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Cryo-Laboratories for Test and Development of Propellant Storage and Management Technologies

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The paper gives an overview on the test possibilities of the Cryogenic Laboratories in BREMEN and TRAUEN of the DLR Institute of Space Systems with regard to the research and development of propellant management and storage technologies for successful future launcher and advanced cryogenic upper stage systems. To satisfy the current and future need for testing and research, different test facilities have been built up and are available in the labs. In particular a hexapod system and a cryogenic tank demonstrator, provided by Astrium ST, are useable for testing. The test possibilities of the cryogenic laboratories and the available test facilities will be presented.

Nomenclature

g	gravity acceleration	m/s^2
m	mass	kg
p	pressure	Pa
v	velocity	m/s
σ	surface tension	N/m
ρ	density	kg/m^3
T	temperature	K

Subscripts, Abbreviations

A5ME	ARIANE 5 Midlife Evolution
CFD	Computational Fluid Dynamics
CTD	Cryogenic Upper Stage Tank Demonstrator
CUST	Cryogenic Upper Stage Technologies
DLR	German Aerospace Center
FLOW-3D	Commercial CFD-Tool
FLPP	Future Launcher Preparatory Programme
FiPS	Final Phase Simulator
GPPS	Gas Port Phase Separator
LH2	Liquid Hydrogen
LN2	Liquid Nitrogen
LOX	Liquid Oxygen
PMD	Propellant Management Device
PMT	Propellant Management Technology
SIL	System Integration Level
TRL	Technology Readiness Level
ZARM	Center of Applied Space Technology and Microgravity

1 INTRODUCTION

Meeting the future market demands for orbital payloads and interplanetary missions, this requires flexible, powerful and competitive launcher systems. Successful launcher developments premise the knowledge and understanding as well as the application of intelligent and effective propellant storage and management technologies for future advanced cryogenic upper stage systems allowing more mission flexibility such as multiple restart options paired with long duration ballistic phases.

For the development and testing of cryogenic upper stages the availability of test facilities enabling the utilization of the real propellants LH2 and LOX are of fundamental importance. Depending on the maturation level of development material tests, tests on components and subsystems under different conditions up to full scale tests have to be performed up to flight level.

Astrium ST in Bremen is responsible for the planned new cryogenic upper stage A5ME of the European launcher ARIANE 5 ME. To cover the mission requirements, the upper stage is equipped with the re-ignitable VINCI engine. For the development and production of the upper stage tank, a joint company EuroCryospace was founded in Bremen 2012.

In order to support the European launcher industry and to secure and to enhance the upper stage competence in the field of propellant storage and management technologies, the DLR decided to establish a cryo-laboratory at the Institute of Space Systems in Bremen. With the intention to serve the future industrial as well as scientific demands, an extension of the laboratory in the vicinity of Bremen (Trauen) is planned allowing the utilization of a larger amount of cryogenics. The cryogenic laboratories will be equipped with a supply system for the liquid gases LH2, LOX and LN2, and their respective gases, as well as gaseous helium. Cold tests in the labs are to be performed with liquid volumes of up to 1'000 l of LH2/LOX and to 10'000 l of LN2. The technical capabilities of the laboratories and test facilities, as well as the strategic direction are presented in the following.

2 NEED FOR TESTING

For the maturation of new technologies for advanced cryogenic upper stage systems, corresponding laboratory and testing facilities are of essential necessity[1]. The individual requirements on the laboratories and testing facilities are depending on the Technical Readiness Level (TRL, see Fig. 1) and on the System Integration Level (SIL) of the according test object. In general, the test object has to meet with growing TRL- and SIL-level increasingly the real circumstances at flight conditions with respect to the fluids, thermal conditions, geometry, forces, accelerations, radiation to name some of the parameters. First feasibility tests (TRL1-2) of a new cryogenic application can be performed with storable liquids and a scaled geometry. The intention of these tests is to proof the assumed postulated physical behavior. A test of TRL4 or higher level requires tests with cryogenic liquids. Investigations at further increasing TRL-level necessitate tests with the real cryogenic propellants under full scale conditions and finally integrated in the complete system at real conditions.

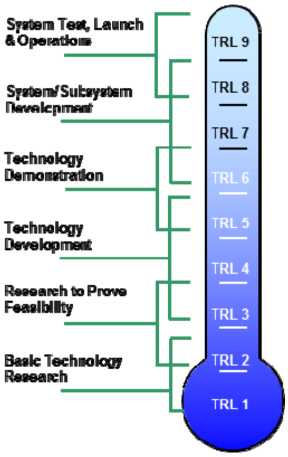

Figure 1: TRL-level in reference to ESA[2]

In accordance to the maturation of advanced technologies there are testing needs to proof scaling laws and to validate CFD tools particularly for simulating the cryogenic fluid behavior on subsystem level. Full system analyses taking into account all critical flow phenomena are currently only barely feasible with actual CFD tools.

Further test needs are required with regard to the development of advanced sensor technologies particularly for cryogenic applications. The fluid behavior in cryogenic tank systems can be described at present not sufficiently. For example, the measurement of the time dependent free surface topology still remains a challenge. New measurement techniques might allow the determination of the actual fill level and/or the liquid position during the ballistic flight phases[34]. Knowing and predicting the exact residuals over the mission time, the margins with respect to the needed amount of propellants can be minimized and the payload capacity can be increased leading thus to the overall improvement of the mission performance.

The existing and planned laboratory capacities of the DLR Bremen provides an ideal test environment for system and subsystem testing, starting from research level up to satisfying the demands of industrial testing. The available and planned test facilities including the vacuum chamber, the hexapod system and the Astrium Cryogenic Tank Demonstrator are adequately in accordance to the needs studying the critical phenomena, conducting benchmark tests for tool validation, investigating of hardware components or technology demonstrations, technology maturation and sensor technology development. The cryogenic laboratories including their test facilities are described in more detail below.

3 CRYOLAB TEST SITES

At the Bremen site, together with Astrium ST, ZARM University of Bremen and the DLR Institute of Space Systems, it exists an effective and complementary research and development network[5]. ZARM operates a drop tower with a free flight time of up to 9.4 s under micro-gravity conditions and is specialized in experiments on flow phenomena with cryogenic liquids. Furthermore, within the TEXUS-program, Astrium provides the opportunity to perform cryogenic µg experiment up to six minutes on sounding rocket flights[6]. The possibility of using the drop tower or sounding rocket flights offers an ideal opportunity for the study of critical flow phenomena that occur during the ballistic phase. The DLR Institute of Space Systems operates a Cryo-Lab facility with the intention to be able to perform research and development in the field of cryogenic propellant management and storage technologies. For safety reasons the test capacities at the Cryo-Lab in Bremen are limited with respect to the amount of liquid cryogenics particularly LH2 and LOX. In order to serve the future industrial and scientific demand of large scale tests, a test facility at the DLR site Trauen (approx. 1 hour drive from Bremen) is planned. The vicinity to Bremen enables the performance of focused and cost-effective test campaigns. The existing test facilities and capabilities of the two laboratories are presented below.

3.1 Cryo-Lab Bremen

The concept of the cryogenic laboratory (Fig. 2) provides the possibility to perform cold subsystem and component tests with the cryogenic propellants of the upper stage (LH2, LOX). In addition, for preliminary testing, storable liquids or liquid Nitrogen (LN2) is available. The liquid gases are stored in cryogenic liquid storage tanks outside of the laboratory and can be supplied on request through an insulated supply line. In addition, the following technical gases are available: N2, H2, O2, and He. The gases are stored in high pressure bundles.

The Cryo-Lab has a floor area of about 475 square meters and is structured spatially and functionally into the following areas: main test area, exploration protected lab, cleaning lab, measurement technology lab, pre-integration room, mechanical work shop, the cryogenic storage area, the supply system and technical equipment room.

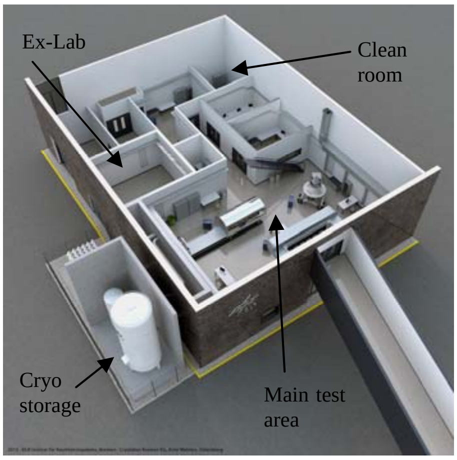

Figure 2: Sketch of Cryo-Lab Bremen

The main test area has a height of eight meters and features a ceiling crane with five ton lifting capacity. In this laboratory part are located fixed installations including a planned vacuum chamber and a Hexapod-system. The foreseen vacuum chamber has a dimension of about 2 m diameter and a length of 4 m. The Hexapod-system provides a movable platform with six degrees of freedom, for e.g. investigations of sloshing phenomena[7].

The cryogenic lab provides a separate room, an explosion protected laboratory room (Ex-Lab). The Ex-Lab can be completely flooded with inert gas in order to run experiments having a high risk of leakage. By external supply of nitrogen, the oxygen content can be reduced below ignitable concentrations. By slight pressurization of the ex-lab, the inflow of oxygen can be prevented. In addition, the electrical system of this room is of explosion protected design. The experiments are controlled outside from a control room.

For necessary cleaning of components or materials a clean laboratory can be used. Special purity requirements must be maintained in case of preparing experiments with oxygen. Free particles or organic residues on surfaces of materials can lead to spontaneous reactions with oxygen. In this laboratory, the used materials and components can be cleaned mechanically and chemically. A verification of the purity can be issued.

In the pre-integration area, the cleaned components are to be integrated in the laboratory experiments. The integration is carried out under a flow zone of purity class 7 (10'000 U.S.), which ensures that the components and/or the experiment are not re-contaminated with undesirable substances. After completion of the pre-integration the test objects in the vacuum chamber or in the ex-laboratory can be further integrated.

For the design of the electrical part and the sensor equipment of the experiments and test facilities, a electronic laboratory is available. In addition, the calibration of sensors can be performed in this lab. For mechanical work a mechanical workshop is available.

3.2 Cryo-Lab Trauen

The DLR test site in Trauen offers an ideal research and test environment for test campaigns exceeding scales that are not manageable at the DLR site Bremen. The site provide a 80 ha (800'000 m²) areal including all mandatory licenses concerning fire protection as well as the handling of cryogenics and explosives. The neighborhood to Bremen supports the necessary prerequisites to establish low-cost and efficient future campaign activities to continue development, research and testing.

The test site in Trauen (Fig. 3) will have the opportunity to perform cryogenic cold tests with liquid hydrogen and liquid oxygen of quantities up to 1'000 l in the experiment. Performing tests with liquid nitrogen up to 10'000 l will be possible. The concept of the laboratory in Trauen provides the following building units: main building, test labs and an open test field, supply and drain appliances for the liquid and gaseous media, each equipped with security and control technique.

The main building comprises as an essential element a control room to externally control the experiments in the test laboratories for safety reasons. In addition, offices and meeting rooms are available. On the ground floor a storage room and a mechanical workshop is planned.

At safe distance to the main building two connected enclosed test laboratories are placed. The test labs have a ceiling height of 8 m and are equipped with ventilation flaps. The access is realized via large roller doors that can be left open in case of need. In addition, pressure release surfaces are installed. In the test halls ceiling cranes are available. The experimental halls are equipped with chimney deduction for hydrogen gas. The H2 chimneys extend to a height of 15 m for blowing not desired hydrogen gas safely into the environment. Additionally the test laboratories are equipped with sensors to measure the oxygen concentration and the presence of gaseous hydrogen.

Figure 3: Architecture view of Cryo-Lab Trauen

For emergency disposal of liquid oxygen and liquid nitrogen evaporator areas are foreseen adjacent to the test labs. The evaporator areas comprises of large troughs, filled with pebbles. The large number of stones ensures that a controlled and safe evaporation can take place.

The stationary supply tanks for the cryogenic liquids LH2, LOX and LN2 are located directly adjacent to the test halls, complemented by the gas storage. Design goal was to keep the supply lines between storage area and experiment as short as possible. In this way cost of expensive cryogenic supply lines can be saved and the heat input into the cryogen on the flow path from the tank stand to the experiment can be minimized.

The stationary tanks are provided with the following capacities: Liquid hydrogen and liquid oxygen: 10'000 l, liquid nitrogen: 50'000 l. Industrial gases Hydrogen, Oxygen, Helium and Nitrogen are available. They are stored in high pressure cylinders in bundles.

For further experiments, an open test area is available that is shielded by a protective wall. This area is also equipped with evaporation areas and connected with the chimneys.

Adjacent to the cryogenic laboratory at the Trauen site optional additional expansion areas are available where, depending on the future requirements, other offices and/or test areas can be built.

4 TEST FACILITIES

The cryogenic laboratories in Bremen and Trauen provide different test facilities available for the research and development of propellant management and storage technologies. These include cryostats for liquid nitrogen and liquid hydrogen or oxygen, a vacuum chamber, a moving table with six degree of freedoms (hexapod), a tilting table, as well as a Cryogenic Upper Stage Tank

Demonstrator (CTD), specially designed for the research, development and demonstration of advanced cryogenic upper stage technologies, and provided with courtesy of Astrium ST Bremen.

4.1 Cryostats

Two cryostats for liquid nitrogen are available with a volume of 120 liters, as shown in Fig. 4. The cryostats can be operated up to 5 bar tank pressure. One cryostat has an outlet flange, thus both cryostats can be connected to realize flow through experiments.

Two other available cryostats for the temperature range of liquid Hydrogen have a capacity of 60 liters and are also designed for pressures up to 5 bar. These cryostats are also suitable for tests with liquid oxygen. One of them is equipped with an additional flange at the bottom, in the same manner as at the Nitrogen cryostat. Both types of cryostats (LN2, LH2/LOX) are equipped in addition to the usual supply connections with flanges for the implementation of sensor connections.

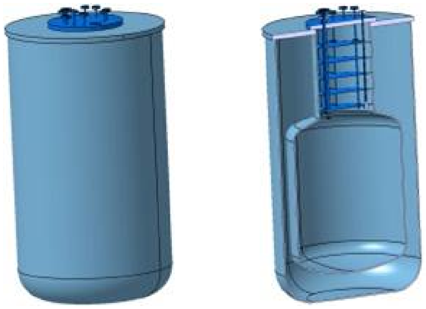

Figure 4: LN2-Cryostats

4.2 Vacuum chamber

The planned vacuum chamber will be used to perform experiments and tests with cryogenic media LN2, LH2 and LOX under defined and reproducible thermal boundary conditions and to simulate the orbital environment. The vacuum chamber is equipped with a shroud which can be cooled down to the temperature of liquid Nitrogen. This way, the radiation from the inner wall of the chamber can be minimized. In the chamber, a vacuum pressure of 10^{-4} mbar can be realized. The horizontal chamber has a diameter of two meter and a length of four meter. An illustration of the vacuum chamber is provided in Fig. 5. The chamber is mounted on a rail system and can be opened by a lid. Experiments can be integrated and mounted on a movable thermally insulated platform.

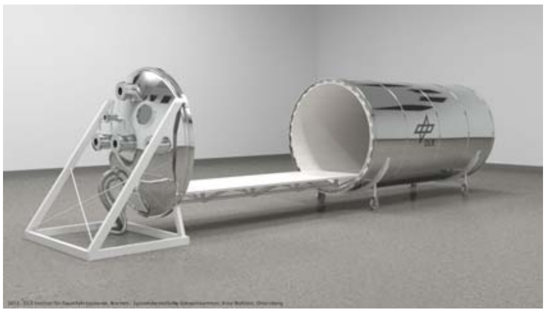

Figure 5: Sketch of the vacuum chamber

4.3 Hexapod System

As a particular test equipment to generate excitation, a hexapod system is available in the cryogenic laboratory at DLR Bremen. The hexapod system consists of a platform, which can be excited with six degrees of freedom by six independent movable legs, Fig. 6.

Payloads up to 2.5 tons can be mounted on the hexapod system. The payload can be excited to oscillations between 0-10 Hz, the amplitude in each direction in space can be varied in the range of plus/minus 0.3 m and a maximum acceleration of 0.6 g can be achieved. The platform can be tilted to a maximum inclination of 20° while in motion. For mounting the payloads the hexapod system is equipped with an experimental platform. This platform is connected via six struts. Force sensors are integrated into the struts. Thus, the acting forces on the payload can directly be measured during the test runs. In addition to the load cells, the experiment platform is equipped with acceleration sensors. With the measured quantities of forces and accelerations, it is possible to perform meaningful analyzes and further supplementary studies. Furthermore, the hexapod system can be excited based on realistic ascent profiles to e.g. simulate the launcher behavior and the tank content.

Figure 6: Sketch of the Hexapod system

4.4 Turn Table

The hexapod system is additionally equipped with a turn table, which corresponds to the striped platform on top of the hexapod system (see Fig. 6), to enable the superimposition of a rotational motion. Angular rates up to 30°/s are possible.

4.5 Tilt Table

In the laboratory, it is also possible to operate the turn table separately on a tilt table as shown in Fig. 7. The tilt table can be tilted up to 20° while providing rotation rates up to 45°/s. The tilt table is designed for a payload mass up to 2.5 tons. The experiment platform of the turn table is equipped with an own power supply and a data acquisition system located on the platform. Using this technical solution, the experiment and the sensors can be supplied with the necessary energy during the operational mode of the turn table. The recorded measurement data are wireless transmitted to the control computer.

Figure 7: Sketch of the Tilt Table equipped with the Turn Table

4.6 Cryogenic Upper Stage Tank Demonstrator

For the investigation of issues related to propellant management technologies and storage technologies in complex tank geometries with respect to real applications, i.e. cryogenic upper stage tanks, a Cryogenic Upper Stage Tank Demonstrator (CTD) is available as shown in Fig. 8 and Fig. 9. The geometry of the CTD is therefore deliberately chosen as the scaled form of the A5ME hydrogen tank compartment. The tank demonstrator is designed and provided by Astrium ST Bremen.

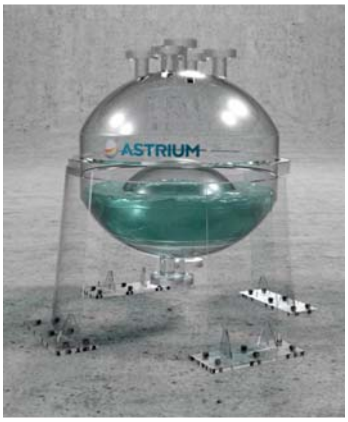

Figure 8: Transparent illustration of the Cryogenic Upper Stage Tank Demonstrator (CTD)

The tank demonstrator is designed as a cryo-container made of stainless steel and contains vacuum insulation between the outer and inner tank walls. The inner tank diameter is 1 m. The tank has a concave bottom and a convex upper dome. The central part of the tank is cylindrical and has a flange equipped with an appropriate cryogenic seal.

The cylindrical part of the tank can be expanded with an available modular intermediate ring to allow also other tank geometries. The flange regions are protected with an outer foam insulation to minimize the penetration of unwanted heat. The tank bottom is equipped with two flanges, one for drainage and a further flange for mounting necessary installations such as the common bulkhead, other structural components or sensor elements. Furthermore, the tank can be equipped with a modular baffle system allowing horizontal and vertical baffle concepts. The upper dome is designed with five flanges for cryo supply and sensor cabling purpose. Two mounting ears are attached on the upper dome inside. The mounting ears can be used for supporting sensors or structural components. The tank demonstrator can be operated for nominal pressures up to 10 bar. The mainstays are designed to fit on the experiment platform of the hexapod system, so that the tank demonstrator can be used on the hexapod system as shown in Fig. 9.

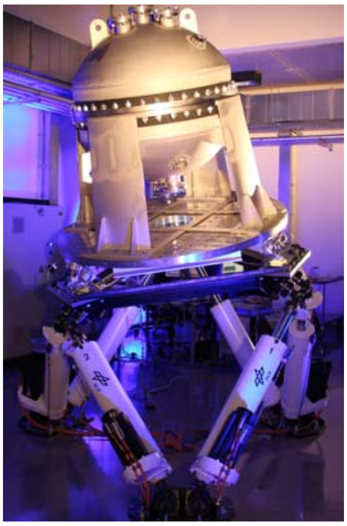

Figure 9: CTD mounted on Hexapod System

The tank demonstrator is basically equipped with temperature sensors and pressure sensors as pictured in Fig. 10. The temperature sensors will be used to determine the wall temperature, the temperature profiles in the liquid and the temperature profiles in the gaseous phase. The degree of filling of the tank is determined by level measurement. For observation purposes an optional camera systems will be available that can provide pictures or videos from the inside of the tank. Furthermore, the composition of the ullage shall be measured at different locations to be able to determine concentration gradients of helium and/or vapor.

By operating the CTD on the hexapod, the sloshing forces can be determined from the force sensor data. In addition, the data of the acceleration sensors are recorded and can be used for analysis. Depending on the test objective the tank demonstrator and/or the hexapod system can be equipped with additional sensors.

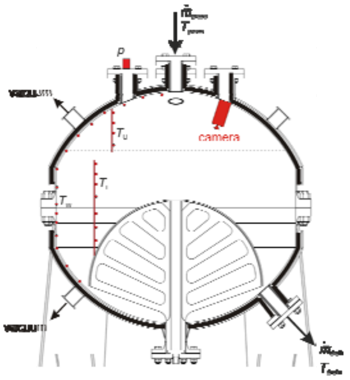

Figure 10: Instrumentation of the CTD

The cryogenic tank demonstrator in combination with the hexapod system and the cryogenic laboratory is an ideal test bed for investigation and research of critical phenomena, conducting benchmark tests for tool validation, testing of hardware components or technology demonstrations, technology maturation and for sensor development in the field of cryogenic propellant management and storage technologies with regard to the application in future advanced upper stage systems.

To be able to meet the future market demands, the requirements on the performance and mission flexibility of future advanced upper stage systems has to be increased. The Cryogenic Upper Stage Tank Demonstrator is an important tool to satisfy these needs.

5 INDUSTRIAL APPLICATION AND RESEARCH OPPORTUNITIES

With the laboratories and test facilities, it is planned to perform research on the following issues in the field of propellant management and storage technologies: critical fluid phenomena, tank operations, tank geometry effects, functional tests of tank components, tool validation and verification and cryo sensor technology.

Critical Fluid Phenomena: An optimal design of the launcher system which meets these requirements can be performed only with a deep understanding of the relevant critical fluid phenomena and design constraints, under the indispensable condition that appropriate validated and reliable tools are available[8].

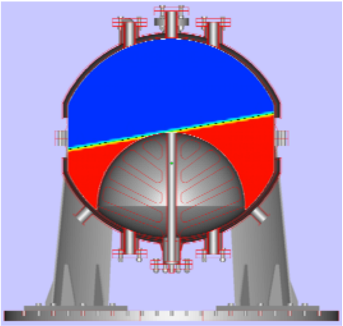

Figure 11: Simulation of Propellant Sloshing with FLOW-3D (red = liquid phase, blue = gaseous phase)

Particularly for the validation of the design tools on application-oriented experiments with regard to the relevant critical phenomena, the cryogenic tank demonstrator will make a significant contribution.

One critical phenomenon, which can be investigated with the tank demonstrator, is the sloshing behavior with the fluid dynamic effects, such as the sloshing forces, the sloshing frequency and the decay of sloshing motion, as well as the effect of sloshing on the thermodynamic conditions of the propellant, see Fig. 11. The propellant motion distorted the stratified liquid and gaseous phase, in consequence heat and mass transfer at the gas-liquid interface could cause significant pressure variation in the void region due to evaporation and condensation processes. Further critical phenomena are temperature stratification; the effects of pressurization with inter gas; boiling processes at the gas-liquid interface, at the tank wall, internals and in the feed line system.

Most of existing models based on considerations obtained with simple geometries of small size. The transferability of the findings to complex geometries of larger scale is limited and lacking.

Tank Operations: In addition to the critical phenomena, there is a need to realize a possibility to be able to investigate the different processes which are connected to the tank. These processes include: filling, draining, and pressurization.

Complex Geometries: The tank demonstrator will also be used to investigate the influence of complex geometries; to develop new advanced technologies; as well as to increase the technical maturity or for technology demonstration.

A significant geometry effect on the propellant behavior at the current upper stage development of A5ME is given by the common bulk head of the hydrogen and oxygen tank. The tank demonstrator gives the ideal opportunity to investigate the influence of the common bulkhead on the frequency and damping behavior of the liquid in case of sloshing. The measured data of the acceleration sensors and sensor data of the load cells will provide the necessary data for analysis. For comparison purposes, the tank demonstrator with and without common bulkhead can be operated.

Functional Tests of Tank Components: For the successful performance of missions with long ballistic flight phases, the efficient conditioning of cryogenic propellants is essential. In addition to an effective thermal insulation it must be ensured that in case of a necessary venting maneuver only gas leaves the tank and the valuable propellant remains in the tank. Based on the mission profile, it may be possible that propellant is located in front of the gas outlet. The venting of liquid causes fluctuations in the cold gas thrust system.

In order to address this problem, Astrium ST currently being developed a Gas Port Phase Separator (GPPS) in the frame of the FLPP CUST program[910], as shown in Fig. 12.

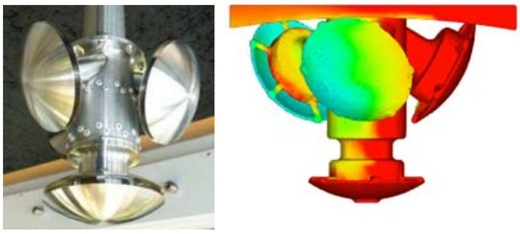

Figure 12: left: 1:5 scaled model of GPPS, right: calculated temperatures during liquid penetration

The phase separator device is located inside the tank as outlet for the venting line to allow liquid free venting. It achieves sure and reliable phase separation under cryogenic conditions by taking advantage of capillarity, geometrical design, and the capillary characteristics of metallic screens.

The CTD and the hexapod system provide the necessary ground test environment with respect to the test needs. The GPPS component test evaluates the influence of the GPPS device during gas venting and tank pressurization in relevant cryogenic environment. Main focus is the liquid free venting of the device in 1g condition and during lateral liquid penetration.

The GPPS engineering model is therefore mounted inside the tank demonstrator (Fig. 13), which is filled with LN2 at cryogenic temperature. The Hexapod is able to generate the liquid motion for the liquid penetration of the GPPS. GN2 and GHE are used as pressurant gas to observe the GPPS in similar and relevant environment for the LOX and LH2 tank. Temperature sensors determine liquid penetration and global temperature distribution. Pressure sensors evaluate the main tank pressure and pressure loss of the GPPS device. Video cameras mounted inside the tank observe the liquid motion and liquid penetration of the device. The venting and pressurization mass flow in and out of the tank are defined by supersonic flow through exchangeable orifices.

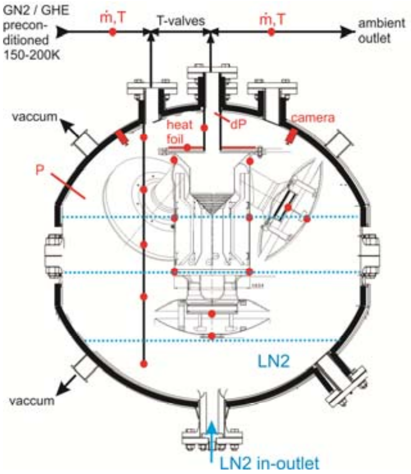

Figure 13: Instrumentation for the full scale GPPS tank component test

Another objective of the study is to determine the effects of baffles for attenuation of unwanted fluid movements and the change or shift of natural frequency of sloshing. The hexapod system provides ideal opportunities to simulate various excitation scenarios. For example, the damping behavior of sloshing cryogenic liquids can be observed and evaluated.

Tool Validation: Undesired sloshing of the propellants in the tanks of the upper stage system exerts significant forces on the space craft. The guidance navigation control system has to react. The task of the guidance navigation control system is to maintain the desired mission trajectory, with the requirement to keep the fuel consumption for the attitude control system minimal. This can be achieved only if the controller reacts effectively according to the sloshing phenomena in the tank systems. The hexapod system together with the tank demonstrator can here be used for test purposes in an ideal manner. For the development of an intelligent control system and to investigate the coupled phenomena Astrium ST has developed the FiPS-tool, in which the attitude control system and the rigid body dynamics are coupled with the forces resulting from the sloshing behavior of the propellants[11]. The fluid behavior in the closed loop simulation is calculated with the CFD-Tool FLOW-3D. With the tank demonstrator and the hexapod system, the prediction and control accuracy of the FiPS tool will be verified and validated.

For the calculation and prediction of fluid behavior in cryogenic tanks generally used different CFD tools. The different tools have different strengths for calculating different flow phenomena. A complete analysis, taking into account all effects occurring: considering the large scale of the real tank geometry, extreme fluid properties of liquid hydrogen, heat and mass transfer processes (boiling, evaporation), free surface problems, two-phase flow and two species problem and the possible situation of large disturbances of the free surface is at the present time not feasible for a single CFD tool.

There is an urgent need for the generation of benchmark data with application reference for the further development and validation of CFD tools. The tank demonstrator equipped with the available measurement sensors will serve as test facility to generate the required test data.

Sensor Technology: In addition to the desired test data, there is a need for further development of cryo sensors for the detection of fluid behavior in cryogenic tank systems[12]. In addition to the temperature and pressure measurement in the liquid and gaseous phase, exact measurement data of the time dependent location of the free surface is of interest. With accurate knowledge of the propellant residuals, a more efficient mission planning is possible. A further need exists in the measurement and knowledge of the content of dissolved pressurization gas in the propellants. Concentration measurements could provide insights. The tank demonstrator offers ideal opportunities to provide the required test environment.

6 CONCLUSION

The cryogenic labs in Bremen and Trauen provide opportunities to meet the current and future needs for research, test and development of issues with respect to propellant management and storage technologies from a scientific level up to the testing requirements for industrial applications on sub-system level. The special test equipment, the vacuum chamber and the hexapod system, provide the basis to realize the required boundary conditions for testing. The provided tank demonstrator offers ideal test opportunities to investigate comprehensive questions directly related to the development of advanced cryogenic upper stage systems. The results obtained will contribute to more precise predictions regarding to full size application, to proof and further development of existing scaling laws, create benchmark data and to develop advanced sensor technologies.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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[1] Krüger, J.; Berkes, U.: Technology Maturation for the Reignitable Cryogenic Upper Stage, 7th International Symposium on Launcher Technologies, Barcelona, Spain, 2-5 April 2007

[2] Technology Readiness Levels Handbook for Space Applications, TEC-SHS/5551/MG/ap, Issue 1, Revision 6, September 2008

[3] Rahim, R.A., Rahiman, M.H.F., Chan, K.S., Nawawi, S.W.: Non-invasive imaging of liquid/gas flow using ultrasonic transmission-mode tomography. Sensors and Actuators A: Physical 135, 337–345, 2007

[4] Chen, T., Wang, Q., Chen, R., Zhang, B., Lin, Y., Chen, K.P.: Distributed liquid level sensors using self-

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heated optical fibers for cryogenic liquid management. Applied Optics 51, 6282–9, 2012

[5] Gerstmann, J., Dittrich L., Montenegro, S., Gauer, M., Manfletti, C., Hühne, C., DaCosta, R.: German Research Cooperation Upper Stage, CEAS 26-29 October, 2009

[6] Behruzi, P., Klatte, J., Fries, N., Netter, G., Kranz, T., Sirbi, A.: Cryogenic Propellant Management during Ballistic Flight Phases, Space Propulsion Conf., Bordeaux, France, 7-10 May, 2012

[7] Dodge, F.T.: The new dynamic behavior of liquids in moving containers, Southwest Research Institute, San Antonio, Texas, 2000

[8] Propellant Behavior in Launcher Tanks An Overview of the COMPERE program,Dreyer, M. Behruzi, P., Colin, C., Dufour, A., Hopfinger, E., Lacapere, J., Legrand, B., Kranz, T., Vila, J.P., 7th International Symposium on Launcher Technologies, Barcelona, Spain, 2-5 April 2007

[9] Behruzi, P., Netter, G., and Krüger, J. "A Propellant Tank Concept for Future Cryogenic Upper Stages", Space Propulsion Conf., Heraklion, 2008

[10] Behruzi, P., Klatte, J., Netter, G.: Passive Phase Separation in Cryogenic Upper Stage Tanks, Joint Propulsion Conf., July 2013 – to be published

[11] Behruzi, P., de Rose, F., Netzlaf, P., Strauch, H.: Ballistic Phase Management for Cryogenic Upper Stages; DLRK (DGLR Conference); Bremen; 2011

[12] European Space Research and Technology Centre, Advanced Measurements Techniques for Validation of CFD for Cryogenic Flows in Reduced Gravity, ITT, SOW, TEC-MPA/2013/1208/RS, Feb. 2013