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TARES2020: TECHNOLOGIES FOR FUTURE LIQUID PROPELLANT ENGINES AT ARIANEGROUP

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Abstract

Within a federal grant project, supported by the German Space Agency DLR, research and technology investigations were performed in the domain of liquid rocket engine propulsion. The activities focussed on the key products developed and manufactured by ArianeGroup at its site of Ottobrunn, namely fluid control equipment and thrust chamber assemblies. Theoretical and numerical investigations addressed the performance of seals in cryogenic valves, injection and ignition systems for cryogenic propellants, modelling strategies for combustion and heat transfer management in combustion chambers as well as materials and processes for manufacturing of the individual components. While several tasks addressed dedicated topics of additive manufacturing, also classical manufacturing technologies were considered.
The publication uses some dedicated examples to illustrate the scope of applications addressed and the contribution of research institutes and universities.

Abbreviations, Acronyms & Symbols (to be completed)

α_0	Expansion coefficient	G*	Complex shear modulus
γ	Glass transition parameter	HCF	High Cycle Fatigue
CAD	Computer Aided Design	λ	Thermal conductivity
CFD	Computational Fluid Dynamics	LAI	Laser Ablative Ignition
CH4	Methane	LOX	Liquid Oxygen
c_p	Specific heat	LPBF	Laser Powder Bed Fusion
CNES	Centre national d'études spatiales	LPI	Laser Plasma Breakdown Ignition
DFG	Deutsche Forschungsgesellschaft	$\dot{m}$	Mass flow rate [g/s], [kg/s]
DLR	Deutsches Zentrum für Luft- und Raumfahrt	PCTFE	Polychlortrifluorethylene
E*	Complex elasticity modulus	PEEK	Polyether-ketone
F	Force	SFB	Sonderforschungsbereich
FEM	Finite Element Method	TCD	Thrust Chamber Demonstrator

1 Introduction

While preparing the nominal operations of the new Ariane 6, ArianeGroup is performing several long-term research and technology projects to continuously assess and prepare innovative technologies for future liquid rocket engines. In this context, ArianeGroup has conducted the R&T programme "Technologies and Applications for Rocket engine Systems 2020 - TARES 2020", which has been dedicated to increase the technology readiness level of selected technologies to a technology readiness level of TRL = 3-5 for later application on launcher engines. This activity was performed in the time from February 2017 until March 2021 and was supported by the German Space Agency DLR by a federal grant. Different fields of liquid propulsion subsystems have been addressed, covering cryogenic valves, ignition systems, gas generators and thrust chamber technologies.

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Figure 1 shows the work breakdown structure of the project. In work package 1000, all project management and administrative tasks were done. Work package 2000 was dedicated to systems engineering activities, such as the performance of technology trade-offs or the provision of relevant requirements for the technology demonstration activities in the other work packages. Additionally, this work package was dedicated to all activities crossing the boundaries between the different engineering disciplines. In work package 3000, all engineering tasks were allocated: Design, structure thermo- and fluid mechanics. Within this work package, different tasks addressed various topics of interest, such as design tools for additive manufacturing or investigations on heat transfer and two phase flow phenomena. Work package 4000 was dedicated to R&T activities in the field of materials and processes. Apart from pure material characterisation tests for new alloys, individual tasks were dedicated to additive manufacturing technologies as well as classical manufacturing technologies, such as forming and welding of sheets for nozzle structures. All activities to generate test data for validation of models and to demonstrate the feasibility of technologies were performed in work package 5000. Finally, work package 6000 was dedicated to the cooperation with various research institutes and universities, which is an essential part of ArianeGroup's R&T strategy.

The following text illustrates the activities with some selected topics covering the entire scope of R&T for ArianeGroup GmbH in Ottobrunn.

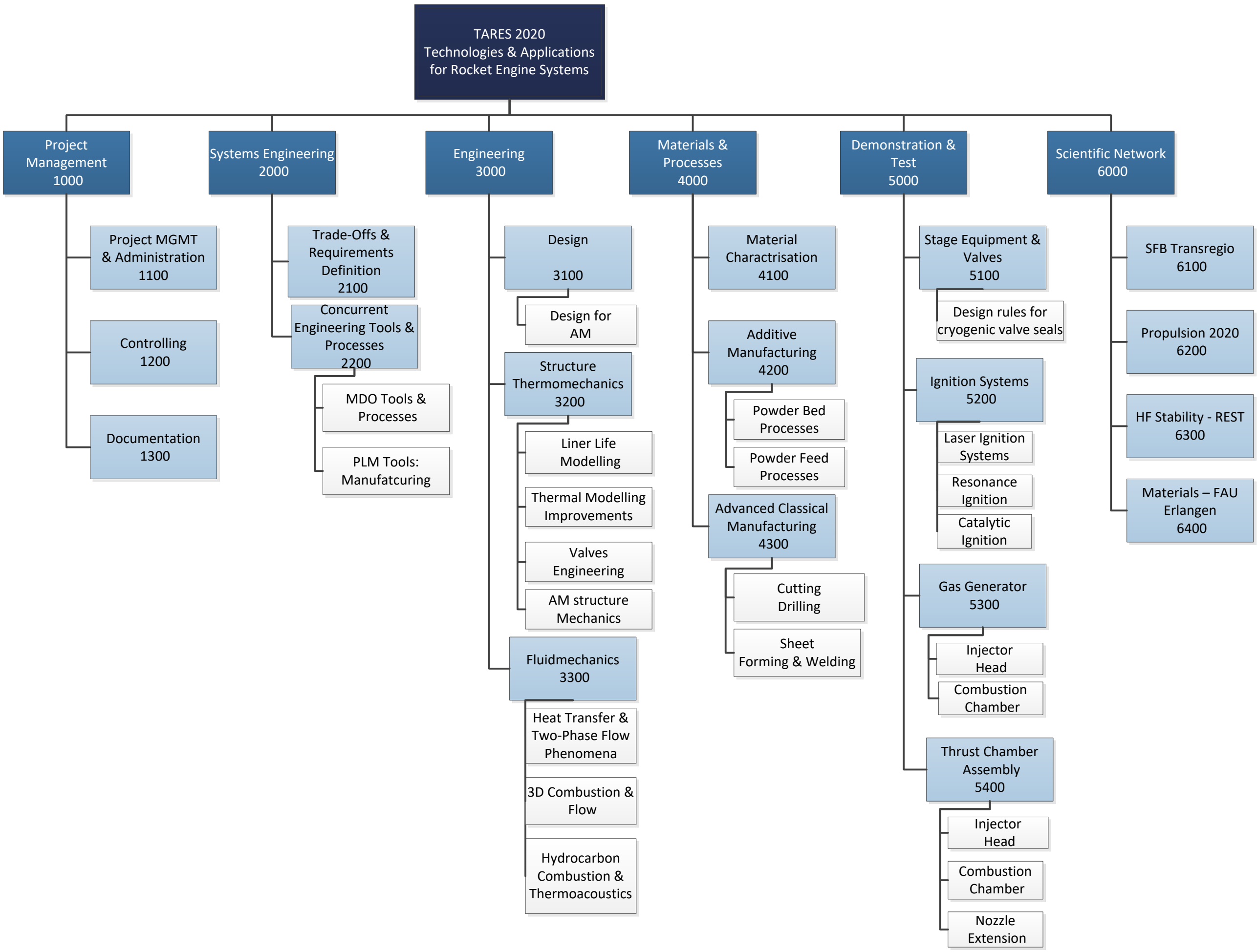


Figure 1: Work breakdown structure of TARES2020

DOI: 10.13009/EUCASS2022-4834

2 Fluid Control Equipment

2.1 Overview

Apart from the liquid rocket engine itself, the propellant feed system with its various valves is also a key element of a liquid rocket propulsion system. ArianeGroup GmbH in Ottobrunn has specialised in large propellant feed valves and pressurisation valve assemblies used to control the pressure in the propellant tanks of the launcher. Leakage phenomena in valves do not occur during flight; however, they may cause delay of launch preparation operations when detected late in the integration process of the propulsion system, thus causing significant cost. Being able to properly predict the behaviour of the sealing system is essential to properly design a robust valve, which operates reliable in the entire mission cycle. Especially challenging is the fact that these valve assemblies are designed for the operation with liquid oxygen and liquid hydrogen at temperatures down to 20 K. In this temperature range, the polymeric seal material undergoes a so called glass transition, with which the behaviour of the material changes from rubbery and elastic to glassy and brittle or stiff. An infamous example of this are the rubber O-ring seals, which caused the catastrophic failure on Space Shuttle Challenger's solid rocket motors.

Figure 2 illustrates the sealing system of the solenoid valves installed in Ariane 5's and Ariane 6's lower stage pressurisation system, which was considered during the study. The left image shows a magnified cutaway CAD view of the seal configuration. The polymeric seal is illustrated with green colour. The right part of the image illustrates the model used for numerical investigations: The steel poppet (dark green) can slide freely in vertical direction, executing a force on the sealing ring. The sealing ring itself (grey) can slide laterally; its vertical movement is blocked by a support ring.

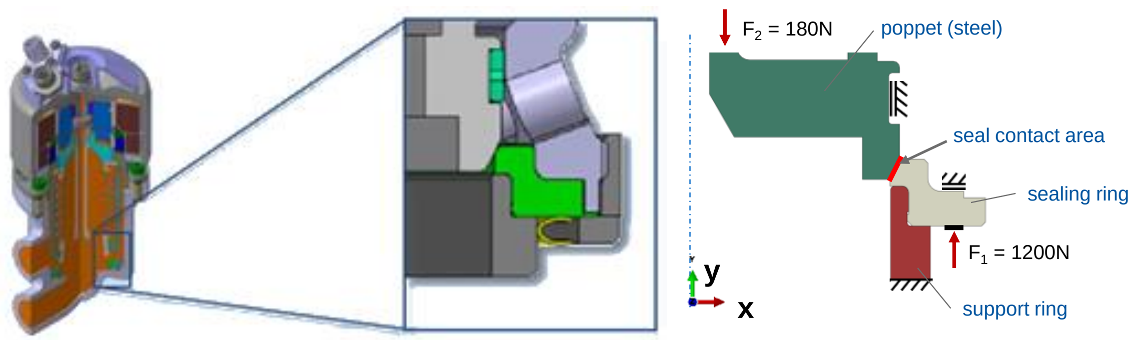


Figure 2: Solenoid valve used in pressurisation system;
left: CAD view with zoom on seal area; right: FEM model boundary conditions

To properly describe the behaviour of the seal contact area during an operation cycle, ArianeGroup established a cooperation with the institute for applied mechanics of the Rheinisch-Westfälische Technische Hochschule (RWTH). Within this cooperation, a material characterisation program and numerical model development have been performed to predict the material behaviour of polymeric seal materials during the operation cycle, stretching from room temperature down to cryogenic operating conditions. ArianeGroup has been responsible for the material characterisation program for various polymeric seal materials to characterise the elasto-plastic deformation behaviour and to identify the glass transition temperature, if applicable. The materials considered in this characterisation program were Vespel®, polyether-ketone (PEEK) and polychlortrifluorethylene (PCTFE). With the material data RWTH Aachen has established a numerical model to describe the contact force and deformation of the seal during its operation cycle.

2.2 Material characterisation

As mentioned before, three different polymers were investigated during a material characterisation campaign: Vespel®, PEEK and PCTFE. The following material properties were required for the model to properly describe the deformation behaviour of the seals (for details, see Table 1):

- expansion coefficient α_0,
- heat capacity c_p
- thermal conductivity λ
- complex shear and elasticity modulus G* and E* (complex moduli allow to differentiate between elastic and viscous contribution to deformation behaviour)

DOI: 10.13009/EUCASS2022-4834

The tests were performed at Netzsch GmbH and the University of Federal Forces (UniBW) in Neubiberg. The data was also analysed to identify the glass transition temperature level. As expected for the temperature range of interest, PEEK does not feature such a glass transition. For Vespel® a glass transition was recorded at 323 K. For PCTFE, two glass transition levels were found, at approximately230 K and 340 K, respectively.
The recorded material data was fed to the numerical model which was used to describe the evolution of the contact pressure on the seal surface during operation. The change in material behaviour at the glass transition point is taken into account with a dedicated temperature-dependent glass transition parameter y: With $\gamma = 0$, the material is in its rubbery phase; with $\gamma = 1$, the material behaviour is glassy.

Table 1: Material properties investigated for modelling

Parameter	**Test**	**Temperature range**	**No. of tests**		
			PCTFE	VESPEL	PEEK
Heat capacity c_p	Direct scanning calorimetry DSC	123 K – 523 K	3	3	3
Expansion coefficient α_0	Thermal mechanical analysis TMA	123 K – 523 K	3	3	3
Thermal conductivity λ	Hot disc method HDM	223 K, 295 K, 373 K	9	9	9
Complex shear modulus G* / Complex elasticity modulus E*	Combined dynamic mechanical analysis from 10 Hz to 80 Hz	123 K – 323 K	3	3	3

2.3 Modelling

The finite element simulations used a three-dimensional thermo-viscoelastic material model taking into account effects of creep and stress relaxation. The simulations were fully coupled with respect to the thermo-mechanical behaviour, i.e. taking into account the effect of the material temperature on its deformation and vice versa. The material properties were taking into account the change in the behaviour of the polymers at the glass transition temperature. Figure 3 recalls the model used for the finite element analysis. The seal (grey) is fixed in the valve by the support ring, acting with a vertical force of 1200 N. The seal may slide laterally. If the valve is closed, a vertical force of 180 N is applied via the poppet. The numbers to identify different nodes in the computational mesh are given on the right side of Figure 3.

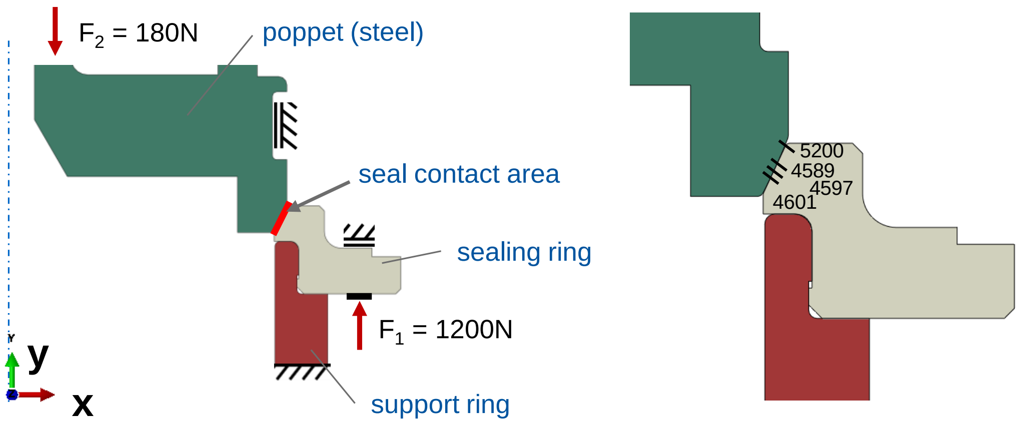


Figure 3: FEM model with boundary conditions used for deformation analysis (left) and nomenclature of nodes for analysis (right)

The valve is a normally-closed type, i.e. during operation, the poppet applies a constant load of 180 N before the chill-down of the fluid system starts. Once the valve has reached the thermal equilibrium, the valve is operated at constant temperature for various opening and closing cycles. To analyse the general behaviour of the simulation, the evolution of the contact pressure of the closed valve during chill-down was analysed for two extreme and artificial cases: $\gamma = 0$, fully rubbery behaviour and $\gamma = 1$, fully glassy behaviour. Exemplarily, Figure 4 shows the transient temperature profile for PEEK at different locations in the seal and the local contact pressure. Due to the low thermal conductivity of the material, the seal material is predicted to require more than 15 seconds to achieve thermal equilibrium. Different values of local contact pressure persist after the seal assembly is cooled down.

DOI: 10.13009/EUCASS2022-4834

Figure 5 shows similar simulation results for PCTFE, plotted along the contact area for different time steps of the chill-down process. Due to the cooling, the upper region contracts and allows for a downward displacement of the seal. Cooling further, the contact area moves upwards. As the length of the contact area is nearly constant throughout the cooling process, the seal is expected to be leak-proof. Additional simulations were performed to investigate the effect of different combinations of pressure upstream and downstream of the seal. These allowed assessing the superimposed effect of temperature and pressure balance (or imbalance).

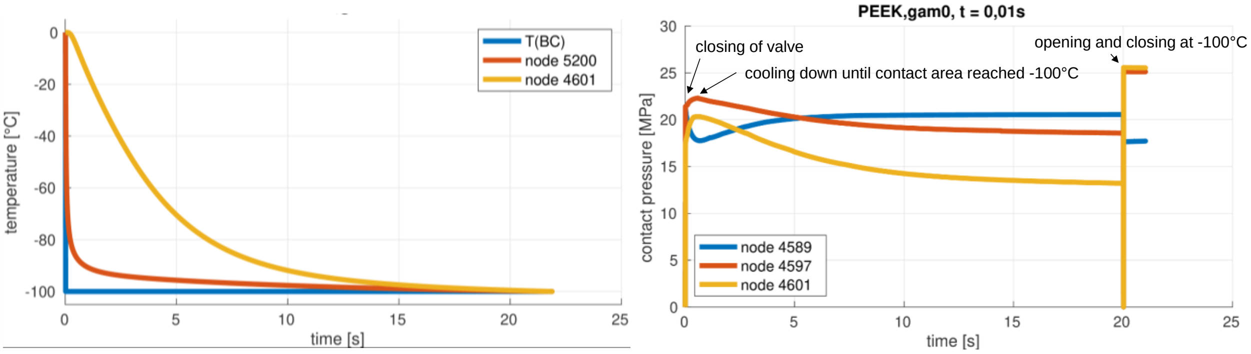


Figure 4: Left: Temperature evolution in seal during chill-down at different locations; right: evolution of contact pressure during chill-down (γ = 0)

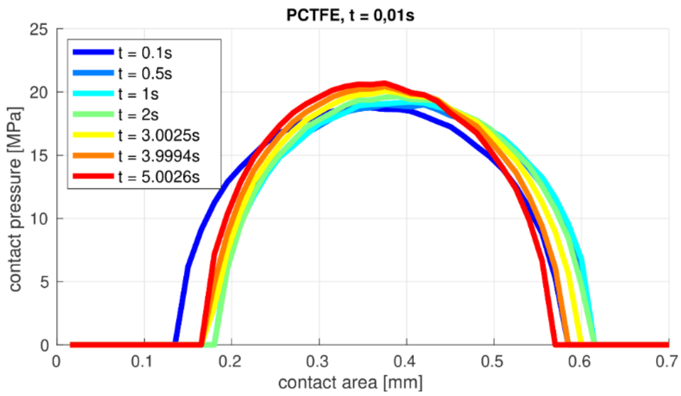


Figure 5: Contact pressure profile for PCTFE during chill-down

DOI: 10.13009/EUCASS2022-4834

3 Additive Manufacturing

The Laser Powder Bed Fusion (LPBF) process, also known as Selective Laser Melting (SLM), is already being used for engine components of Ariane 5. However, there are several open points to be addressed to better understand the process factors influencing the material properties and to subsequently optimise the manufacturing process. To address these open points, a joint research activity was performed together with the Chair of General Material Properties of the Friedrich-Alexander Universität of Erlangen-Nürnberg. Within the activity, the following aspects were investigated regarding Ni-base alloys processed by LPBF:

- Factors influencing the material anisotropy
- Correlation of fatigue properties with data recorded by an optical tomography system
- Effect of heat treatment temperature of fatigue behaviour of Inconel 718

In the following sections, the research activities are illustrated in more detail.

3.1 Factors influencing material anisotropy

Tensile testing of Ni-base super alloys as well as stainless steel 316L processed by LPBF resulted in anisotropic material behaviour with significantly lower strength values perpendicular to the build direction of the samples. Additionally, the tested samples exhibit in general a non-negligible ovalisation of the fracture surface, when the specimen is tested parallel to the build direction (see Figure 6).

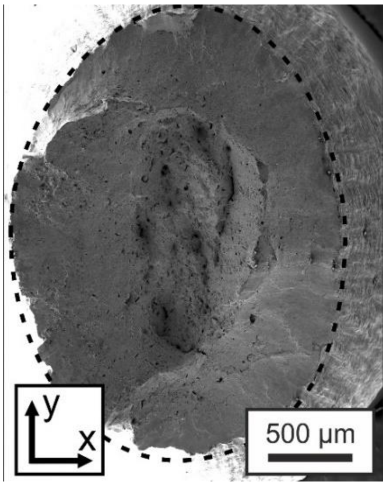


Figure 6: Ovalisation of fracture surface of Hastelloy X tensile test specimen [2]

An in-depth investigation of the operating parameters applied during the LPBF process allowed to explain this anisotropy with the varying orientation of the stripe angles used during the layer-wise build-up of the part [2]. Figure 7 illustrates the correlation of the process with the stripe angles: In the LPBF system used at ArianeGroup, the recoater moves perpendicularly to the Argon shielding gas flow across the powder bed. To achieve a most homogeneous crystal structure, the scan vectors are varied by a certain degree after each layer. However, there is a certain range of stripe angles which is not feasible with this machine setup to minimise the interaction of the fusion process with potential spatter being emitted from the surface. As a consequence, the melt pool shows an inhomogeneous structure with the observed stripe pattern being dominant in certain directions of the xy-plane (see Figure 7, right). Due to the limitations in the selection of the stripe angles, the xz-plane is characterised by molten pools with high widths and molten pools which are cut in longitudinal direction. In contrast, the yz-plane is characterised by a rather low width of molten pools. The inhomogeneous grain structure and texture leads to an anisotropy in Schmid factors. As the movement of dislocations occurs preferably in directions with high Schmid factors, anisotropic mechanical properties in all three directions can be observed, explaining also the ovalisation of the tensile samples.

DOI: 10.13009/EUCASS2022-4834

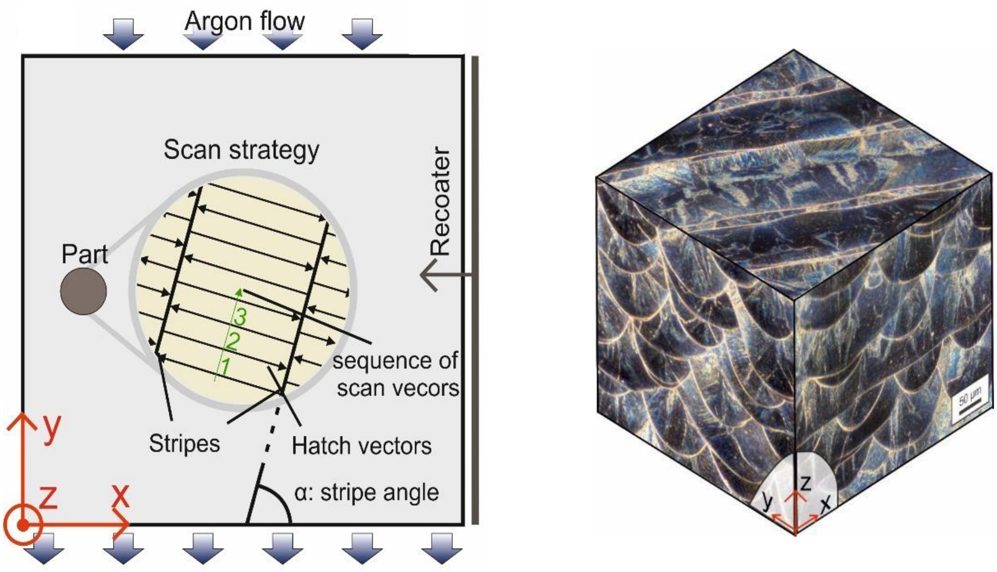


Figure 7: LPBF process illustration (left) and 3D illustration of structure (right) [2]

To counteract this phenomenon, a recrystallization of the alloy can be achieved by using a suitable solution heat treatment. This was also investigated within the context of the TARES2020 program. Figure 8 illustrates the effect of two different heat treatments applied to samples made of the nickel-base super alloy Hastelloy X. Compared to the as-built condition, where a significantly lower strength can be observed in z-direction, the first heat treatment (A) does not yet allow the grain structure to fully recrystallize. Only the second heat treatment (B) results in a uniform strength behaviour along all three main directions. The overall strength level in this case is comparable to the minimum level of the as-built condition.

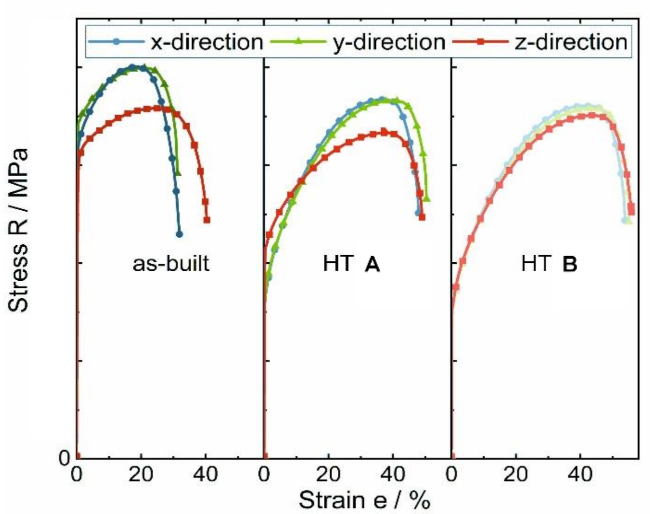


Figure 8: Qualitative effect of solution heat treatment procedures on material anisotropy of LPBF Hastelloy X

The detailed analysis of the scanning strategy during the LPBF process and its effect of the anisotropy of the material properties in combination with the investigation of suitable heat treatments allowed to define a robust process window for the manufacturing of propulsion parts.

3.2 Effect of heat treatment temperature of fatigue behaviour of Inconel 718

Another investigation performed in the scope of the cooperation with the University of Erlangen-Nürnberg focussed on the effect of two different heat treatments for Inconel 718 manufactured in the LPBF process. Inconel 718 is typically heat treated to achieve highest strength levels by the formation of different precipitates, categorized in different phases as illustrated in Figure 9. A discussion of the effect of the different phases can be found in reference [3]. Two different heat treatment temperatures were selected to investigate the effect of the so-called δ-phase on the

DOI: 10.13009/EUCASS2022-4834

fatigue behaviour of the alloy. The first heat treatment was performed at a temperature of 960 °C ("WB960"). To fully dissolve the δ-phase, the second solution heat treatment was performed at 1000 °C ("WB1000"). Figure 10 compares the fatigue behaviour of the two different heat treated LPBF materials with conventionally cast-forged Inconel 718. The Woehler curve shows that for the two LBPF alloys, a decrease in fatigue life exists for the entire load range. Obviously, the fatigue behaviour is not influenced significantly by the existence of the δ-phase. Instead, microsections of the fracture surfaces showed that for the LPBF samples crack initiation and propagation were driven by the presence of pores or unmolten particles (see Figure 11), whereas for the reference materials the fracture occurred along brittle phases. Most likely, this explains the observed reduction in fatigue life of Inconel 718 made by LPBF.

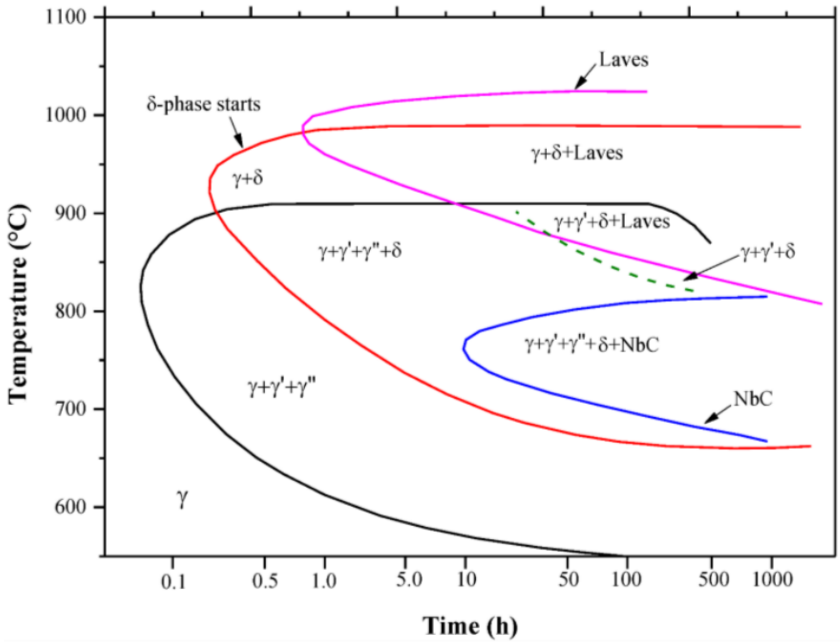


Figure 9: Phase transformation of precipitates in Inconel 718 as function of time and heat treatment temperature [3]

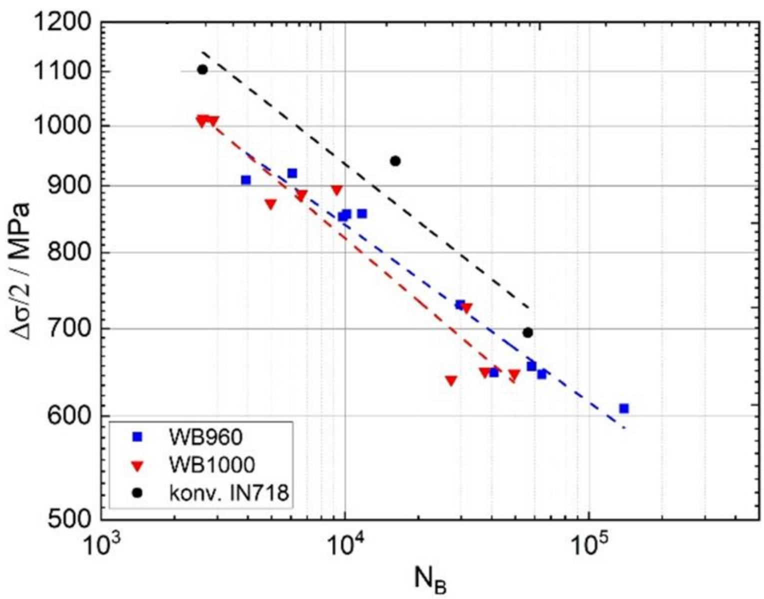


Figure 10: Woehler diagram for Inconel 718 in different heat treatment conditions

DOI: 10.13009/EUCASS2022-4834

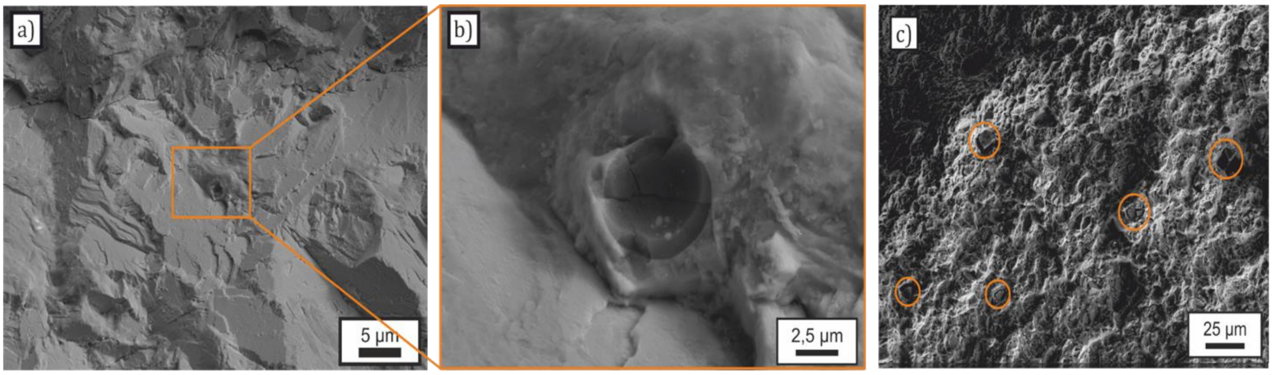


Figure 11: Fracture surface of LBPF Inconel 718 after fatigue testing; a) individual unmolten particle; b) magnification of a); c) exemplary distribution of unmolten particles

3.3 Correlation of OT monitoring results with fatigue properties

A third example of the investigations around the process chain of additive manufacturing illustrates the correlation of indications of a process monitoring system with results of high-cycle fatigue tests performed at the University of Erlangen-Nürnberg.

At ArianeGroup, Hastelloy-X is being processed on an EOS M290 LPBF machine. The system is equipped with a so-called "Optical Tomography" (OT) setup, which allows monitoring the thermal emission profile of the build platform and identifying areas of temperature anomalies, which may be caused by local overheating (hot spots). Fatigue samples were taken from different positions on the build platform, which are known to be prone to an increased number of anomalies indicated by the OT, and compared to samples from the centre of the platform, where anomalies are typically rare. Figure 12 illustrates where on the build platform the samples were taken and presents the HCF results achieved with a loading ratio of R = 0.1 at ambient temperature. Obviously, the samples taken from areas with an increased number of OT indications stand out with significantly decreased fatigue life properties in the Woehler curve shown in Figure 12. Electron scanning microscopy images of the fracture surfaces gave evidence of the fact that open pores or lack-of-fusion defects are responsible for the early initiation of cracks. Consequently, the OT system can now be calibrated as reliable tool to predict the material behaviour of LPBF manufactured Hastelloy X.

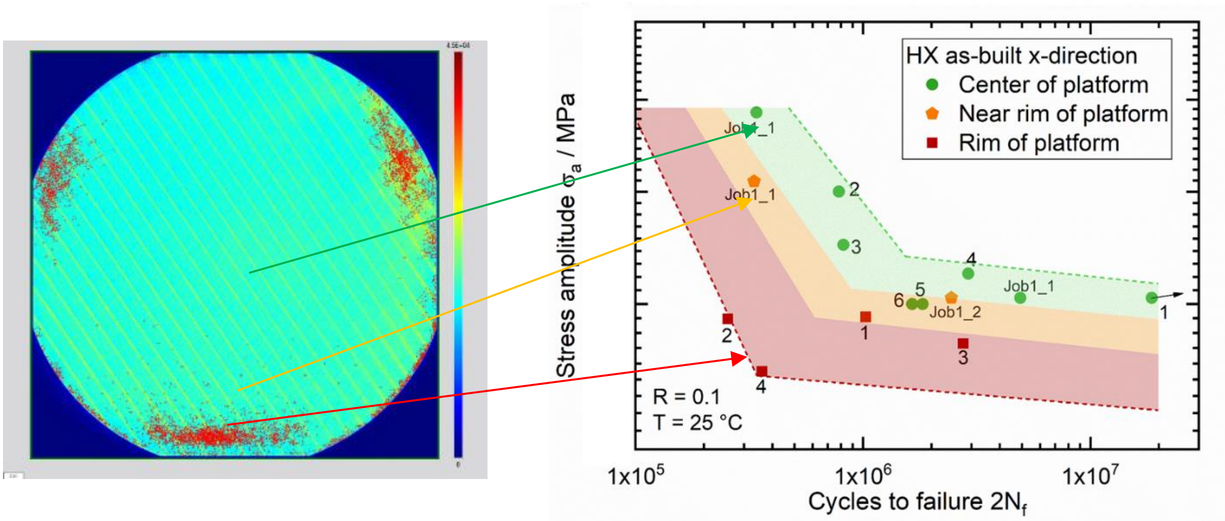


Figure 12: Correlation of OT images with high cycle fatigue results

DOI: 10.13009/EUCASS2022-4834

4 Investigations for LOX/CH4 combustion chambers

A significant amount of effort was spent on addressing key issues linked to the use of liquefied natural gas or methane as rocket fuel. For example, different ignition systems were benchmarked in a test campaign at representative transient start up conditions in a subscale test campaign. In a joint R&T activity with CNES, a test campaign was performed to characterise the heat transfer characteristics of methane in sub- and transcritical operating conditions. Data were used to validate design tools in use at Arianegroup and scrutinised with respect to the effect of the so-called heat transfer deterioration, which is expected to occur if the coolant flow conditions inside the cooling channel approach the critical point of the fluid.

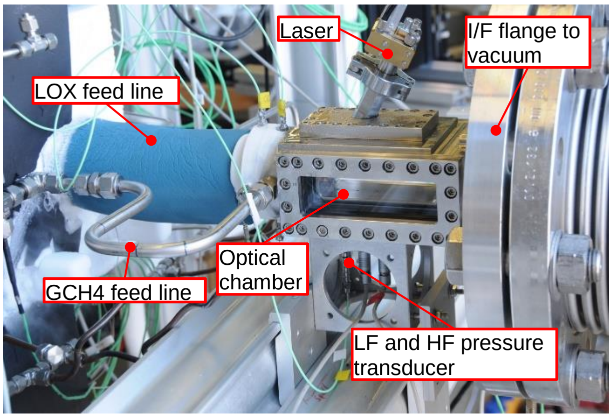
4.1 Ignition Systems

For future cost efficient and lightweight propulsion systems, laser ignition systems provide a number of benefits compared to state-of-the-art gas torch igniters. Operating without a high pressure gas feed system, a laser ignition system is easier to install and handle on the propulsion system and provides significant benefit in terms of system mass. Within TARES2020, basic research activities investigated the applicability of laser plasma breakdown ignition (LPI) as well as laser ablative ignition (LAI) configurations. A more detailed presentation of the experimental setups used and the results obtained can be found in [1].

Following the results published by Börner et al. on the ignition of LOX/CH4 mixtures in coax-shear injector configurations, ArianeGroup performed a joint test activity with CNES to investigate the robustness of LPI in a subscale injector setup. The tests investigated the pressure build-up during the ignition transient under the influence of preconditioning the chamber and a variation of the propellant mass flow rates and to assess the robustness of the setup against a variation of the exact position of the focus spot of the laser. A total of 36 ignition tests were performed, all of which resulted in a successful ignition of the chamber. In some cases, in which the propellant supply system could not provide adequate mass flow rates to stabilise combustion and anchor the flame at the injector, combustion extinguished after initial ignition. From this it can be concluded that the laser ignition system provides a reliable, robust and reusable ignition system not only for LOX/H2, but also for LOX/CH4 liquid rocket engines.

A next step towards the application of a laser ignition system in an actual full scale engine was taken with a series of experiments which investigated the applicability of a LAI and LPI to a so-called high mass flow injector, as it is used in the PROMETHEUS[1] engine demonstrator. To investigate the general feasibility of this technology, research activities were performed to tune the laser ignition system to the PROMETHEUS injector configuration and to investigate the minimum pulse energy required to safely ignite the combustion chamber. First experiments were performed in a single-element setup using DLR's M3.1 test facility in Lampoldshausen, which also allows investigating the setup at reduced ambient conditions down to 50 mbar. The setup was used to investigate a LAI concept as well as a LPI concept.

Figure 13 shows the setup installed for run-in tests. The LOX feed line is equipped with an LN2 jacket cooling to provide LOX at relevant injection conditions during the ignition transient. The LAI configuration was installed with the focus being pointed at the injector's fuel sleeve (see). Low- and High-frequency pressure transducers were used to record the chamber pressure during ignition. To be able to mimic ignition at altitude conditions, the optical chamber was connected to a vacuum tank at M3.1. High-speed imaging was used to record Schlieren images and collect information on the OH* emission.



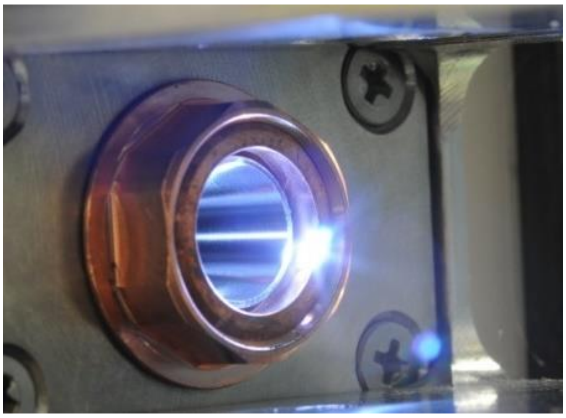


Figure 13: Ablative LIS setup installed at M3 (left), location of ablation on injector fuel sleeve (right)

[1] PROMETHEUS is a registered trademark owned by ArianeGroup

DOI: 10.13009/EUCASS2022-4834

The theoretical mixture ratio at ignition was estimated to range from 1.0 to 5.0, depending on oxygen lead and backpressure. To take into account different phases during a mission scenario for a reusable booster engine, ignition tests were performed at a chamber pressure of 100 mbar, 1 bar and 2 bar, respectively. As additional parameter, the pulse energy of the laser was varied during the tests to investigate the minimum pulse energy to reliably initiate combustion. Using different transmission filters, the pulse energy was reduced successfully from nominally 33 mJ down to 9 mJ with the LAI configuration.

The results of the single element laser ignition tests were used subsequently to investigate effects of scaling up to a more relevant size of engine. In 2020, ArianeGroup performed a subscale test campaign on the P8 research test facility in Lampoldshausen, using a 36 element injector with a chamber diameter of 180 mm. The setup used two laser ignition systems to characterise both the ablative ignition and the plasma-breakdown. The overall injector and the position of the individual elements which were targeted for laser ignition are illustrated in Figure 14. During this campaign, the LPI was tested for its robustness against a radial shift in the position of the focus spot. For the ablative laser ignition setup, the configuration was identical to the M3.1 setup. Using the pressure and mass flow control valves in the bench's propellant supply system, the pressure profile in the injector was tuned to mimic a flight-like start-up. LOX was injected at around 90 K; CH4 was injected after having passed the cooling circuit of the combustion chamber.

In total, 21 ignition attempts were performed with this setup, 13 with the plasma breakdowns system (LPI) and eight with the ablative configuration (LAI). Each of the LPI tests resulted in a successful ignition. For the LAI, only 4 resulted in a successful ignition of combustion. Data indicate that the ablative configuration is more sensitive against changes or perturbations of the flow field close to the injector during the ignition transient.
After the tests, data of the pressure evolution in the injector were compared to unsteady simulations. Figure 15 shows a superposition of test data with simulation results to match the ordinate scale. The two different axes of abscissae have been scaled for identical spacing but offset against each other to more easily asses the pressure build-up in the chamber.

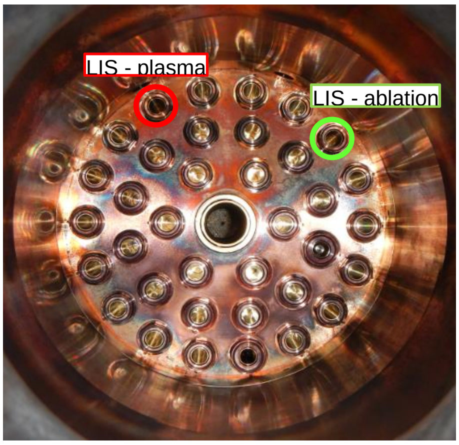


Figure 14: Subscale injector setup used for laser ignition experiments with high mass flow injectors

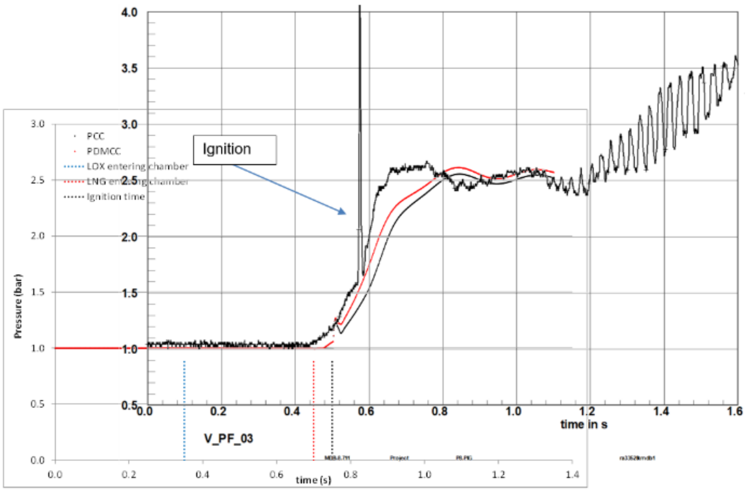


Figure 15: Comparison of transient simulations with test data recorded

DOI: 10.13009/EUCASS2022-4834

4.2 Heat Transfer Phenomena

Another field of research at ArianeGroup is the management of cooling circuits of combustion chambers using methane as coolant in operating conditions with transcritical or subcritical pressure. In these operating conditions, two phenomena need to be mastered: Two phase flow and heat flux deterioration.

When using hydrocarbon fuels or storable propellants as coolant, the operating conditions inside the cooling channel of the combustion chamber may result in pressure levels where two-phase flow can occur due to the heat input. For typical engine cycles of launcher first stages like gas generator cycle or staged combustion cycle, this phenomenon is only to be taken into account during mission phases with throttled operating conditions, as they may occur in reusable systems during landing. Nevertheless, it needs to be well mastered in order to guarantee a reliable and predictable operation of the propulsion system during the entire mission. Another aspect to be taken into account in methane-cooled engines is the so-called "heat transfer deterioration". This term describes a phenomenon which is caused by the drastic change in thermal and transport properties of fluids close to the critical point in the supercritical regime. Here, no phase change is to be expected. However, if the fluid is heated at supercritical pressure close to the critical point, the fluid's density, specific heat and thermal conductivity feature steep gradients. In CFD simulations, this behaviour results in the formation of an isolating boundary layer inside the cooling channel, which drastically limits the cooling performance. Figure 16 illustrates this in a simulation of a subscale setup: In areas with heat flux deterioration, a hot boundary layer forms inside the cooling channel (see Figure 16, left). Due to the limited cooling capability in this area, the wall temperature increases locally (see Figure 16, right). The simulation results in Figure 16 not only show the typical increase in wall temperature in the convergent section of the combustion chamber towards the throat, but also an area of very high wall temperatures upstream in the cylindrical section, caused by the heat transfer deterioration.

To validate the numerical model describing this phenomenon, only limited data from engine test was available; therefore, it was decided to perform a dedicated test campaign to investigate the cooling behaviour of methane.
With the support of CNES and DLR, ArianeGroup performed a Franco-German test campaign in a cooperation of the projects BOREAS and TARES2020. The tests used an injector head provided by ArianeGroup Vernon in combination with a subscale combustion chamber from ArianeGroup in Ottobrunn. Focus of the experiments was the variation of operating conditions of the cooling circuit. During the tests, supercritical as well as subcritical operating conditions were realised. Figure 17 shows the operating conditions of the coolant circuit in a T-s-diagram. During the tests, the pressure at the inlet of the coolant circuit was reduced from initially 173 bar down to 40 bar with an inlet temperature ranging from 135 K to 142 K, covering the entire range of interest. In Figure 17, coloured squares indicate the measured outlet conditions of the coolant circuit during different tests. The corresponding solid lines illustrate the expected evolution of the fluid properties inside the cooling channel using ArianeGroup's RCFS-II tool, which uses one-dimensional correlations to predict the flow in cooling channels of rocket combustion chambers.

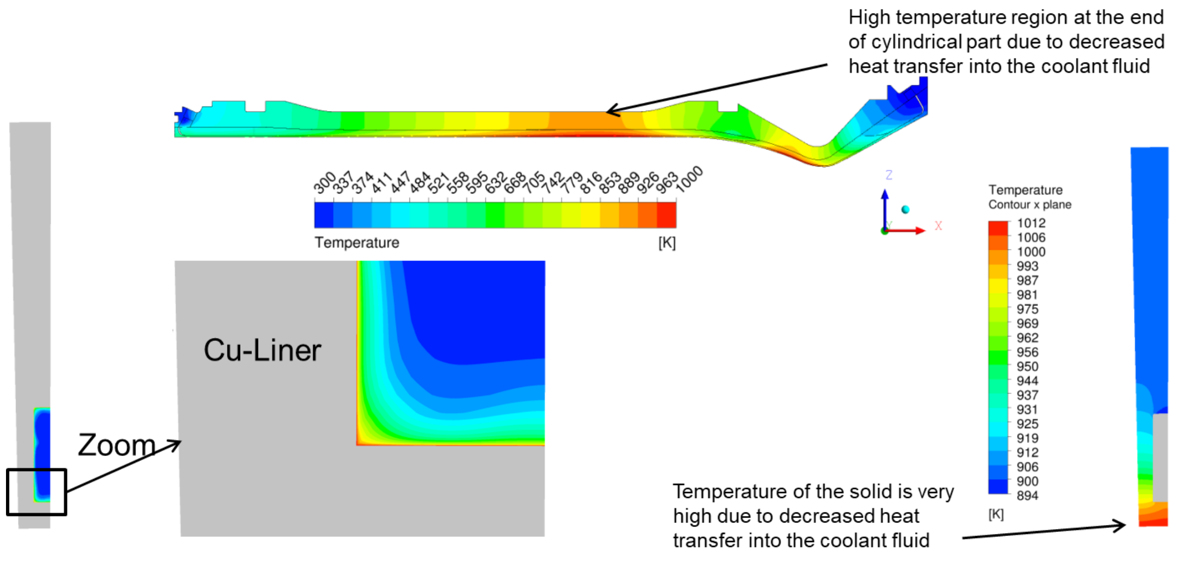


Figure 16: Simulation of heat transfer deterioration in rocket combustion chamber: Fluid temperature (bottom left) and structure temperature (top and bottom right)

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A comparison of CFD simulation results with experimental data is shown in Figure 18. The individual data points shown have been recorded with surface thermocouples on the outer surface of the model combustor, i.e. on the jacket made of electrodeposited Nickel. The simulation results, shown with the solid line, have been calculated using a conjugate heat transfer analysis. In this, the combustion process was calculated with ArianeGroup's Rocflam3, while the conduction of heat in the combustion chamber wall and the flow inside the cooling channel was modelled using Ansys CFX. Unfortunately, the experimental setup does not allow to measure the structural temperature on the combustion chamber wall.

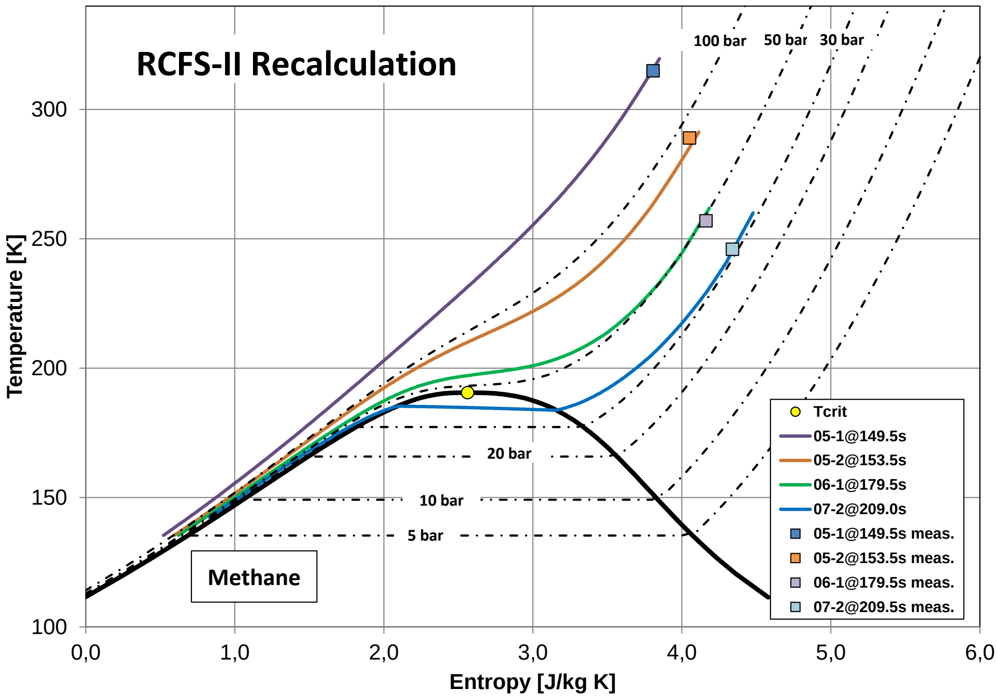

Figure 17: T-s diagram of coolant circuit operating conditions realised in joint BOREAS/TRARES2020 test

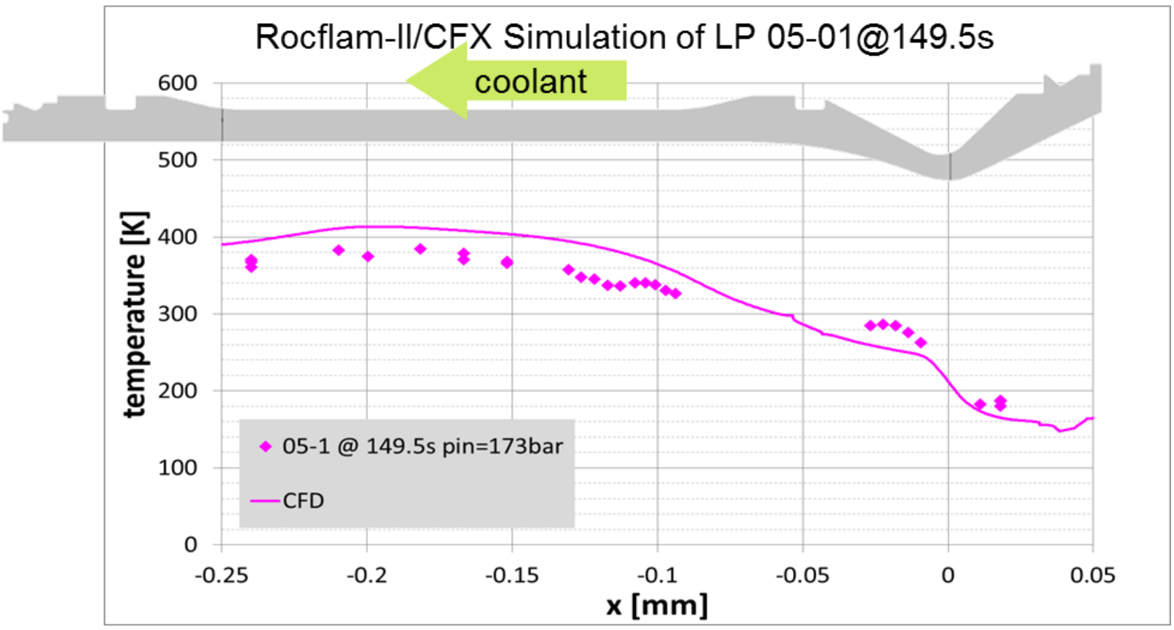

Figure 18: Comparison of simulation and test data for wall temperature on outer shell of model combustor

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5 Scientific Network

In all of these fields, a regular exchange of results and alignment of future research activities has been performed with the research centres of DLR within the cooperation Propulsion 2025. Likewise the contribution to research networks like the French-German REST group or the German SFB Transregio 40 is to be mentioned. This fruitful exchange with universities and academia ensures the high level of research in combination with an orientation towards the application on future space engine systems.

5.1 DFG Sonderforschungsbereich Transregio 40

ArianeGroup acted as industrial member of a research consortium in a so called “Transregio” project funded by the German research Foundation (Deutsche Forschungsgesellschaft, DFG). The project TRR 40 was dedicated to the investigation of fundamental technologies for the development of future space transport system components under high thermal and mechanical loads [4]. The consortium comprised researchers from the Technical University of Munich, the University of Braunschweig, Rheinisch-Westfälische-Technische Hochschule Aachen, University of Stuttgart and Universität der Bundeswehr München. Additionally, the Institute of Space Propulsion of DLR was a member of the consortium.

Within the project, ArianeGroup contributed with the definition of so called “virtual thrust chamber demonstrators”, which set the requirements for the validation of the different modelling and experimental activities performed in the various sub-tasks of TRR40. Three different use cases were defined:

- **TCD1** Thrust chamber of an upper stage expander cycle engine using LOX/H2 as propellant combination; for this demonstrator, the potential to reduce the combustion chamber length by improving the heat transfer to the coolant circuit was investigated.
- **TCD2** Thrust chamber of a 1000 kN LOX/H2 gas generator cycle engine; research activities addressed the potential to reduce the total pressure loss in the cooling circuit and injection system in order to relax performance requirements for the turbomachinery. Studies focussed on the assessment of combustion stability and additional measures to reduce the heat input to the cooling circuit, such as thermal barrier coatings or film cooling
- **TCD3** Thrust chamber of a 1000 kN engine using the gas generator cycle with either LOX/CH4 or LOX/H2; the focus in this demonstrator was on the design of a cooling circuit and injector system which provides a robust operation for both fuels, hydrogen and methane.

As an example of ArianeGroup’s contribution to TCD1, ArianeGroup investigated the effect of different injector patterns on the wall temperature profile along the chamber wall. Simulations were performed by coupling the Rocflam3 code for the combustion process with an Ansys CFX model to simulate the heat transfer to the cooling channel and the conduction of heat within the structure. Figure 19 compares two wall temperature profiles for different injector configurations. The different colours indicate the radial position of the virtual temperature measurement, e.g. red at the hot gas wall, blue at the bottom of the cooling channel. Due to the fact that the 3D-simulations resolved the injector pattern in circumferential directions, the range of temperature is given (shaded area) as well as the average (solid line). From the example given, one can see that a change in the injector pattern results in a higher overall heat load close to the injector face plate (offering the potential to reduce the chamber length), but also in a significant higher scatter of temperature distribution in circumferential direction.

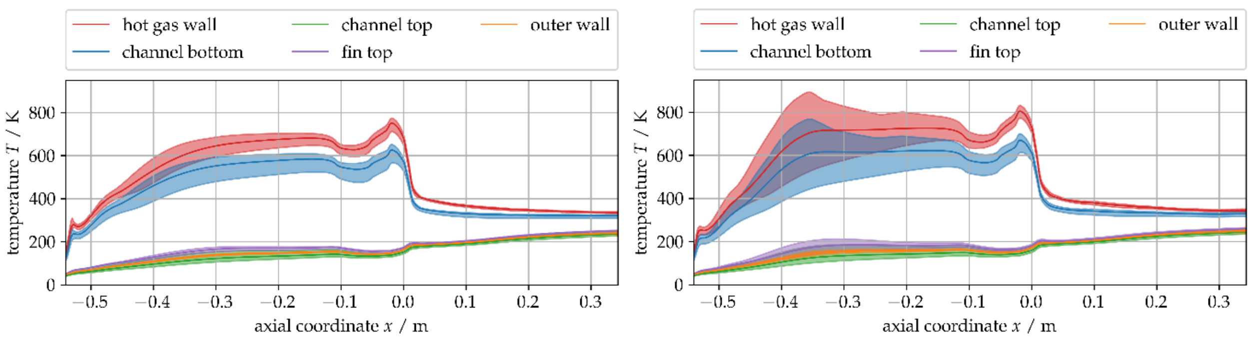

Figure 19: Wall temperature profiles for two different injector configurations in TCD1

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5.2 Propulsion 2025

Within the scope of a framework agreement between DLR and ArianeGroup, a research cooperation called “Propulsion 2025” is dedicated to the alignment of individual research activities in different domains related to liquid rocket propulsion engines. Each of the parties has full responsibility for their own research activities. ArianeGroup contributes with expertise from the various departments in Ottobrunn; from DLR, the research institutes of rocket propulsion (Lampoldshausen) and of Aerodynamics and Flow Technology (Göttingen) contribute to the exchange. During bi-annual workshops, which are protected by a nondisclosure agreement, results of the partners’ R&T activities are discussed and potential topics for joint R&T activities are identified.

Within Propulsion 2025, the following research topics are addressed:

- Injectors
- Ignition systems and ignition phenomena
- Heat transfer and regenerative cooling
- Combustion modelling
- Nozzle flow
- Combustion stability
- Life prediction of cyclic loaded structures
- Turbomachinery

Recent examples for the cooperation in this field are investigations on ignition phenomena using laser ignition systems, joint analysis of heat transfer phenomena in cooling circuits like the aforementioned heat transfer deterioration or the investigation of flow separation phenomena of exhaust nozzles and the interaction of the exhaust jet with the surrounding test facility installations. Tests were performed by DLR on the P6 test facility using gaseous nitrogen. The different test configurations aimed at investigating the effect of the geometry of the exhaust duct guide tube as well as the effect of several measures to counteract oscillations, such as chevrons at the exit of the nozzle or baffles in the guide tube (see Figure 20).

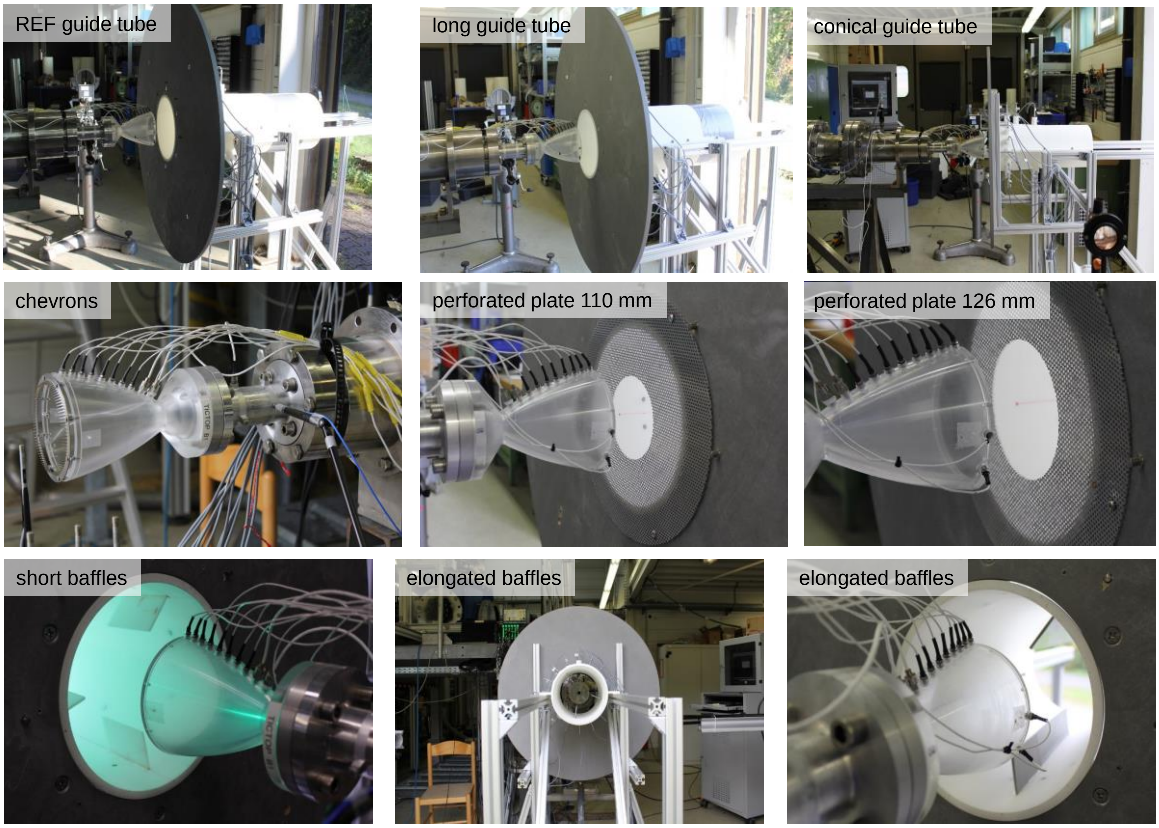

Figure 20: Nozzle and guide tube configurations investigated by DLR

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5.3 REST Working Group

The REST stability working group provides a platform for the cooperation of French and German research institutes and universities dedicated to the modelling of high frequency combustion instabilities in liquid rocket engines. The following partners participate in the REST working group:

- ArianeGroup
- Institute of Thermodynamics TU München
- ONERA Office national d'études et de recherches aérospatiales
- CERFACS Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique
- ECP École Centrale Paris
- IMFT Institut de Mécanique des Fluides Toulouse
- CORIA Université de Rouen
- CNES Centre national d’études spatiales
- DLR Institute for rocket propulsion

An example of the joint research activities in this area is a modelling test case, which was defined jointly in the working group. The test case describes a single element coaxial shear injector being operated with liquid oxygen (LOX) and methane as fuel (see Figure 21).

The following operating conditions were selected for the simulations: Combustion chamber pressure pc = 100 bar, fuel injection with $\dot{m}_{\text{fuel}}$ = 0,136 kg/s, T_{fuel} = 231 K, LOX injection with $\dot{m}_{\text{LOX}}$ = 0.460 kg/s, T_{LOX} = 100 K. The numerical studies investigated the effect of a forced mass flow excitation of ±10% of oxidiser and fuel, respectively. The frequency of the fuel mass flow excitation was set to 5 kHz; for LOX, excitation frequencies of 5 kHz and 1 kHz were investigated.

ArianeGroup used Ansys CFX for the simulations. The simulations used a structured grid with 3,5 million cells. The combustion was modelled using a one-step eddy-dissipation model with an additional Arrhenius factor and a limiter for the maximum temperature. Oxygen was modelled as real gas, while methane and the combustion products were modelled as ideal gas. With this rather simple and cost efficient approach, ArianeGroup achieved the simulation results which are exemplarily shown in Figure 22. The image compares the time-averaged temperature profile in the combustion chamber for the different excitation modes (no excitation, 1 kHz on LOX, 5 kHz on LOX, 5 kHz on fuel). Whereas the temperature field is not significantly affected by the fuel mass flow modulation, the modulation of the oxidiser mass flow results in a significant reduction of the flame front. Detailed results together with a comparison with the other partners’ results can be found in [5], [6], and [7].

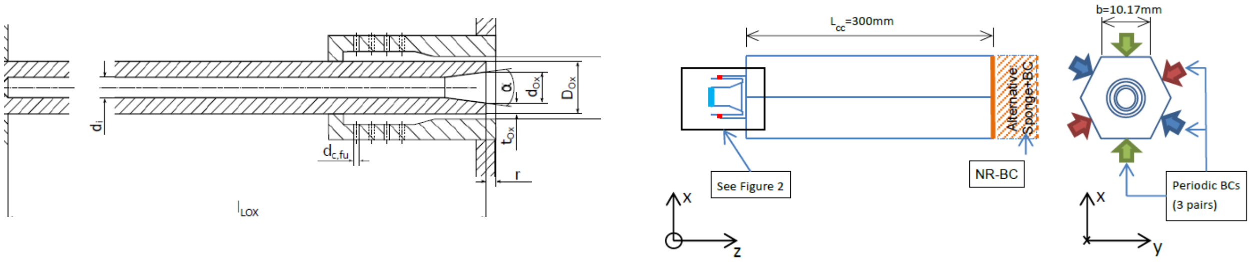

Figure 21: REST single injector test case

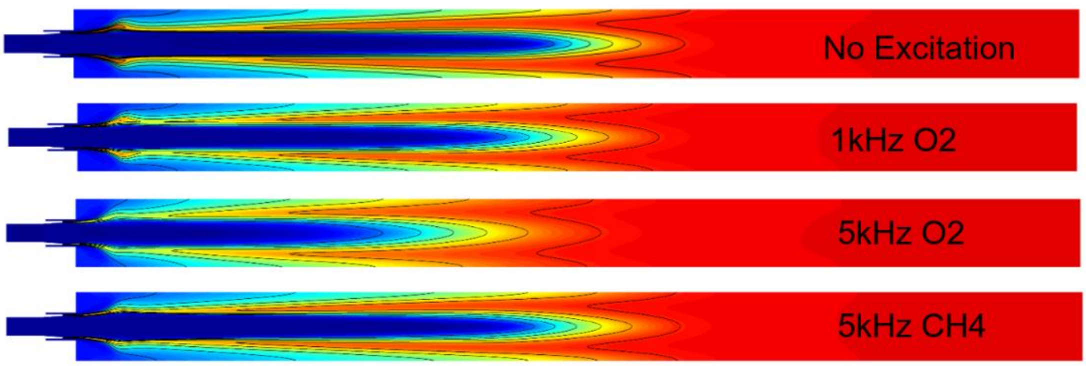

Figure 22: Temperature profiles calculated for different excitation modes

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6 Summary

Within a federal grant project, supported by the German Space Agency DLR, research and technology investigations were performed in the domain of liquid rocket engine propulsion. The activities focussed on the key products developed and manufactured by ArianeGroup at its site of Ottobrunn, namely fluid control equipment and thrust chamber assemblies. Theoretical and numerical investigations addressed the performance of seals in cryogenic valves, injection and ignition systems for cryogenic propellants, modelling strategies for combustion and heat transfer management in combustion chambers as well as materials and processes for manufacturing of the individual components. While several tasks addressed dedicated topics of additive manufacturing, also classical manufacturing technologies were considered.
All research activities at ArianeGroup are embedded into a R&T strategy, which puts strong emphasis on a network with research institutes and universities. This was reflected by numerous activities which were performed in cooperation with universities and research centres of DLR and the Fraunhofer Gesellschaft.
The results of the investigations are building blocks for the development of future launcher propulsion subsystems and are used by development programs such as the various FLPP programs like PROMETHEUS or SPE.

7 Acknowledgements

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The cooperation with CNES in the field of LOX/CH4 propulsion, especially by performing a joint test campaign at P8, is highly appreciated.

A special acknowledgement is given to Universities in Munich, Aachen and Erlangen as well as to the DLR research institutes in Lampoldshausen and Göttingen for the fruitful and open-minded fruitful cooperation.

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