexity.

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3.2 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 (Figure 10). Recent investigation shows that PMI foam and PI foam withstand at least 10 cycles and only a small decrease of the insulation properties has been observed [20].

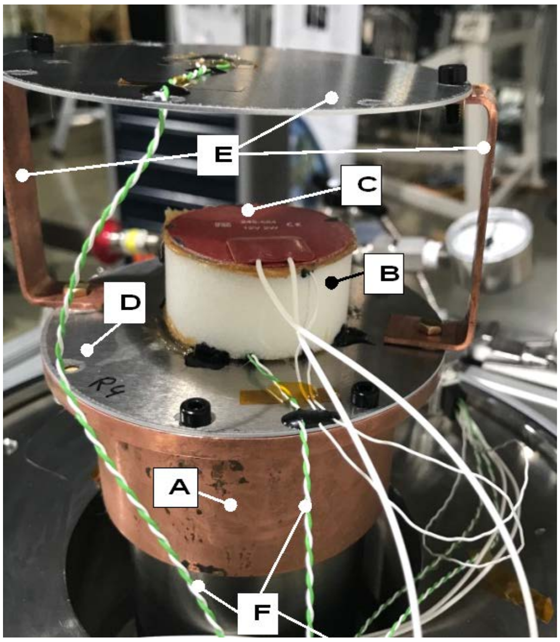

Figure 10: Complex test arrangement for determination of insulation foam heat conductivity (material probe is shown at B)

3.3 Integration of insulation and external thermal protection

A separate workpackage investigates the issue of the design of an integrated system comprising the cryogenic fuel tank with added thermal insulation and a thermal protection system. 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 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 [21]. 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.

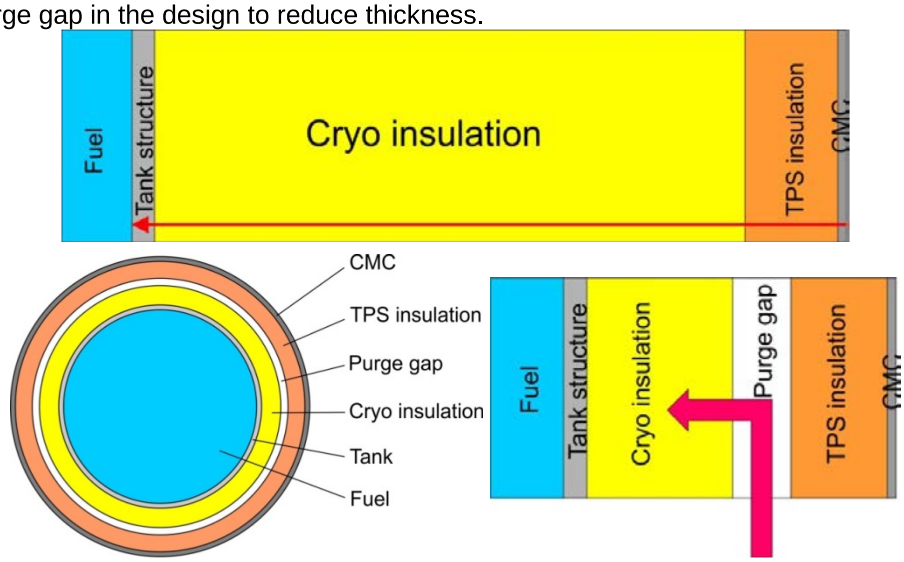

Figure 11: Schematics of conventional cryo-insulation combined with TPS (top) and alternative purge gap option (bottom) [21]

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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.

Quantitative results of FEM analyses (Figure 12) 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.

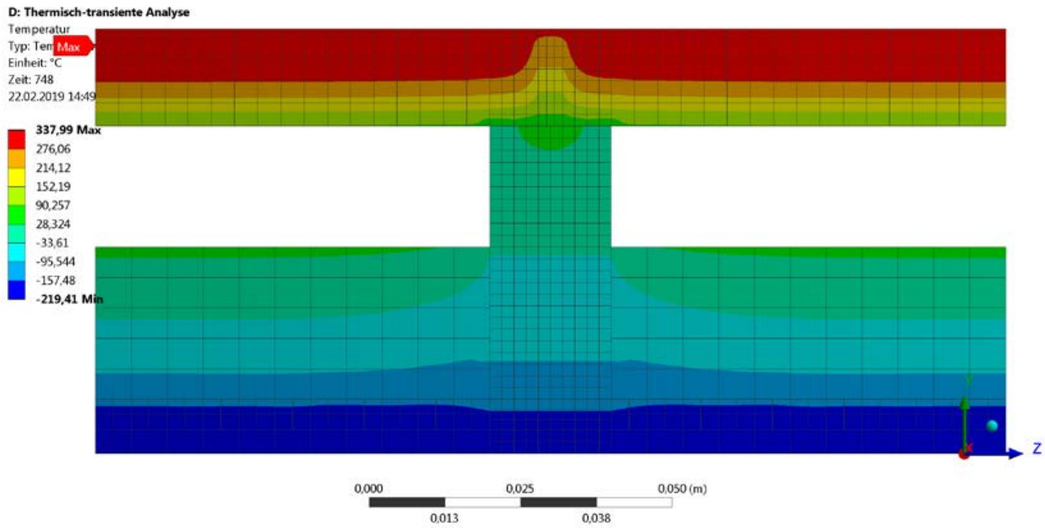

Figure 12: Transient simulation result at time when maximum temperature is reached on cryo-insulation (approx. 90°C below 100°C) [21]

3.4 Health-Monitoring of insulation integrity

Although several insulation concepts are investigated in the AKIRA-project, the health monitoring is focused on foam insulation which is the most promising concept. In general different kinds of defects can occur in foam insulations for cryogenic propellant tanks which include delaminations of the insulation from the tank structure, cracks in the insulation or, as a worst case, spalling of insulation parts due to effects like cryopumping. Detection and repair of such damages are important to ensure the insulation reliability for a reusable system. As maintenance work is a driving cost factor for reusable systems, it is beneficial to install a health monitoring system into the insulation that can directly indicate possible defects without the need of intensive investigations during maintenance.

Different kinds of sensors were investigated for the application as health monitoring sensors in the foam insulation at cryogenic temperatures. Finally, temperature sensors were chosen to detect possible damages in the insulation via changes in the temperature distribution caused e.g. by delaminations. 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. 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. The measurements were also used to validate corresponding numerical models. 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 [22].

3.5 Integrated Test Object (ITO)

The projects insulation concept will be investigated by developing an integrated test objects (ITO), which include the cryogenic insulation, the TPS and system health monitoring (SMH). Similar devices, which combine different layers of structure and insulation material and are beyond sample probes but are less

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complex than a tank demonstrator, allow for fast cyclic testing. NASA Langley extensively tested in the past such probes for cryotank structures and insulation [23]. DLR builds in AKIRA three ITOs of similar layout and layer thickness but different planar size which will be tested in three different test facilities.

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. 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.

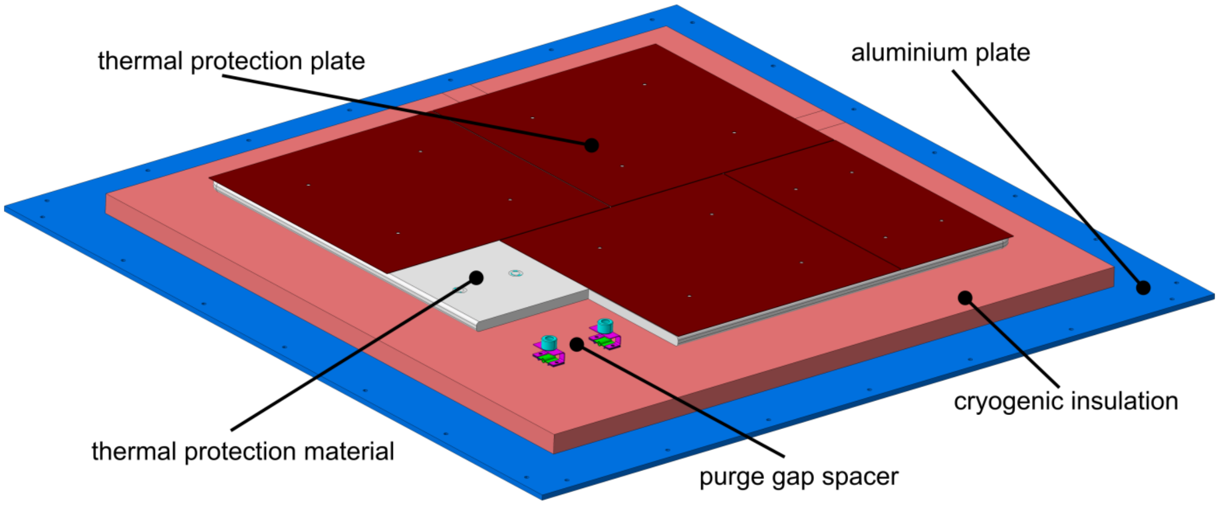

Figure 13: CAD Model of the largest Integrated Test Object (ITO) to be manufactured in AKIRA

In addition to the tests with foam samples (section 3.4), another smaller ITO of reduced size is designed for wind tunnel tests incorporating the liquid nitrogen tank, the foam insulation and an outer thermal protection (alumina fibre mat and Inconel steel sheet). The model will be tested in an arc-heated facility of DLR-Cologne simulating the convective heat transfer during reentry.

4 Topic 3: RLV-stage and engine structural technologies

4.1 Structural concepts of wing-fuselage-tank intersections

Structural concepts of wing-fuselage-tank intersections of RLV have been investigated by systematically studying design options of such stages. Primary structures of winged RLV are much different to expendable launchers or vertically landing stages as used with the Falcon9 of SpaceX. Introducing the wing loads into the integral tank structure is a major challenge if the structure should be as light-weight as possible.

An iterative sizing loop using the tool HyperSizer including Finite Element calculations has been introduced investigating different connection and strengthening elements and different materials. Figure 14 gives an overview of the FEM-model and its constraints and shows that the sections have been optimized section-wise.

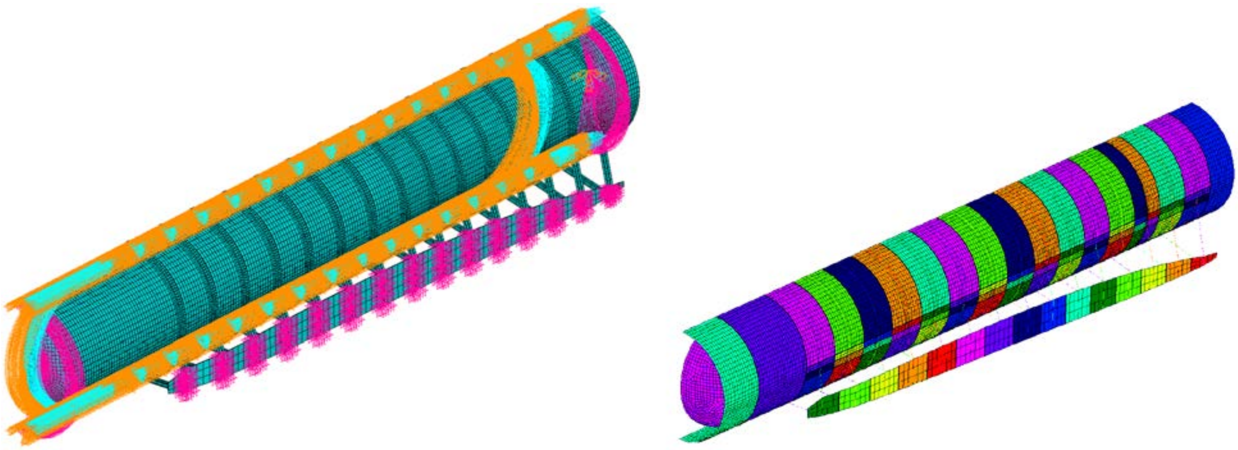

Figure 14: FEM model and constraints of RLV tank-wing intersection and HyperSizer components (right)

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4.2 Thin-ply CFRP structures

The use of thinner laminat-layers in CFRP structures, the use of so-called thin-ply technology, promises increasing mechanical properties of the material. Layers of 0.3 mm and 0.03 mm are experimentally tested for the conditions Open Hole Tension, Plane Tension, Open Hole Compression, and Plane Compression using the Prepreg 80EO-736/CF with 0.3 and 0.03 mm thickness of the layers. Further, hybrid structures using additional layers of steal foil have been tested. Results of Open-Hole-Tension tests are shown in Figure 15.

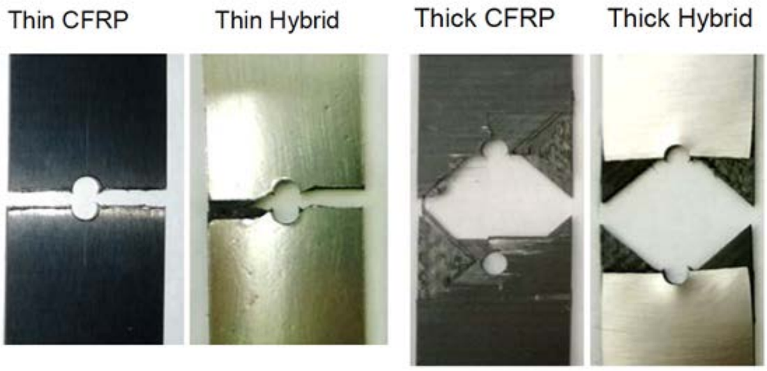

Figure 15: Different proof structures after Open-Hole-Tension tests

All tension and compression tests planned within AKIRA have been finished and data are evaluated.

4.3 Combustion chamber wall

A sufficiently high rocket engine life is critical for establishing economically efficient RLV. The regeneratively cooled wall of the combustion chamber of a liquid booster engine is extremely loaded by the high temperature in the chamber and the pressure difference between the coolant and the hot gas. A cyclic operation of such a chamber usually causes a Low Cycle Fatigue (LCF) failure of the wall structure. For the AKIRA tests, cyclic laser heating was (as replacement for the cyclic hot gas loading) applied to an actively cooled small section of the hot gas wall of the real engine - the so called Thermo-Mechanical Fatigue (TMF) panel. In Table 2, the AKIRA TMF panel test conditions are compared to some typical (nozzle throat cross-section related) Liquid Rocket Booster hot-run conditions.

Table 2: AKIRA TMF panel test conditions and comparison to hot-run conditions at RLV main stage liquid rocket engine nozzle throat

thermal and mechanical loading	Laser-loading area of a TMF panel	nozzle throat of a typical liquid rocket booster
maximum heat flux, caused by the thermal loading	20 MW/m^2	about 100 MW/m^2
maximum temperature, caused by the thermal loading	1000 K	about 1000 K
applied coolant and its inlet temperature	160 K (supercritical N_2)	about 30 K (supercritical H_2) to ambient (liquid Kerosene)
pressure difference between the coolant and the thermally loaded side	about 5 MPa	about 10 MPa

The AKIRA TMF panel hardware (before the test) is shown in Figure 16.

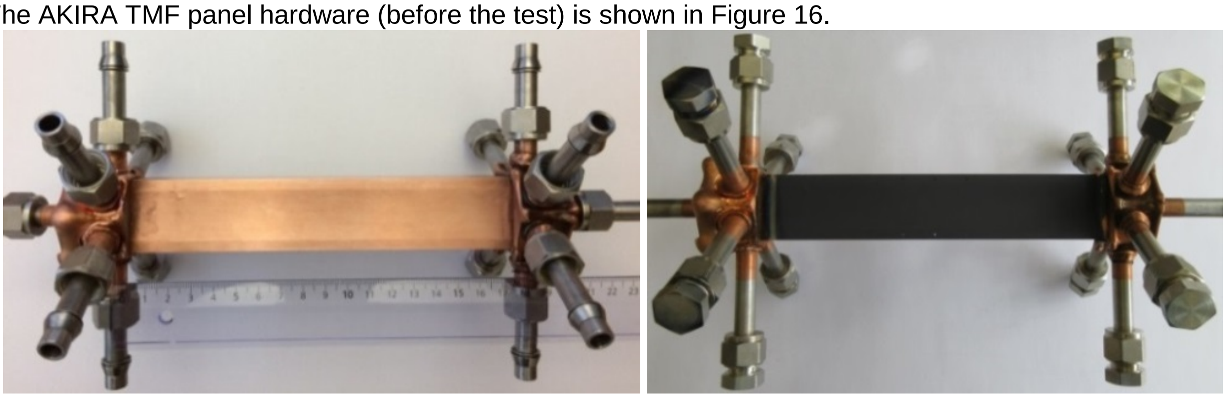

Figure 16: The AKIRA TMF panel made from CuCrZr in its laser-loading section (left) and coated AKIRA TMF panel (right)

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The AKIRA TMF panel failed (due to a crack developing in the center cooling channel) at the 369th laser loading cycle. Cross sections of the AKIRA TMF panel (all at the end of the LCF failure cycle 369) in decreasing distance to the crack are shown in Figure 17.

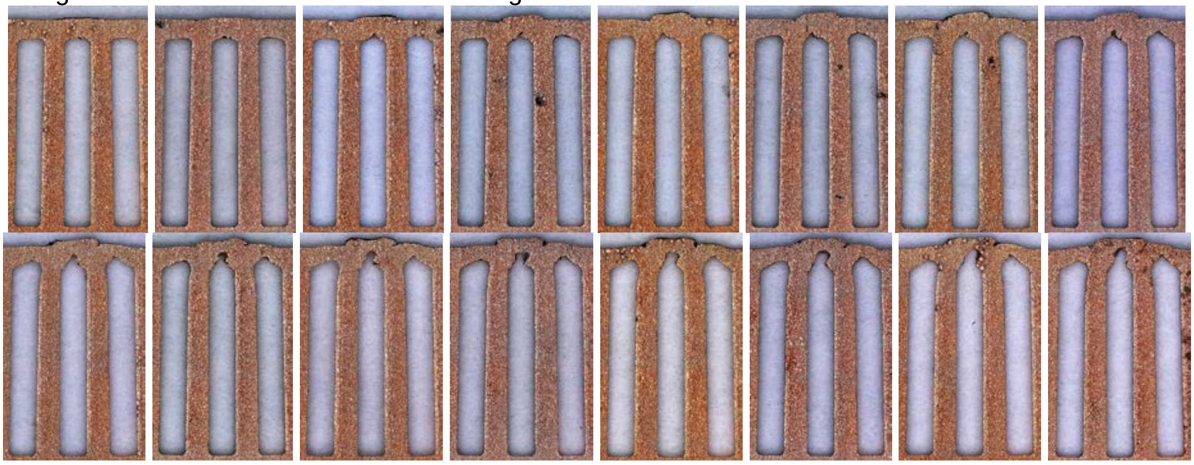

Figure 17: Cross sections of the AKIRA TMF panel (all at the failure cycle 369) in (from left to right and from top to bottom) decreasing distance to the crack.

More details of this AKIRA TMF panel test (like test set-up, measurement devices and more results) are e.g. shown in reference 24. The results of this AKIRA TMF panels test are mainly used for the (Liquid Rocket Booster Low Cycle Fatigue related) validation of structural Finite Element analysis and fatigue life analysis methods and a follow-on optimization of geometric parameters of Liquid Rocket Booster chamber walls.

5 Conclusion

The internal DLR 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 two reference vehicles, the RLV return and recovery methods are addressed including low-speed flight tests using DLR's UAV experience, the assessment of suitable reusable cryo insulation for tanks, and investigations of advanced structures and materials including simulated Low Cycle Fatigue tests of regeneratively cooled combustion chambers of rocket engines.

The innovative method for the recovery and return of RLV first stages "in-air-capturing" is demonstrated by lab-scale experiments. This technology has been transferred into a new project, named FALCon, funded in the H2020-scheme of the EC which allows for faster realization and for the involvement of European players outside of DLR.

The AKIRA project will finish at the end of 2019 after raising the TRL of several key-technologies. A follow-on project focusing on metallic and CFRP cryo tanks for RLV with different integration concepts of the TPS is now in preparation and should be started early 2020.

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