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SCIENCE DIRECT

ACTA ASTRONAUTICA

Acta Astronautica 53 (2003) 597–605

www.elsevier.com/locate/actaastro

TECHNOLOGY DEVELOPMENTS FOR THRUST CHAMBERS OF FUTURE LAUNCH VEHICLE LIQUID ROCKET ENGINES

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ABSTRACT

In this paper an overview of recent technology developments for thrust chambers of future launch vehicle liquid rocket engines at Astrium, Space Infrastructure Division (SI), is shown.

The main technology developments shown in this paper are:

- Technologies for enhanced heat transfer to the coolant for expander cycle engines
- Advanced injector head technologies
- Advanced combustion chamber manufacturing technologies.

The main technologies for *enhanced heat transfer* investigated by subscale chamber hot-firing tests are:

- Increase of chamber length
- Hot gas side ribs in the chamber
- Artificially increased surface roughness.

The developments for *advanced injector head technologies* were focused on the design of a new modular subscale chamber injector head. This injector head allows for an easy exchange of different injection elements. By this, cost effective hot-fire tests with different injection element concepts can be performed.

The developments for *advanced combustion chamber manufacturing technologies* are based on subscale chamber tests with a new design of the Astrium subscale chamber. The subscale chamber has been modified by introduction of a segmented cooled cylindrical section which gives the possibility to test different manufacturing concepts for cooled chamber technologies by exchanging the individual segments. The main technology efforts versus advanced manufacturing technologies shown in this paper are:

- Soldering techniques
- Thermal barrier coatings for increased chamber life.

A new technology effort is dedicated especially to LOX/Hydrocarbon propellant combinations. Recent hot fire tests on the subscale chamber with Kerosene and Methane as fuel have already been performed. A comprehensive engine system trade-off between the both propellant combinations (Kerosene vs. Methane) is presently under preparation.

1. INTRODUCTION

Since 1996 major technology programs for liquid rocket engines are being performed by Astrium under sponsorship of the German Aeropspace Research Center DLR. The technology program TEKAN (1996 to 2000) was focused on technologies for cryogenic liquid rocket engines [1], the follow-on technology program ASTRA-propulsion (since 2000) is focused on technology developments for cryogenic as well as for LOX hydrocarbon liquid rocket engines for future launch vehicles [2].

Both programs are performed in close cooperation with the DLR Institute of Space Propulsion Lampoldshausen. Above all, the test bench P8 at DLR in Lampoldshausen is used for hot-fire tests of the new technologies at subscale chamber level under representative conditions.

The main objective of these technology programs is the development of the technologies for the next generation of expendable and reusable liquid rocket engines.

For expendable rocket engines the main technology efforts are focused on low-cost manufacturing technologies and on advanced thrust chamber designs meeting the performance requirements. For reusable rocket engines new thrust chamber technologies have to be developed in order to meet the high performance and the long lifetime requirements at reasonable cost.

The present technology programs are an important step to prepare the development of advanced rocket engines for the next generation of launch vehicles.

0094-5765/03/$ - see front matter © 2003 Published by Elsevier Science Ltd.
doi: 10.1016/S0094-5765(03)00166-8

2. TECHNOLOGIES FOR ENHANCED HEAT TRANSFER

2.1 Rationale

An expander cycle engine needs a design that provides as much heat input to the coolant as possible and at the same time keeps the necessary coolant pressure drop as low as possible. Since 1996 considerable efforts have been undertaken by Astrium to develop technologies for enhanced heat transfer to the coolant for future application in expander cycle engines.

Detailed cycle and cooling analyses for expander cycle engines [3] for an upper stage application in Ariane 5 have shown that the most efficient and most straightforward design measure for increased heat transfer is the increase of the hot gas wall surface in the thrust chamber. For that reason the main focus of the technology developments at Astrium was concentrated on designs allowing an increase of the hot gas wall surface of the combustion chamber. In order to provide a maximum heat transfer capability to the coolant hydrogen, highly conductive copper-alloy chamber liners with enhanced propellant heating features based on the in-house experience with integral chambers have been baselined.

The following concepts for enhanced heat transfer to the coolant have been selected and investigated experimentally by comprehensive subscale chamber hot-fire tests:

- increase of hot gas wall surface by increased length of chamber cylinder
- increase of hot gas wall surface by hot gas wall ribs
- enhancement of heat transfer by increased surface roughness

The idea to investigate the effect of increased surface roughness as a means for heat transfer enhancement was based on the test experience with subscale and full scale thrust chambers. The relevant test experience has revealed an increased heat transfer to the coolant over life time which can be attributed to the increased surface roughness due to aging of the hot gas wall surface.

All hot-fire tests reported here have been performed with the Astrium subscale chamber [4], [5] shown in Fig. 2.1. This chamber consists of three parts, the injector head, a cylindrical water-cooled section with an inner diameter of 80 mm and a water-cooled nozzle with a throat diameter of 50.6 mm. The total length of the combustor (from injector face plate to nozzle exit) amounts to 409 mm and includes a 20 mm long igniter ring flanged between the injector and the cylindrical, water-cooled section.

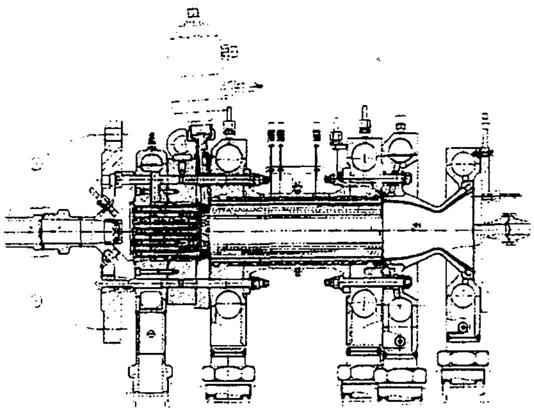


Fig. 2.1 Astrium subscale chamber

An injector consisting of 19 co-axial injection elements was employed in all tests. The injection element pattern is shown in Fig. 2.2. A schematic of the co-axial injection element configuration designed for the propellant combination gaseous hydrogen and gaseous oxygen is given in Fig. 2.3.

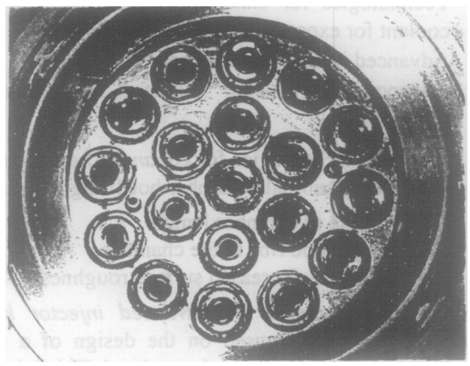


Fig. 2.2 Injection element pattern of subscale chamber

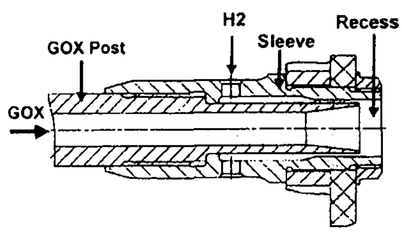


Fig. 2.3 Schematic of co-axial injection element configuration

2.2 Increased Length of Chamber Cylinder

A simple means to increase the hot gas wall surface in order to enhance the heat transfer to the coolant is an increase of the length of the cylindrical part of the combustion chamber. This allows to maintain the well proven manufacturing process of Astrium for integral chambers with milled coolant channels in a highly conductive copper alloy chamber liner with an electrodeposited Nickel outer closure.

In order to investigate the influence of a considerably increased chamber length on the axial evolution of the heat transfer to the coolant subscale chamber tests with a doubled length of the cylindrical part of the chamber have been performed as shown in Fig. 2.4.

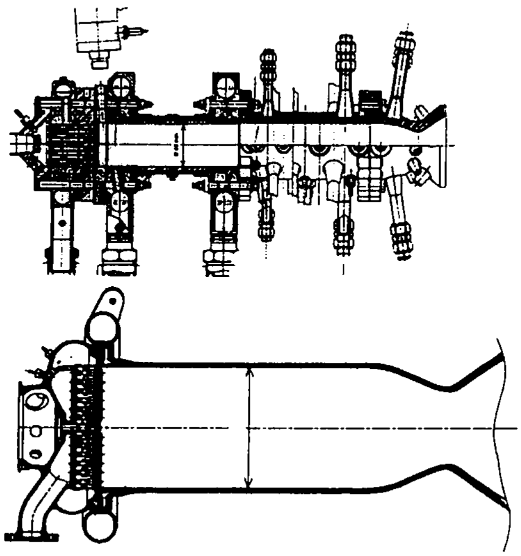


Fig. 2.4 *Upper part*: Subscale chamber with doubled length of cylindrical part, second part of cylinder and throat section: calorimeter chamber
Lower part: Full scale chamber (VINCI concept, status 1999)

Two chamber cylinders have been combined resulting in a length of about 500 mm of the cylindrical part. In order to measure the axial evolution of the heat transfer the downstream half of the cylindrical part of the subscale chamber consisted of the calorimeter subscale chamber [6] which measures the axial heat transfer by 11 water-cooled cylindrical segments. For comparison the full scale combustion chamber of the VINCI expander cycle engine is shown which makes use of an increased chamber length for enhanced heat transfer to the coolant, the length of the cylindrical part is similar to the length of the (doubled) subscale chamber length shown in Fig. 2.4.

The subscale tests have been performed on the F3 test bench of Astrium located in Ottobrunn. The propellants are gaseous hydrogen and gaseous oxygen. The mass flow was adjusted to chamber pressures between 10 and 40 bar, the mixture ratio was varied from 5 to 7.

The measured evolution of the heat transfer to the coolant (water for the subscale tests) is shown in Fig. 2.5. The evolution of the heat transfer of the first cylindrical part (which consisted in these tests of a part with axial coolant channels) was derived from former measurements under same conditions with the calorimeter chamber.

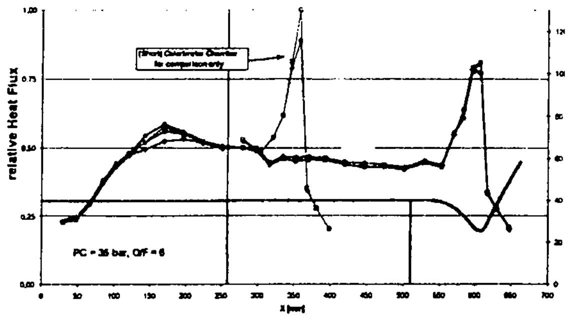


Fig. 2.5 Measured heat transfer to subscale chamber with doubled cylinder length. (red line: results for short calorimeter chamber for comparison)

The slight decrease of the heat transfer in the axial direction is caused mainly by the increase of the boundary layer thickness in axial direction.

Further tests with the same subscale chamber configuration have been performed at the P8 test facility in Lampoldshausen. In these tests liquid oxygen and gaseous hydrogen representative for the injection conditions of the VINCI engine have been tested with chamber pressures up to 70 bar.

These tests gave valuable inputs for the validation of the Astrium combustion simulation tool CryoRoc [7] thus allowing to predict the influence of an increased chamber length on the heat transfer enhancement.

2.3 Enhanced Heat Transfer by Ribs

The greatest effort for enhancement of the heat transfer was dedicated to the design of axially oriented cooled or uncooled ribs in the hot gas wall of the cylindrical part of the combustion chamber. The cylindrical part of the subscale chamber was manufactured with altogether 8 different rib designs shown in Fig. 2.6. The results of the experimental program with the subscale chamber with altogether 8 different rib configurations have been reported in [4] and [5].

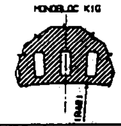
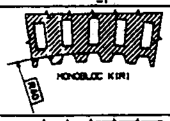
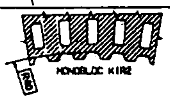
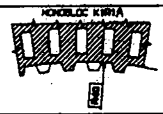
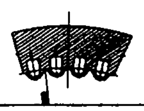
Configuration	Rib Type	Surface Area Increase	No. of Coolant Channels
	1	0% (Reference)	86
	2	41%	86
	3	30%	86
	4	21%	86
	5	30%	86
	6	35%	48
	7	35%	48
	8	29%	48

Fig. 2.6 Overview of different rib configurations investigated in subscale chamber hot-fire tests

The tests on the F3 test bench with gaseous hydrogen and gaseous oxygen as propellants with chamber pressures up to 40 bar have demonstrated the heat enhancement due to the ribbed chamber surface. The maximum heat enhancement was achieved with the large cooled rib (configuration 6) and the simulated tubular hot gas wall surface (conf. 8) and amounts to about 25% compared to the smooth wall (conf. 1).

2.4 Enhanced Heat Transfer by Increased Surface Roughness

Based on the test experience with enhanced heat transfer due to increased surface roughness as a result of a certain aging effect of the hot gas wall surface it was decided to investigate this effect experimentally. The main objective of this investigation was to find a way to manufacture a reproducible, well defined hot gas wall surface roughness and to measure the heat transfer enhancement compared to a smooth wall. All subscale chamber investigations with an increased surface roughness have been applied to the cylindrical part of the subscale chamber with axial coolant channels (conf. 1 in Fig. 2.6).

The increase of the surface roughness is normally caused by the interaction between the combustion flame and the wall. The interpretation for the heat transfer enhancement is that the increasing roughness continuously disturbs the boundary layer leading to higher turbulence which promotes the heat exchange.

The observed degree of this roughness was rather small in the course of the test series at F3 facility due to the short duration of one test sequence (32 s). So it was decided to apply the artificial aging within two steps. From the manufacturing point of view the easiest and fastest possibility was to introduce an M3-thread into the chamber liner (cylindrical part of the subscale chamber made of copper alloy). Figure 2.7 shows an example of the sharp-edged groove shape.

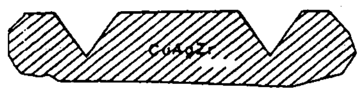


Fig. 2.7 Scheme of sharp-edged groove shape 1

The evaluation of the real liner surfaces showed significant deviations of the shapes compared to the scheme presented above which were mainly caused by manufacturing limitations.

In order to improve the reproducibility of artificial grooves in the hot gas wall surface a new cutting tool with a semi-circular cutting edge made of diamond material was introduced, see Fig. 2.8.

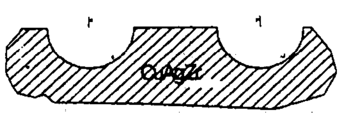


Fig. 2.8 Scheme of semi-circular groove shape 2

The manufacturing results of the newly applied cutting tool were of very good quality as confirmed by surface measurements.

A comprehensive series of screening tests with different number of grooves, i.e. groove distance Δl of shape 1 and 2, applied to the cylindrical part of the subscale chamber, have been performed. The tests were performed at the F3 test bench with gaseous hydrogen and gaseous oxygen as propellants, the test sequence was the same as for the tests with the ribbed configurations (water-cooled cylinder and throat section, chamber pressure variation from 10 to 40 bar, mixture ratio between 5 and 7).

As a result of the screening tests it was decided to continue with a sensitivity analysis how the distance between two grooves influences the heat transfer. For all following investigations the groove type 2 with the semi-circular shape was selected.

Figure 2.9 shows the strong influence of the groove distance on the measured heat transfer increase compared to a smooth wall.

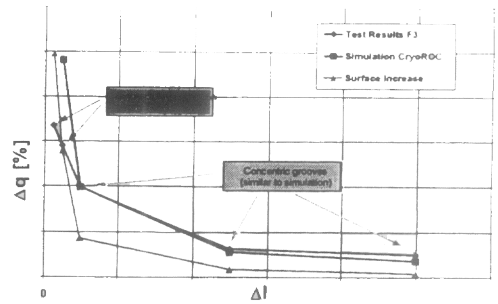


Fig 2.9 Comparison of experimental (F3) and simulated (CryoROC) heat transfer results for different groove differences Δl and measured chamber surface increase

After having evaluated the F3 test results with the different groove distances the simulation tools of Astrium (CryoROC) were adapted in order to improve the possibilities to calculate the heat transfer for such grooved combustion chamber surfaces. Several groove configurations were simulated with the CryoROC code. Once the standard groove configuration (with groove shape 2 as shown in Fig. 2.8) was chosen the distance between two neighbored grooves was varied. The simulation results show a good agreement with the experimental results allowing to predict the heat transfer of grooved surfaces in the future.

Following the results of the adapted simulation tool CryoROC it was discussed to implement the current knowledge into a new test series at P8 facility. This facility enables specimen operation at conditions which are representative for full-scale application of an expander cycle engine with LOX/GH2 adapted injection elements. The calorimeter subscale chamber was used for this test series since it allows for both distinct application of groove groups in segments and direct measurement opportunity to evaluate the effect.

The main objectives of the hot-firing tests with the calorimeter chamber with grooved surface were selected as follows:

- how do groove packages influence the heat transfer?
- how do grooves at different axial positions influence the heat transfer?

The most promising idea was to use the grooves in order to "design" the axial heat transfer in such a way that a nearly constant value along the chamber's x-axis can be achieved. Thus, in the first part of the chamber a fast increase to the so-called plateau value is envisaged. As a consequence, in this region narrow neighbored grooves should be applied. In the plateau region the chamber is already highly loaded so a further heat increase is undesired. Former test campaigns revealed a slight decrease in the heat transfer values along the chamber's x-axis. Here, this decrease shall be avoided by applying grooves but with longer distances than in the first group.

Based on analyses with CryoROC the following groove configuration as shown in Fig. 2.10 was selected for hot-fire tests at the P8 test facility.

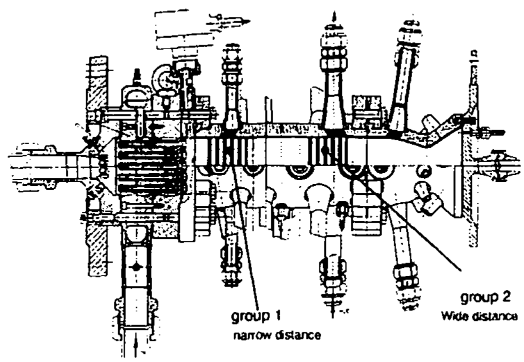


Fig. 2.10 Configuration of grooved calorimeter subscale chamber for P8 tests

The test results of this campaign are compared for the load case p_c=60 bar and O/F=6.0 since for these operational conditions the most measurement data exist with the smooth (ungrooved) liner surface. Figure 2.11 shows the measured heat flux evolution for the smooth and for the grooved cylinder surface of the calorimeter chamber.

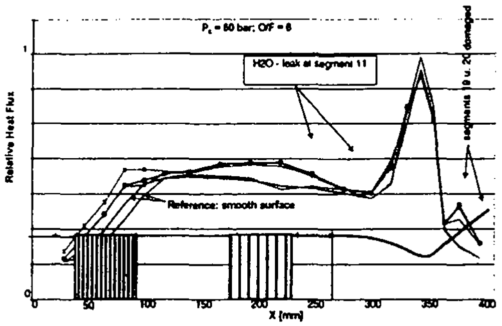


Fig. 2.11 Heat flux comparison of P8 grooved chamber test results with smooth reference chamber at p_c = 60 bar and O/F = 6. Remark: results downstream of segment No. 10 not reliable due to water leak (film cooling effect)

The direct comparison of the heat flux test results can be summarized as follows:

- steeper heat flux increase at the beginning of the chamber (first group of grooves)
- almost identical heat flux at smooth segment No. 7 (position x=150 mm)
- heat flux decrease along the chamber's x-axis avoided by the second group of grooves (segment No. 9 – 10),
- heat flux in segment No. 8 already increase despite of the fact that this segment is smooth (interpreted as heat conduction effect from the neighbored segment No. 9, as well), and
- statement concerning reduction effect in the throat section not reliable due to undesired water leak at segment No. 11

The hardware, especially the grooves, were in a good condition after the tests and no local overheating could be observed.

The tests with the calorimeter chamber have demonstrated the possibility to influence the axial evolution of the heat transfer to the coolant by introducing packages of grooves in appropriate locations. The next steps prior to an application of this technique in a full scale engine will be long duration hot-fire tests with cryogenic cooling to investigate the influence of grooved surfaces on chamber life and on the structural integrity of the hot gas surface.

3. INJECTOR HEAD TECHNOLOGIES

Subscale Chamber Injector Configuration

Within the frame of the present technology programs different injection elements for LOX/H_2 and LOX/HC propellants will be tested on the subscale chamber. The main objectives of these investigations are:

- development of high mass flow elements in order to considerably reduce the total number of injection elements
- investigation of the influence of the injection element distribution and of the element to wall distance (injection element pattern) on combustion efficiency and on the heat transfer to the wall
- development of injection elements for staged combustion cycle engines, i.e. injection elements for hot, preburned propellants.

For the subscale chamber a new modular injector head has been designed which allows a cost effective testing of a great variety of different injection elements, see Fig. 3.1.

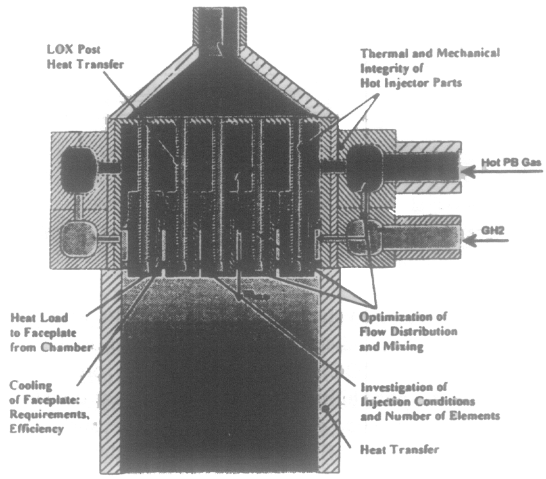


Fig. 3.1 Subscale chamber injector head with exchangeable injection element support structure. for hot-fire tests of different injection elements

For this purpose an easily exchangeable injection element support structure has been developed as shown in Fig. 3.2.

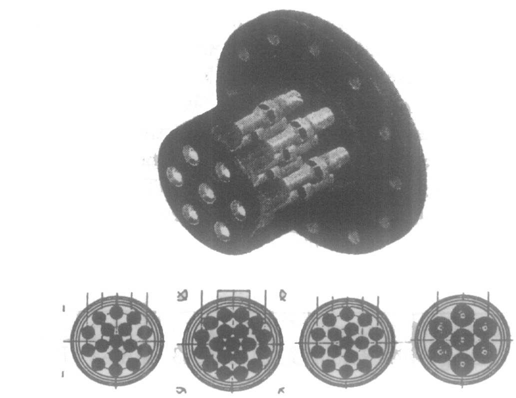


Fig. 3.2 Exchangeable injection element support structure and different injection element patterns to be tested

By this modular design, only the injection element support structure has to be adapted to the new injection elements to be tested, the LOX dome and the hydrogen manifolds are the same for all tested element configurations. The capability to inject hot propellants simulating e.g. fuel-rich hot gases from a preburner and the mixing with cold hydrogen coming from the coolant circuit in the injector has been foreseen in the design of this injector head as shown in Fig. 3.1.

4. ADVANCED COMBUSTION CHAMBER MANUFACTURING TECHNOLOGIES

Rationale

Most of the present cryogenic high pressure rocket engines have regeneratively cooled, integral combustion chambers made from milled slotted liners of highly conductive copper alloys with an electro-deposited outer Nickel jacket (typical examples: Ariane engine family HM7, VULCAIN and VINCI, Space Shuttle Main Engine, etc.).

Within the frame of the present technology program ASTRA alternative manufacturing technologies are investigated at Astrium with the main objective to reduce manufacturing cost and time.

One major step versus a considerable reduction in manufacturing time was the recent introduction of a new electrodeposition technique for the outer Nickel jacket, the pulse plating [8]. The pulse plating technique involves the use of high-intensity current pulses with pulse durations in the millisecond range instead of direct current, which was up to now the standard technique used for applying the Nickel outer jacket to the combustion chambers of the HM7 and the Vulcain engines. By this new pulse plating technique the overall processing time of the electrodeposition process could be reduced down to 30% of the standard direct current technique [8]. This new pulse plating technique represents the present core process of Astrium for manufacturing the Vulcain and the VINCI thrust chambers.

Segmented Subscale Chamber as Technology Demonstrator

The subscale chamber serves as a demonstrator for the different chamber technologies under investigation. In order to enable hot-fire tests with different manufacturing techniques at moderate cost a segmented design of the cooled cylindrical part of the subscale chamber has been designed and manufactured. The cylindrical part (with a total length of 250 mm) is subdivided into five cooled segments made of copper alloy as shown in Fig. 4.1. The coolant can be either water or liquid hydrogen. The individual segments can be manufactured by different manufacturing techniques to demonstrate this technique by hot fire tests. In addition, the segmented chamber is the new demonstrator for thermal barrier coating tests. Especially with cryogenic cooling the tests with thermal barrier coatings can be performed in a relevant environment to demonstrate the thermoshock behavior of the coatings. The segmented subscale chamber is designed for chamber pressures up to 120 bar (LOX/H_2 propellants).

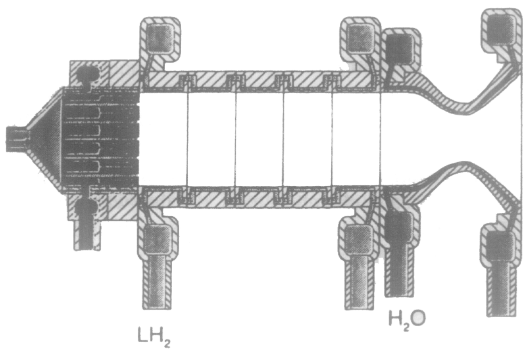


Fig. 4.1 Segmented subscale chamber

Combustion Chamber Soldering

Within the frame of the ASTRA technology program the soldering of combustion chambers is presently investigated on the basis of different subscale demonstrators. Figure 4.2 shows an example of the present activities.

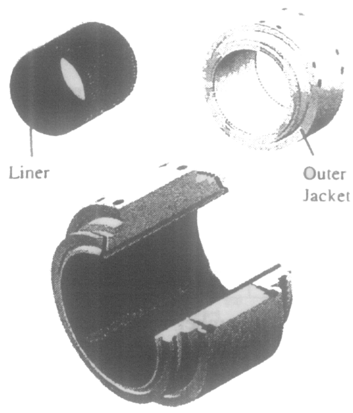


Fig. 4.2 Subscale chamber segment manufactured by soldering technique

The copper alloy liner with the milled cooling channels is closed with an outer Inconel jacket, which is soldered to the liner. The soldering technique and the qualitiy of the soldering contact is presently the focus of the technology developments.

Thermal Barrier Coatings

The application of thermal barrier coatings (TBC), e.g. ZrO_2, on the combustion chamber hot gas wall leads to a reduction of the hot gas side wall temperature and thus to a considerable reduction of the total strain rates and plastic deformations of the liner material. As a result, chamber life can be enhanced accordingly.
In the past six years Astrium has performed a comprehensive screening program where different coating concepts have been applied to the baseline chamber wall material of a high conductivity copper alloy. Subscale chamber tests on the water-cooled DLR subscale calorimeter chamber with GH_2 and LOX propellants and chamber pressures of 100 bar have been performed [5].

As a result of the screening program three coating concepts were finally selected and improved in different steps:

- electrodeposited NiCr layer
- ZrO_2 layer applied by an APS technique
- ZrO_2 layer applied by a pulsed laser deposition (PLD) technique

The PLD technique allows the application of ultra thin layers with a precise, defined thickness. For the tests the PLD layers were applied with 10μm and 20μm thickness, respectively.

Within the frame of the ASTRA technology program the new, segmented subscale chamber (Fig. 4.1) is presently being used for hot-fire tests with thermal barrier coatings. The five segments of the cylinder are equipped with the different coatings to be tested (segment 1 first segment on the injector side, segment 5 last segment of cylinder). Table 4.1 shows the last test configuration (P8 tests in September 2002) with cryogenic cooling and with chamber pressures up to 120 bar.

Segment	1	2	3	4	5
Coating	APS-1	PLD-2 10μm	PLD-3 10μm	APS-2	PLD-E 20μm

Tab. 4.1 TBC tests with segmented subscale chamber

The following Fig. 4.3 shows the status of segments 1, 2 and 3 after the hot-firing tests with chamber pressures from 100 to 120 bar with cryogenic cooling and after cyclic loads between 5 and 7. The condition of the thermal barrier coatings of these segments is very good.

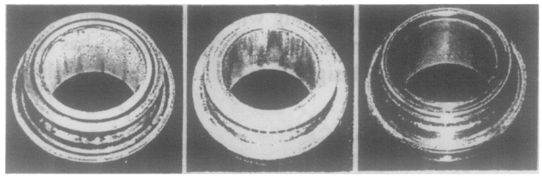


Fig. 4.3 Segments 1, 2 and 3 after hot-firing tests at P8 with cryogenic cooling

Technology Developments for LOX/HC Engines

For the next generation of launch vehicles the application of LOX/HC (liquid oxygen/hydrocarbon) propellant combinations for high thrust booster engines is presently being discussed in Europe as one preferred solution. As hydrocarbon fuel liquid Methane or Kerosene are being considered. At the present time, very limited experience in Europe with these propellants for liquid rocket engine is available. In the frame of the German-Russian cooperation program TEHORA tests with the subscale chamber with LOX/Kerosene and LOX/Methane propellants are presently being performed with the main objective to develop and to optimize injection elements for these propellant combinations [9].

Within the frame of the ASTRA program a detailed engine trade-off for both propellants combinations is presently being initiated. The engine trade-off will be performed for high thrust booster engines in the range of 300 to 400 t thrust for a future reusable launch vehicle application. The engine trade-off will take into account engine life cycle costs, relevant enabling technologies and the cost for the ground infrastructure. The main objective of this trade-off is to give important guidelines for a future selection of the most appropriate propellant combination for future launch vehicle concepts.

5. SUMMARY AND CONCLUSIONS

This paper summarises the present technology work of Astrium, Space Infrastructure Division, for thrust chambers of the next generation of expandable reusable and reusable liquid rocket engines of future launch vehicles. All technologies are prepared for verification under representative, hot firing test conditions.

The comprehensive subscale tests for enhanced heat transfer for expander cycle engines have shown different promising solutions for increased heat transfer to the coolant. It has been demonstrated that the application of an artificial surface roughness by means of grooves in the hot gas wall the axial evolution of the heat transfer to the coolant can be influenced in a way to optimize the heat transfer along the liner.

The Astrium subscale chamber has been extended by introducing a modular design. This enables flexible and low cost investigations of new technologies for new injection elements as well as for new chamber manufacturing technologies. The chamber manufacturing technologies presently are concentrated on soldering techniques for closing of the coolant channels by a metallic outer jacket.

The activities on thermal barrier coatings included the first hot-fire tests of selected coating concepts on the new segmented subscale chamber with cryogenic cooling.

The engine trade-off recently initiated for the LOX/HC propellant combinations LOX and liquid Methane or Kerosene as fuel will give important guidelines for a future selection of the most appropriate propellant combination for future launch vehicle concepts.

As a general conclusion, this technology preparation work will enable Astrium to efficiently start the development of the next generation of advanced, high performance liquid rocket engines.

6. ACKNOWLEDGEMENTS

The activities presented in this paper are part of the German national technology programs TEKAN, and ASTRA that are sponsored by the German Aerospace Research Center DLR. The authors wish to thank the contract officers H.-D. Speckmann and H. Brücker for good cooperation.

The authors highly appreciate the good teamwork of the Astrium engineers contributing to the success of this program, especially F. Grauer, D. Wiedmann, and the DLR test team of the P8 test bench headed by A. Haberzettl.

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