

Advanced Cryo-Tanks Research in CHATT

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An EU-funded study called CHATT (Cryogenic Hypersonic Advanced Tank Technologies) has been initiated early 2012. The project CHATT is part of the European Commission's Seventh Framework Programme and run on behalf of the Commission by DLR-SART in a multinational collaboration. One of the core objectives is to investigate Carbon Fiber Reinforced Plastic (CFRP) cryogenic pressure tanks. Four different subscale CFRP-tanks are planned to be designed, manufactured, and tested.

The paper outlines the study logic of CHATT, gives a detailed presentation of the technology development tasks, and summarizes all major research results already available.

Abbreviations

CAD	Computer Aided Design	TPS	Thermal Protection System
CFRP	Carbon Fibre Reinforced Plastic	TRL	Technology Readiness Level
CTE	Coefficient of Thermal Expansion		
FEM	Finite Element Method	-C	cementable
FEP	Fluorinated Ethylene Propylene		
LH2	Liquid Hydrogen		
LOX	Liquid Oxygen		
PFA	PerFluoroAlkoxy		
RT	Room Temperature		
SME	Small Medium Enterprise		

1 Introduction

In future aviation and particularly in hypersonic systems new propellants will be used, such as liquid hydrogen, liquid methane and possibly liquid oxygen. EU funded studies in Europe such as FAST20XX, ATLLAS or LAPCAT investigate advanced vehicles with these fuels for passenger transport like the SpaceLiner or Lapcat A2 and some of their constituent materials and associated propulsion challenges. The question of cryogenic propellant storage inside an airliner – although of critical importance but by far not yet mastered – has not been addressed in comparable detail until the start of the CHATT project.

The need for more detailed investigations on liquid hydrogen or methane tanks in future airliners is not only urgent in future hypersonic aeronautics, but is also essential for environmental reasons in subsonic aviation. Air traffic has experienced strong growth over a long time, and it is predicted that such growth will continue at rates of 4 – 5 % annually over the next decades. On the other hand, it is generally accepted that the emission of greenhouse gases, most notably of carbon dioxide (CO₂), resulting from human's activities, cannot be allowed to continue increasing if adverse global climate change is to be avoided. Liquid hydrogen, produced on the basis of renewable energy, is the only known new fuel meeting the requirements.

Cryogenic fuel propulsion is already operational in advanced launcher systems and Europe has some expertise with the Ariane rocket. However, the airliner systems will require more complex technology (compared to those existing in today's launchers like Ariane 5), such as ultra-light-weight and reusable propellant tank systems. The propellant tank technologies are critical for the vehicle operations, cost and safety.

New materials and design concepts are required, such as fibre composites, in order to reduce the tank weight and to increase the structural performance. This is particularly important if the tank has load carry-

ing functions. Different to current rocket launch systems, the durability through hundreds or even thousands of flight cycles must be assured. Tank liners are another essential element of a tank design in order to assure the material compatibility over long durations. Embedded structural health monitoring systems are required to assure acceptable turn-around time between flights, to optimize the service and maintenance effort and to allow low design margins without lowering overall safety. Propellant management is imperative for achieving reliable and efficient vehicle operation. The sloshing of cryogenic fluids close to their boiling conditions in tanks of horizontal take-off vehicles is not yet mastered.

2 Organizational structure

The project CHATT is part of the European Commission's Seventh Framework Programme (FP7) and run on behalf of the Commission by DLR-SART in a multinational collaboration. One of the core objectives is to investigate Carbon Fiber Reinforced Plastic (CFRP) cryogenic pressure tanks. Four different subscale CFRP-tanks are planned to be designed, manufactured, and tested. The total budget is exceeding 4.2 M€ with an EU contribution of almost 3.3 M€ [1]. The project started in January 2012 and runs for 42 months with a scheduled end in June 2015.

Eleven different partners from seven European countries are participating in CHATT. A list of all involved partners with their country of origin and full organization name is presented in Table 1.

Table 1: List of CHATT partners

Short Name	Country	Participant organization name
DLR	Germany	Deutsches Zentrum für Luft- und Raumfahrt
FOI	Sweden	Totalförsvarets Forskningsinstitut
SICOMP	Sweden	Swerea SICOMP
ULB	Belgium	Université Libre de Bruxelles
ORB	Austria	OrbSpace
ELTE	Hungary	Loránd Eötvös University (ELTE) Budapest
TUD	Netherlands	Technical University Delft
ECM	Germany	Engineered Ceramic Materials GmbH
CENAERO	Belgium	Centre de Recherche en Aéronautique ASBL
GDL	UK	Gas-Dynamics Limited
ALE	Netherlands	Advanced Lightweight Engineering

The organizational breakdown of the CHATT project is very balanced concerning the type of the partners and is as follows:

- SME: 5 (ORB, ECM, CENAERO, GDL, ALE)
- Research institutes: 3 (DLR, FOI, SICOMP)
- Universities: 3 (ULB, ELTE, TUD)

Large industrial companies are not involved in CHATT. All partners receive a 75 % funding by the EU-commission for their research activities. 25 % are funded by internal contribution of each partner. The financial breakdown per country is shown in Figure 1.

The project is managed by DLR-SART with the support of Work-Package leaders based in partner organizations. Regular meetings are essential for the technical exchange. A total of 6 progress meeting (PM) are planned (every 6-8 months) with two PMs already held in Budapest and Piteå, Sweden. A PM is a 2-3 days event. Ad-hoc meetings on WP level may be organized if necessary.

Financial Distribution Breakdown

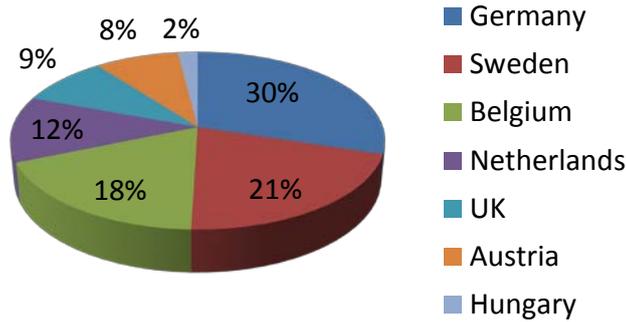


Figure 1: Financial Distribution Breakdown in CHATT per country

Data exchange is organized via a secure electronic team-site (Figure 2), which features a calendar with an announcements & task list, a library section with folders for deliverables, reports, PM presentations, other publications or literature, templates & general documents, as well as partner’s contact data.

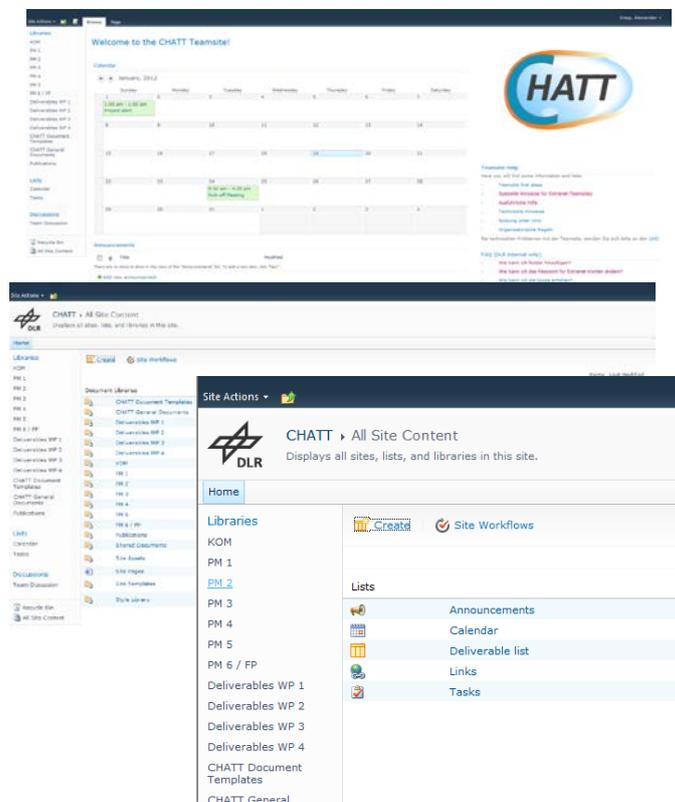


Figure 2: Screen-shots from CHATT team-site

A dedicated public internet site featuring general information about CHATT as well as providing all published papers for download is also available at <http://www.chatt.aero>.

3 Research activities

The intended research in CHATT will increase the knowledge within Europe to a practical cryogenic tank demonstrator level for future aerospace reusable lightweight composite cryogenic structures. The advantages and disadvantages of using liner/linerless tank designs will be investigated as well as issues related to the realization of more complex geometrical tank shapes.

The project is broken down into three main technical activities (Workpackages WP2 to WP4), which have a close interaction as shown in Figure 3.

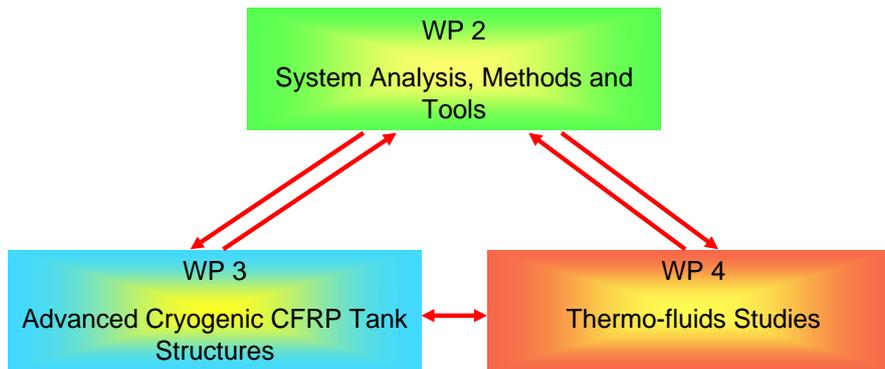


Figure 3: Interaction of different workpackages in CHATT study [1]

A central, steering role is applied to WP2 focusing on system requirements of advanced passenger airplanes, the development, test and implementation of engineering methods and tools. The two remaining workpackages WP3 and WP4 are dedicated to fundamental research with special focus on manufacturing and testing of fully integrated subscale hardware samples. Both WPs are serving as modules supporting the vehicle design and the verification of fast engineering methods.

Four different subscale CFRP-tanks are planned to be designed, manufactured, and tested under mechanical and thermal loads within the scope of the CHATT project. The challenge in developing a cryogenic CFRP tank is finding a solution for the problems caused by differences in thermal expansion coefficients (CTE) on a microscopic scale. If a liner is required, there is also the challenge to overcome the differences in CTE of the liner with respect to the structural shell.

All advanced cryogenic tank technologies to be investigated within CHATT are driven by system demands of future hypersonic passenger configurations. Such vehicles are under study in other EU-funded cooperative projects LAPCAT and FAST20XX [6]: LAPCAT A2, LAPCAT M8, and the SpaceLiner. Thus, the vehicles have already reached a certain level of maturity in their respective propulsion demands and overall size. However, the cryogenic tank systems have not been studied in any detail and major challenges concerning tank weight, sloshing, and insulation have not been addressed much prior to the start of the CHATT project.

One supersonic transport aircraft being researched as part of CHATT is the A2 Mach 5 Civil Transport of Reaction Engines Limited (Figure 4). This aircraft design should be capable of flying from Europe to Australia in 5 hours. The vehicle is intended to have about 20000 kilometers range calling for the use of liquid hydrogen as a fuel which also can be used to cool the vehicle and the air entering the engines via a pre-cooler.



Figure 4: LAPCAT A2 hypersonic Mach 5 Civil Transport in artist's impression [2]

To attain and maintain such high speeds, Reaction Engines Limited would need to develop its newly designed concept engine called the Scimitar, which exploits the thermodynamic properties of liquid hydrogen. The airframe configuration is an efficient structural shape with circular cross section hydrogen tankage and uninterrupted carry-through wing spars. The vehicle is sized to carry 300 passengers.

An interesting alternative to air-breathing hypersonic passenger airliners in the field of future high-speed intercontinental passenger transport vehicles might be a rocket-propelled, suborbital craft. Such a new kind of 'space tourism' based on a two stage RLV has been proposed by DLR under the name SpaceLiner [3]. Ultra long-haul distances like Europe – Australia could be flown in 90 minutes. Another interesting intercontinental destination between Europe and North-West America could be reduced to flight times of about one

hour. The latest reference configuration is the SpaceLiner 7 which has been reached after several evolutionary steps [5] and is shown in Figure 5.

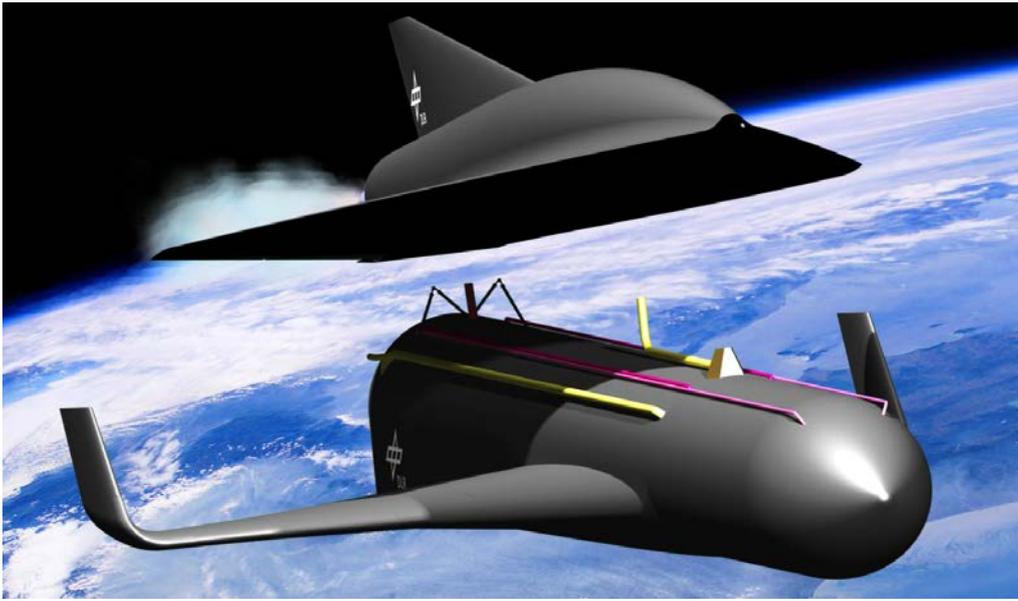


Figure 5: SpaceLiner 7 hypersonic passenger transport in artist's impression

Propellant management is imperative to achieve reliable and efficient vehicle operation. It is therefore the third pillar of the CHATT study and covers tank pressurization, fuel location/retention, and sloshing in horizontal tanks. Apart from thermal aspects, sloshing of cryogenic fluids within the tanks can have a significant impact on flight operation as the liquid excited through vehicle movements may travel distances of considerable lengths compared to the overall size of the aircraft. The vehicle may consequently experience a noticeable shift in its center of gravity and hence its controllability is put into question.

Counter-measures such as anti-sloshing devices and tank design are susceptible to reduce these effects but will come at the cost of increased mass and production effort. As a consequence a trade-off between hardware design and flight control development in order to minimize the impact of propellant sloshing is an important step in the design phase of a hypersonic vehicle. The CHATT study will focus on establishing engineering models for sloshing verified by numerical calculations and experiments. These models will then be applied to flight control simulations of the reference vehicle concepts allowing an evaluation of their overall feasibility.

The propellant crossfeed between the two rocket-powered stages of the SpaceLiner enables a significant performance improvement. However, crossfeed between operational stages is highly innovative and has never been demonstrated in flight. A simulation of the steady and transient behavior in the propellant feed-system will be performed along the powered flight, performance and critical points will be evaluated, and recommendations will be derived. Some early results of the preliminary definition have been presented in [11] and positions of the external feedlines on top of the booster stage are visible in Figure 5.

Heat-exchangers are one of the most essential elements of a tank pressurization system. Two different types of ceramic heat-exchangers will therefore be looked at in CHATT. In addition to fuel tank pressurization, also oxygen tank pressurization will receive a strong focus, because it is required by systems which partially or fully rely on rocket propulsion like the SpaceLiner.

The air-conditioning system for the airbreathing hypersonic vehicles investigated in CHATT like the A2 shown in Figure 4 were planned to be based on a system in which bleed air from the intake exhaust is cooled using cryogenic fuel and then compressed to achieve the conditions required for the cabin air supply. Power for the compressor and other cabin sources should have been provided by a Rankine cycle on the cryogenic fuel [1]. However, during the cabin air-conditioning system study [7] of WP2 it was realized that the out-going cabin air provided a heat sink for the incoming fresh air which can be cooled down and still be used to generate electrical and mechanical power. The cooling cycles defined for the M5T and A2 concept aircraft both use air as the working fluid and the objective is to provide cold low pressure air at the turbine outlet in what is known as an "Air Cycle" [8]. A detailed design of a fast-running prototype radial air-cycle turbine will be developed, constructed and tested.

The aerogel is an open-celled, nanoporous, solid foam which could become an attractive insulation material for cryogenic tanks in the future. Supported by CHATT, a cost efficient production process is developed for alumina cryogels by ELTE [11].

In Table 2 a list of individual items describes in short the objectives in technology development along with their previous TRL. CHATT should provide the opportunity to increase the level towards the TRL-scale shown in the right column.

Table 2: Progress of proposed technologies in terms of TRL-grading

Technology description	Previous TRL	Envisaged TRL
Flight control development sloshing case	1	2/3
Aeroelastic modelisation of tanks	2	3
Tank preliminary design model	2	5
Tank System Engineering Methods	3	5
Liner Design	3	4
Tank Design with Liner	3	4
Cryogenic dry wounded carbon fiber pressure vessel	2	4
Tank Design without Liner	3	4
Tank Design with Complex Shape	3	4
Testing and Health Monitoring	4	5
Tank insulation (Aerogels)	2	3
High Order Methods for Sloshing Simulation	2	5
Sloshing Tests and Modeling	2	4
CMC Heat exchanger technologies	1	3
Cryogenic Rankine Cycle (changed by system analyses)	2	(4)

4 Available Research Results

The CHATT-study officially started on January, 1st, 2012. After approximately eighteen months of work some results of the research are already available. Hardware manufacturing has started and some tests have been performed. The following sections give an overview on requirements and loads definition and preparatory work focused on the CFRP tank studies of WP3. More papers on other CHATT results are to be expected in the future.

4.1 Review of previous CFRP tank designs

Fibre reinforced materials are structurally the most efficient material for pressure vessels because there is the possibility to direct the right amount of fibers according to the orientation and the magnitude of the principal stresses, which makes it an iso-tensoid structure. Carbon fibers are currently known to have the highest specific strength and stiffness which makes it the material of choice when it comes to aerospace structures. For advanced tank wall materials the high specific strength at cryogenic temperatures is one of the most essential parameters. Figure 6 is demonstrating the high interest of a CFRP design. Fracture toughness and stiffness are also important properties. Depending on the type of application, different designs may be favourable and tanks may thus be built as single-, double-wall or sandwich structures.

Within the category of tanks with liner there are two subgroups, namely wet wound tanks and dry wound tanks. The first concept is the classical one. Several institutes have worked out this classical concept into a fully matured product and have published papers on their development process and results. The second concept is patented by ALE, and no standard solutions for the development of this concept for cryogenic propellant storage can be found in the literature [9].

A linerless tank has the advantage over a tank with liner that mass, cost and production time can be reduced. This however means that both the load carrying task, as well as the task of holding the propellant inside the tank should be done by only the composite shell [9]. The X-33 demonstrator tank consisted of a multilobed and linerless configuration with integrally bonded, woven composite joints. However, that tank failed in 1999 during ground testing due to polymer matrix micro-cracking and leakage into the sandwich core material causing delamination between the core and the inner composite skin. The tank showed leakage with subsequent damage, so-called "cryopumping".

Northrop Grumman and NASA later completed within the NGLT project a nine-month test series to demonstrate a cylindrical composite cryogenic tank. The problems that brought the X-33 to a halt were

proven to be solved in 40 load cycles performed without failure. The integral tank, utilizing an impermeable barrier film between the inner tank wall and the honeycomb [4] was filled with LH2 and pressurized. The program highlighted the need to improve the permeation resistance with liner materials.

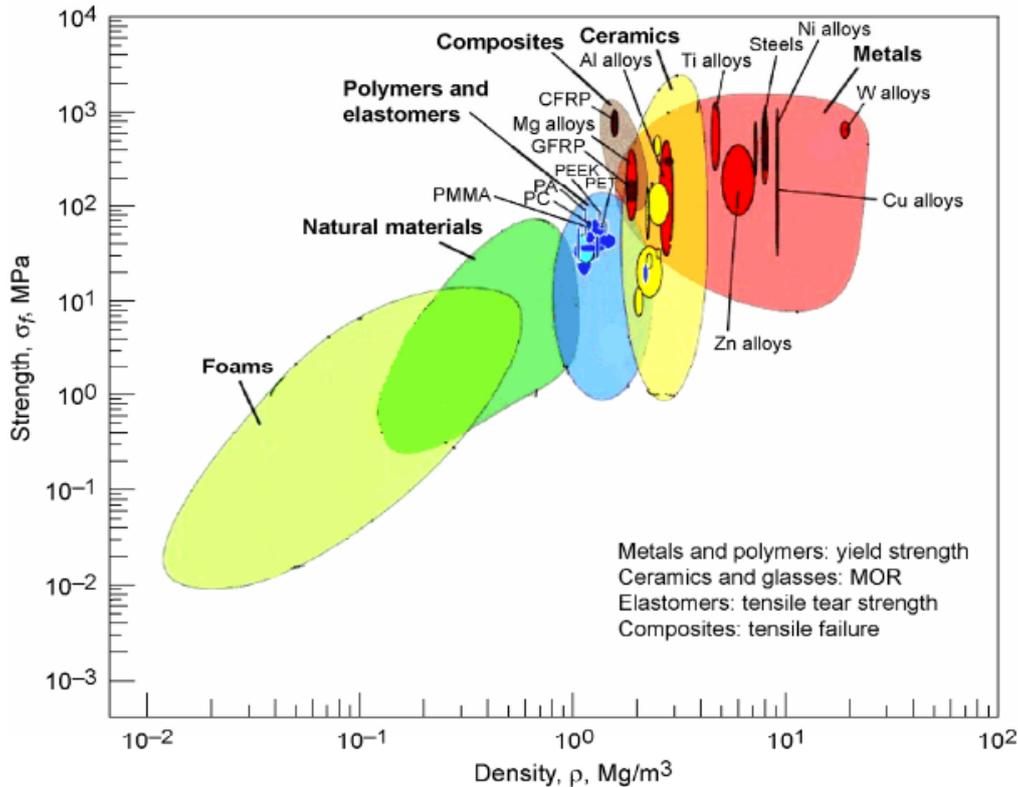


Figure 6: Strength versus mass density for various engineering materials [4]

The advantage of a tank with liner is that the task of holding the propellant inside the tank and the task of carrying the loads are done by two different parts. The liner can be designed to prevent permeation and to be chemical compatible with the propellant without worrying about carrying the loads. The composite can be designed to only hold the load, without worrying about permeation. The disadvantages of the liner tank concept are the increased mass, cost and fabrication time. Moreover a mismatch between the CTEs of the liner and the composite can result in separation of the liner and interlaminar debonding in case inappropriate glue is used in an inappropriate way [9]. For low temperature applications the increasing brittleness of the liner has to be considered to ensure gas-tightness. For typical carbon epoxy composites the vessel structure itself is not critical under cryogenic boundary conditions.

4.2 Assessment of suitable liners

Several liner materials are evaluated by Swerea-SICOMP in CHATT using both numerical analyses and mechanical testing. Five different polymer materials were considered and analyzed for possible application as liners in cryogenic fuel tanks. The selected materials represent two general groups: liquid crystal polymers and fluoropolymers.

Two main candidates are however identified from a literature review [11] as the most promising materials which can also be mixed with nano-particles if it is necessary to match the CTE to the base laminate to decrease thermal stresses:

- Liquid Crystal Polymer (LCP). In particular the Vectran[®] LCP fiber
- Perfluoroalkoxy (PFA), in particular the Teflon[®] PFA TE-7224

First a study of mechanical properties was performed to analyze the dependency of mechanical properties on low temperatures. Tensile test results indicate much higher ductility of fluoropolymer materials at room temperature with strains to failure reaching over 100%. At cryogenic temperatures, however, ductility of fluoropolymers is significantly reduced and a tensile failure strain at -150°C of only 3% was measured. [10] The liquid crystal polymers showed promising mechanical properties; however, they were more brittle and also demonstrated a high degree of anisotropy due to the manufacturing method used at Swerea SICOMP. The fluoropolymer materials are also more attractive from the manufacturing point of view.

Adhesion of polymer sheets on to a base laminate was performed. Good adhesion was achieved for the liquid crystal polymer sheet polymers however weak adhesion was observed for the fluoropolymer liners. For this reason also cementable fluoropolymer liners were used and much better adhesion of fluoropolymer liner with the base laminate was achieved. The adhesive EA9394 is chosen as the baseline for the joining of the liner material to the base laminate. Toray® T700S carbon fiber fabric and Araldite® epoxy 5056 were used for manufacturing. The resin was cured by Swerea SICOMP at room temperature (RT) with post curing for 4 hours at +100°C [10]. Mechanical properties of the base laminate were also studied at low temperatures proving that transverse properties of a unidirectional base laminate ply are more sensitive to temperature than the longitudinal properties.

The purpose of the testing at plate level of liners and liners with laminates is to evaluate the performance of the liner candidates in load cases relevant to a cryogenic tank application. The ability to withstand micro-cracking in the composite layers closest to the liner is identified as a vital property for the overall performance of the liner material [10]. Hence, the testing was intentionally performed so that micro-cracking occur in the composite layers closest to the liner material in the test case “liners with laminates” both in elevated temperatures and also, more importantly, in very low temperatures typical for cryogenic applications.

Base laminates with liners were tested in 4 point bending according to ASTM 6272 to see the possible micro-crack propagation. At RT, fluoropolymer liners proved to be very resistant to cracking due to their low stiffness and high ductility and local yielding in the vicinity of the crack in the base laminate was observed. The liquid crystal polymer liners on the other hand are more prone to develop micro-cracks. Hence, the transverse cracks in the base laminate easily propagated through the liquid crystal polymer liner thus creating a pathway for possible gas leakage in future tank applications. [10]

At -150°C, however, all the studied liner materials were prone to cracking due to increased brittleness. The only exceptional case, where the polymer liner candidate did not fracture in bending test was observed for laminates with non-cementable fluoropolymer liners. The transversal cracks were in that case deflected as delamination cracks instead. Bending tests performed at -150°C for laminates with FEP-C and PFA-C liners showed that the transverse crack propagates in the liner layer. This was observed regardless of the thickness of the 90° layer as shown in Figure 7.

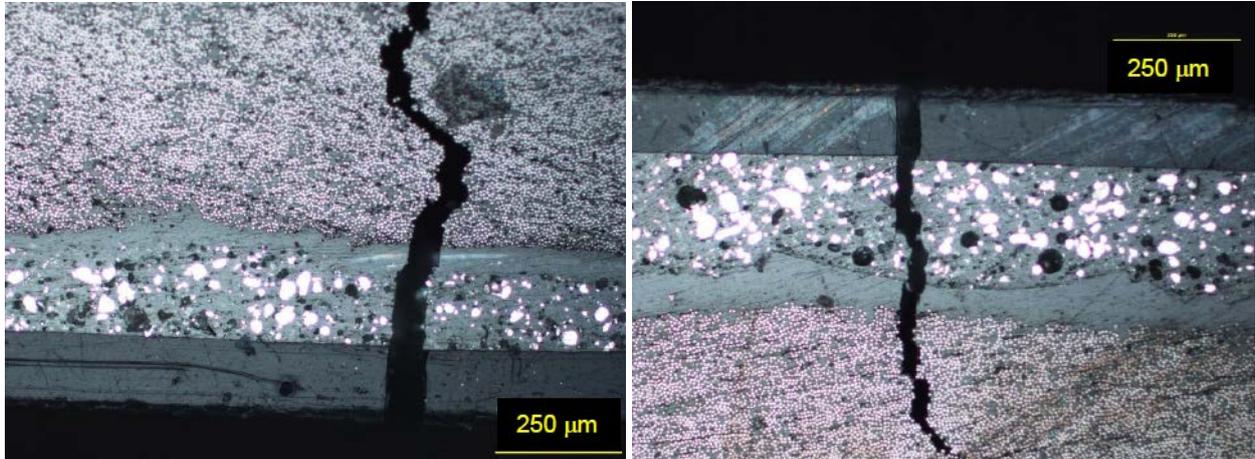


Figure 7: Micro-cracks detected after bending test with FEP C liner at -150°C, base laminates $[90/0]_s$ at left and $[90_2/0]_s$ at right [10]

Additionally, thermal ageing studies were performed for all polymer liner material candidates. Test samples were subjected to 140-200 cycles of immersion into liquid nitrogen (thermal shock) and quick restoration to room temperature. The results show that the fluoropolymer materials have a significant reduction of stiffness and tensile strength, while the stiffness and strength of the liquid crystal polymer materials was not affected by the thermal cycling.

4.3 CFRP demonstrator tank structures

Four different subscale tank concepts will be designed, manufactured and tested within CHATT:

- Cylindrical tank with liner by DLR
- Dry wound cylindrical tank with liner by ALE
- Cylindrical tank without liner by FOI/SICOMP
- Complex shape tank by TU Delft

A cylindrical tank with ≈ 3 m overall length and ≈ 1 m diameter, and with half-spheres on both ends, shall be manufactured by filament-winding at DLR-Braunschweig. The CAD-model of the planned tank is shown in Figure 8.

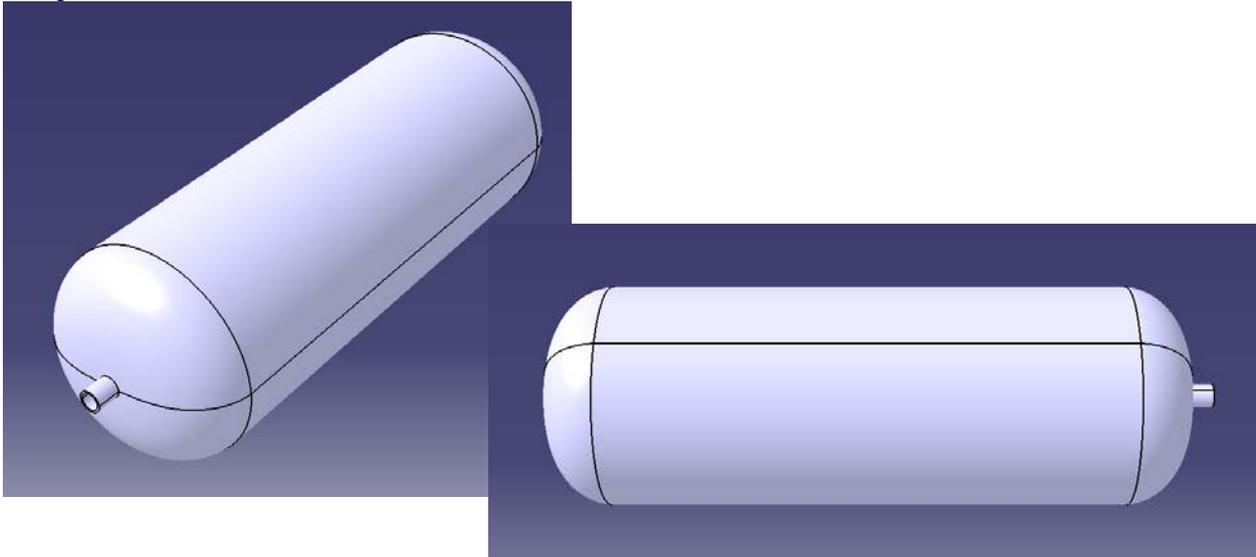


Figure 8: CAD-model of planned DLR CFRP test tank

An unusual multi-part concept is proposed as an option for this filament-wound pressure tank in which the load transfer of the fibers is disturbed because the tank will be cut after winding. However, this approach allows opening of the tank for the installation of equipment or anti-sloshing devices. Such a design could be attractive for very large tanks in hypersonic airplanes which in any case need several cut-outs and openings and which will be operated at moderate internal pressures. The special concept of an annular flange with bolts allows creating a closed tank shell. The tank would be cut after winding in the middle and afterwards glued together with a bandage. The approach has been analyzed in pre-production runs (Figure 9). The test tank was built with a body made of Polystyrene with good results.



Figure 9: Tank with bandage in test production run at DLR

Another, more conventional option for the production of this tank is still under consideration. The decision on the actual approach is due in June and the manufacturing should start soon after. The subscale tank hardware is planned to be ready for testing at the end of the year 2013.

Beyond the wet-wound tanks a dry filament wound cryogenic cylindrical demonstrator tank will also be designed, produced and tested by ALE. The main risk of using a dry filament wound tank in cryogenic environment is that in unpressurized state the fibers could separate from the liner due to the difference in their CTE and start to relocate. This tank has a cylindrical mid-section with two isotensoid shaped ends. The tank has an approximate length of 0.57 m, a diameter of 0.29 m, and a volume of 33 l. [13]

The most important requirement for the demonstrator tank is that it should have a minimum burst pressure of 12 bar during operations with liquid hydrogen. Vectra LCP A435 has been chosen as liner material and will be reinforced with dry wound T700 carbon fiber. The torque-free aluminum insert will contain the liquid hydrogen compatible Astra Seal O-ring. A polyurethane coating can be applied to the outside of the tank to

protect the fibers. The design will be made with the ALE in-house developed program PresVes, the CAD software SolidWorks and the FEA software Abaqus [14].

The production of the liner will be done with the blow molding machines and equipment. The roughening of the liner surface, integration with the insert, fiber winding and coating can be done in the workshop of ALE as well as initial tests at room temperature. The location for performing the tests with cryogenic liquids is still to be determined and is currently explored [13].

The preliminary design of the demonstrator tank using dry filament winding is shown in Figure 10. The individual fibers, modeled as Truss Elements, for both the helical and hoop layer can clearly be seen.

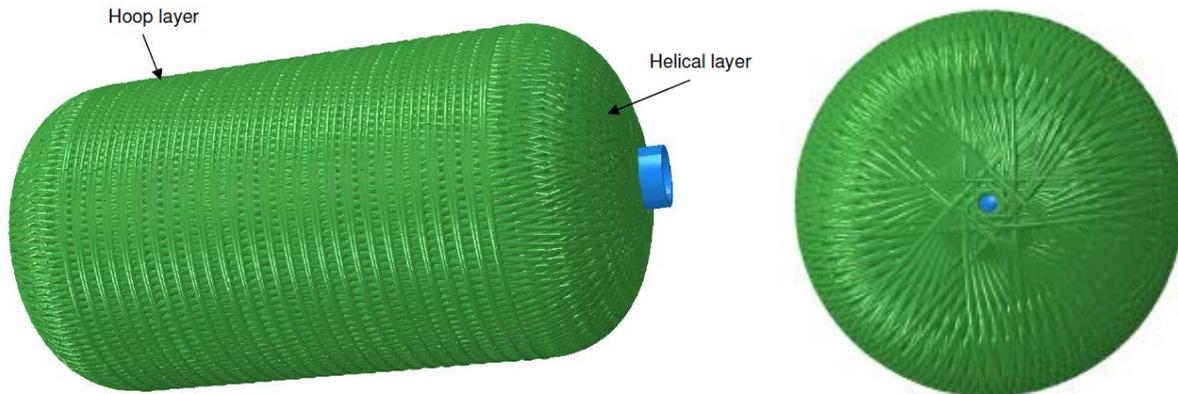


Figure 10: Preliminary design of dry wound cryogenic tank in Abaqus/CAE [13]

The simplest possible structure should be selected for the CHATT scaled prototype of a multibubble tank to be built at TU Delft which, however, contains all the specific design and manufacturing issues of such a complicated spheres arrangement. It has therefore been decided to design, evaluate and produce a planar arrangement of identical spheres with double symmetry as presented in Figure 11. The spheres of the multi-sphere are structurally efficient shell-structures with respect to balancing the pressurization loads. Membrane forces for the sphere are given by the circumferential force.

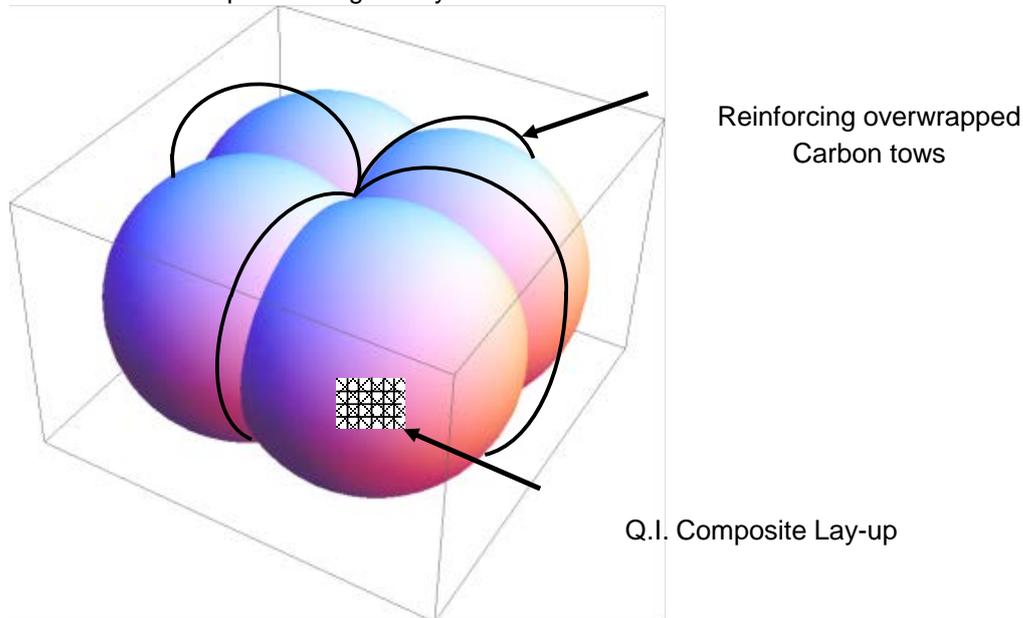


Figure 11: Arrangement of four identical intersecting spheres possessing double symmetry lay-up and external reinforcement of the multi bubble design

The radii of the four bubbles of the intended prototype are all at the same 150 mm. The distance between the centers of the incomplete spheres is equal to $R\sqrt{2}$. The liner is planned to be made in a closed mould by rotation moulding and has a thickness of 3 to 5 mm. Most probably, the liner material will be a liquid crystal polymer to satisfy the requirements of low permeability, resistance to cryogenic temperatures, reduced CTE mismatch, and absence of micro-cracking. At the point where the bubbles meet, the liner possesses a tube-like passage to provide space for the externally overwrapped carbon tows to go through.

The liner is overwrapped by cross ply woven fabrics [90/0]_s that are stacked under an angle of 45° with respect to each other. By this way of stacking, a quasi-isotropic laminate can be created. In a next step the liner, which is now covered by the stacked fabrics, is packed into a bleeder foil and a vacuum foil. The resin is inserted by the vacuum infusion technique. Post processing in an oven or autoclave is necessary to remove any remaining voids and ensure complete curing of the resin. The resin is not determined yet but possibly will be a toughened epoxy.

5 Conclusion

The project CHATT is part of the European Commission's Seventh Framework Programme and run by DLR-SART in a multinational collaboration. The project started in January 2012 and is running for 42 months with a scheduled end in June 2015. The objectives of this effort with a total budget exceeding 4.2 M€ are to investigate different CFRP cryogenic pressure tanks, propellant crossfeed systems, advanced thermal insulation materials, and ceramic heat-exchangers. Four different subscale CFRP-tanks are planned to be designed, manufactured, and tested.

After approximately eighteen months some results from the research work are available. The vehicle reference design loads and conditions have been defined for three reference vehicles representing three different concepts of hypersonic transportation vehicles. Five different polymer materials were considered and analysed for possible application as liners in cryogenic fuel tanks. Tests were run at room temperature and at -150°C. At low temperatures and under bending loads some micro-cracking reaching into the liner material was observed. It will have to be assessed how representative these standardized load tests are for conditions in large cryogenic tanks.

Design of the different subscale CFRP-tanks is advancing and the tanks should be manufactured until the end of the year, to be ready for testing under relevant cryogenic conditions in 2014.

6 Acknowledgements

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7 References

1. NN: Grant agreement for: Collaborative project, Annex I - "Description of Work", Project acronym: CHATT, Project full title: "Cryogenic Hypersonic Advanced Tank Technologies", Grant agreement no: 285117, Version date: 2011-07-11, PART B
2. REL: <http://www.reactionengines.co.uk/lapcat.html>
3. Sippel, M.: Promising roadmap alternatives for the SpaceLiner, Acta Astronautica, Vol. 66, Iss. 11-12, (2010)
4. S. K. Mital et al.: "Review of Current State of the Art and Key Design Issues with Potential Solutions for Liquid Hydrogen Cryogenic Storage Tank Structures for Aircraft Applications", NASA/TM—2006-214346. (2006)
5. Sippel, M.; Schwanekamp, T.; Bauer, C.; Garbers, N.; van Foreest, A.; Tengzelius, U.; Lentsch, A.: Technical Maturation of the SpaceLiner Concept, AIAA2012-5850, 18th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Tours, September 2012
6. Sippel, M.; Votta, R.; Haya-Ramos, R.: Advanced Launcher Technology Maturation Supported by EU-Aeronautic Research Projects, IAC-12-D2.5.6, Naples, October 2012
7. Walton, C.: Cabin air-conditioning study, CHATT Deliverable D2.5.1, 2012

MS.7: PLASTICITY, FATIGUE, DAMAGE AND CORROSION

8. Cain, T; Walton, C.: Development of the aircraft cooling/power cycle (former title: Development of the Rankine cycle), CHATT Deliverable D4.4.1, 2013
9. Fraters, A.: Current state-of-of-the-art knowledge in the structural aspects of advanced composite cryogenic tanks, Literature review of the state-of-the-art of topics relating to design, testing and production, CHATT Deliverable D3.1.1, 2012
10. Mattsson, D.: Report on specification, materials selection and theoretical design, CHATT Deliverable D3.2.1, 2012
11. Sippel, M.; Kopp, A.; Sinko, K.; Mattsson, D.: Advanced Hypersonic Cryo-Tanks Research in CHATT, AIAA2012-5945, 18th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Tours, September 2012
12. Pupurs, A.; Mattsson, D.: Report on testing at plate level of liners and liners with laminates, CHATT Deliverable D3.2.3, 2013
13. Fraters, A.: Report on design considerations for dry filament wounded cryogenic cylindrical tanks, CHATT Deliverable D3.3.2, 2013
14. Koppert, J.J.M.; de Boer, H.; Weustink, A.P.D.; Beukers, A.; Bersee, H.E.N.: Virtual testing of dry filament wound thick walled pressure vessels, in 16th International Conference on Composite Materials, 2007

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