Overview of Astrium's liquid propellant injector investigations for future application

C. Maeding, D. Wiedmann, K. Quering, L. Souverein, O. Knab
Astrium GmbH Space Transportation, Launcher Propulsion, System Analysis, 81663 Munich, Germany

1 Abstract

Astrium-ST is the leading rocket thrust chamber developer for the European launcher family Ariane. In addition Astrium-ST division in Ottobrunn is also actively dealing with different propellant combinations and cycle configurations in order to enlarge the general knowledge and understanding of complex processes in combustion chambers. Crucial know-how is necessary to design the injector properly for respective applications in particular with regard to mass flow rates, mixture ratio and temperature conditions of the diverse propellants. These fundamental investigations serve also as a cornerstone necessary to improve in-house layout tools such as RCFS-II and Rocflam-II in order to enlarge their possible field of application and satisfy the growing demand in terms of prediction accuracy.

2 Introduction

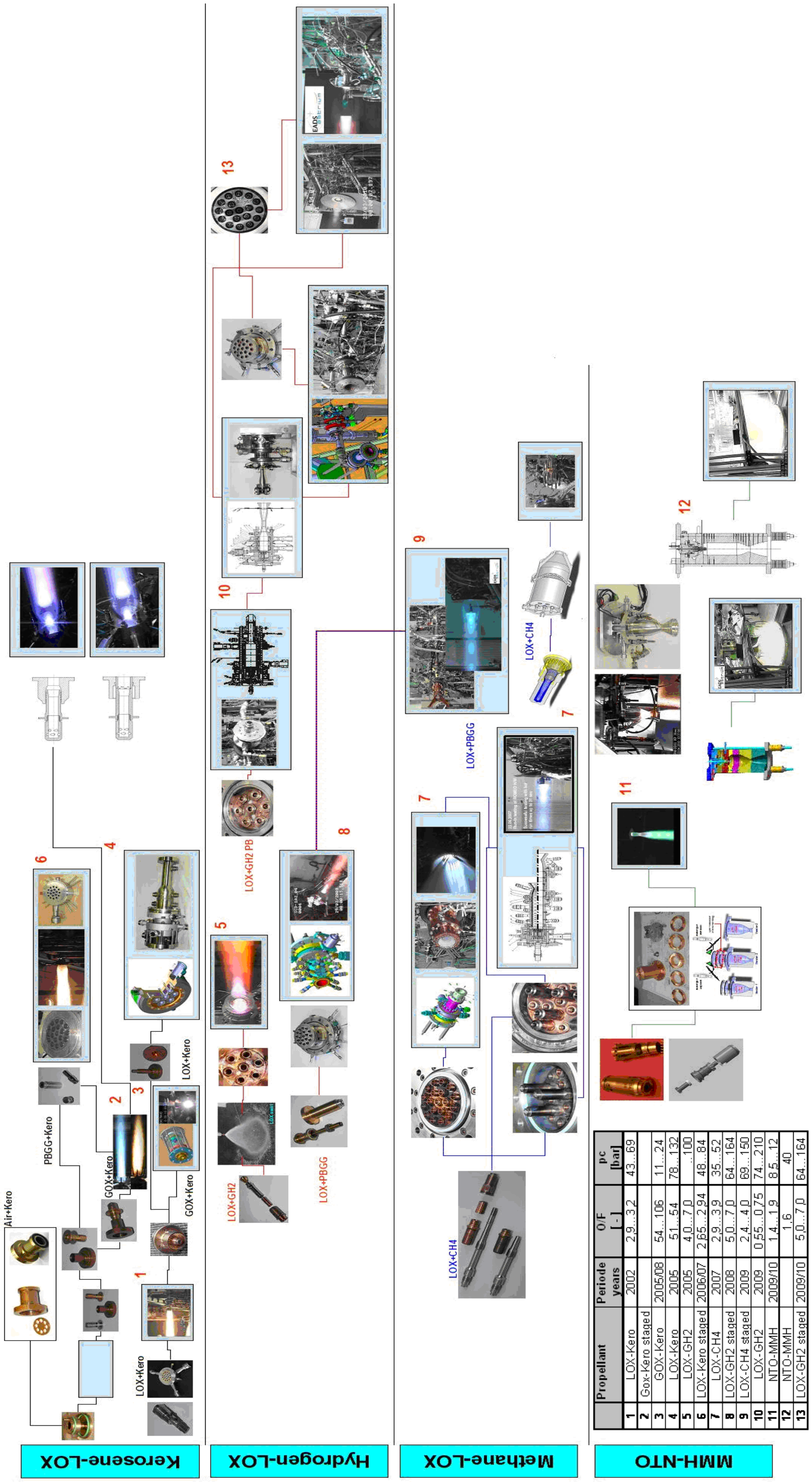
The work on different injection systems is mainly embedded in different dedicated national and international projects covering aspects like stability, performance, throttle capability, heat transfer, material compatibility and pulse mode operation. Within a period of more than 10 years a wide spectrum of propellant combinations and relevant injection systems were treated, including a simultaneous enlargement of application towards other combustion devises like gas-generator and pre-burner. The recent spectrum of propellant combinations comprises GOX-Kerosene, LOX-Kerosene, LOX-CH4, MMH-NTO and LOX-H2, which are currently the most popular liquid propellants used for space application covering all different mission requirements.
A summary of the different development/research activities is given in the **Figure 1**, showing also the synergy effects applying different propellant combinations. Like on real engines that have been developed and flown to date, the injector flow rate has been varied with respect to a possible in-flight application. Therefore, one of the major objectives was to specify an injector design that will produce high combustion performance and stable operation. This task can only be accomplished by choosing the proper element type and element size. A wide variety of injectors like impingement, swirl, jet injectors and their combinations were considered with respect to the applied propellant combination and element loading. The dedicated element design is also driven by the element pattern and the requirements regarding the near wall layer conditions. A proper combination of all these parameters will result in a high performance, stable operation and chamber-injector durability. In addition to that, special measures like actively cooled baffle elements were investigated in some cases to elaborate their impact on the overall combustion process, especially in terms of performance and durability of the protruding element section.

3 Injection element classification

Based on several fundamental investigations the main driving design parameters were determined defining the element type and particular design features. Parameters that influence the general element type selection and its final geometry are as follows:

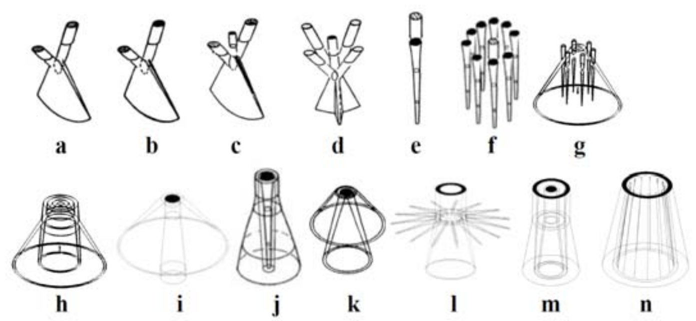
- Propellant combination: hydrocarbon, hypergolic, cryogenic,
- Propellant state at injection: liquid/liquid, liquid/gas, gas/gas,
- Pressure: level at injection: sub- or supercritical,
- Temperature level at injection: sub- or supercritical,
- Stability sensitivity: more or less marginal,
- Throttle capability: low/high mixture ratio and/or low chamber pressure operation,
- TCA operation: steady state or pulse mode,
- TCA design: ablative, uncooled or regenerative cooling,
- TCA sizing: combustion time restrictions,
- TCA life: restart capability, total hot run duration.

All these parameters define not only the injector design, but also impact directly the overall combustion stability, performance, and heat transfer. Therefore, the injector head layout is always linked to a certain chamber design in order to match and balance the most important, and sometimes conflicting, requirements. A general element classification is given in the **Figure 2**.



	Propellant	Periode years	O/F [-]	pc [bar]
1	LOX-Kero	2002	2,9...3,2	43...69
2	Gox-Kero staged			
3	GOX-Kero	2005/08	54...106	11...24
4	LOX-Kero	2005	51...54	78...132
5	LOX-GH2	2005	4,0...7,0	...100
6	LOX-Kero staged	2006/07	2,65...2,94	48...84
7	LOX-CH4	2007	2,9...3,9	35...52
8	LOX-GH2 staged	2008	5,0...7,0	64...164
9	LOX-CH4 staged	2009	2,4...4,0	69...150
10	LOX-GH2	2009	0,55...0,75	74...210
11	NTO-MMH	2009/10	1,4...1,9	8,5...12
12	NTO-MMH		1,6	40
13	LOX-GH2 staged	2009/10	5,0...7,0	64...164

Figure 1 Liquid injector activities overview



a – like on like, **b**- unlike, **c**- **d**- n:1-unlike combinations, **e**- free jets, **f** n:1-parallel jets **g**- jet-swirl, **h**- coaxial injection with central swirl, **i**- coaxial with outer swirl, **j** -coaxial injection, **k**- double swirl, **l**- pintle system **m**- tricoax, **n**- coaxial with increased exit surface of the central element.

Remark: the splash plate injector is not shown

Figure 2 Injection element classification

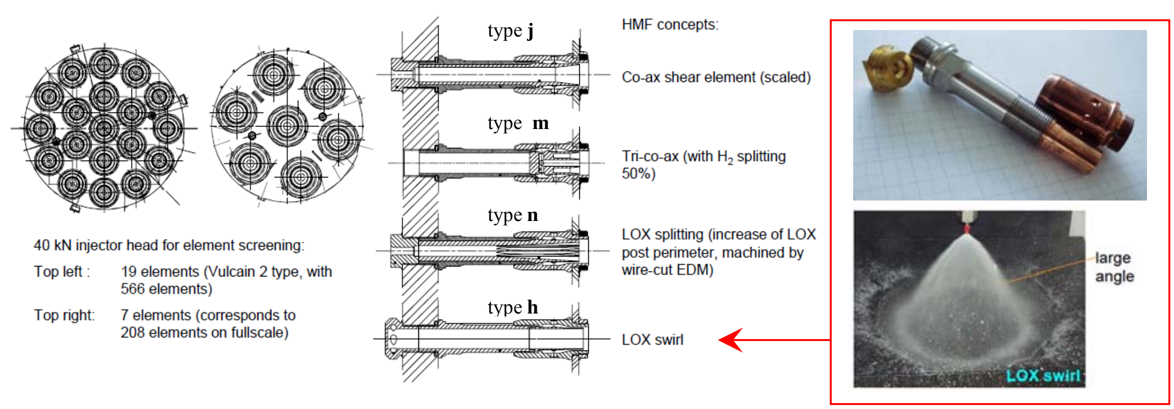
4 Cryogenic injection systems

Due to the high energetic characteristics the O2-H2 propellant combination finds a versatile application for first and upper stages. Another major advantage of this propellant combination presents the lower high frequency instability affinity, especially if hydrogen is injected at higher temperatures (T≥60…70K) affecting the sensitive combustion time lag. The cryogenic injection investigations at Astrium-ST cover open and closed cycle engine application, mainly dedicated to enlarge the knowledge and to prepare engineering data base for future developments.

4.1 Open cycle application

The high reactivity and the wide flammability limits relieve the design effort keeping the main requirements like performance and stability. A huge number of experiments performed worldwide and within Astrium-ST, using this propellant combination clearly shows, that a simple coaxial injection element presents the preferred design taking also into account the low design and manufacturing complexity.

Within the last years several test campaigns were performed investigating performance, durability and stability driving parameters. Taking also into account the cost aspects, the total element number variation was a major issue (see **Figure 3**). Besides the structuring of the element outlet section the impulse ratio $\rho_f \cdot w_f^2 / (\rho_o \cdot w_o^2)$ presents the most driving performance parameter. However the transition to a higher element loading (reduction of the element number) reduces the performance yield, due to the decreasing contact surface between O2 and H2. In order to compensate this drawback of high mass flow elements, different O2 post and H2 sleeve designs were investigated, also with respect to stability and heat load. The application of O2 swirl (type h) did show the most promising results especially with respect to the performance, due to hollow cone injection. These tests revealed also that an O2 swirl reduces the influence of the impulse ratio significantly. A major drawback of an O2 swirl is the drastic heat release change close to the face plate affecting the lifetime of the system. Therefore a moderate hollow cone injection angle should be applied (as depicted in Figure 3).



Subscale injectors type of elements HMF swirl element typical spray pattern of the LOX swirl

Figure 3 HMF injection elements [Ref. 1]

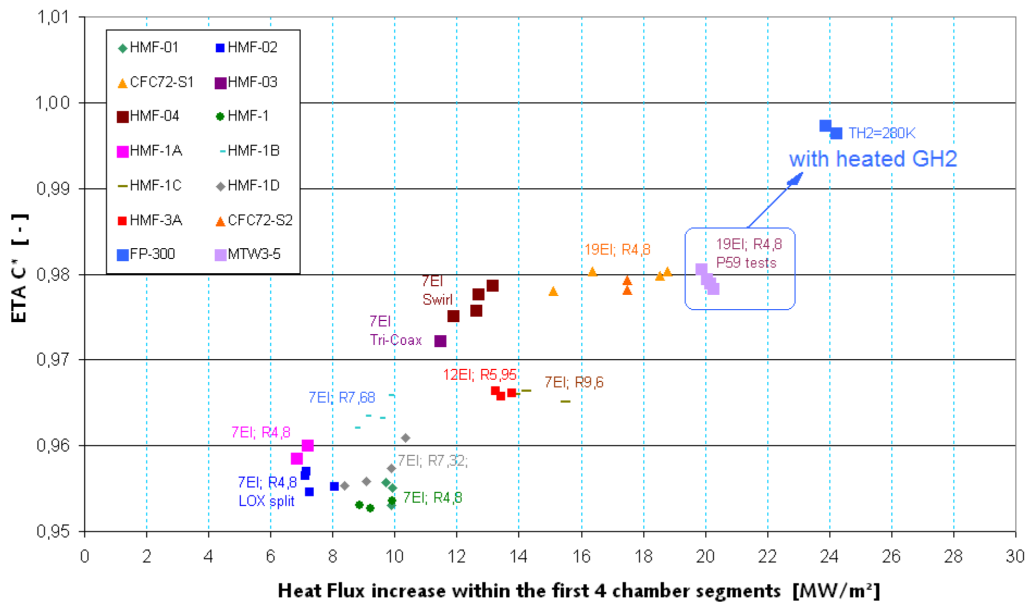


Figure 4 Subscale combustion efficiency depending on element type and number

4.2 Closed cycle application

The FLPP program initiated in 2005 to prepare the fundamentals for a next generation launch vehicle started to investigate also injection systems for closed cycle application. One major objective is the preparation of adequate key technologies and the generation of first test data used for engineering tool development. This specific configuration results also in the necessity to develop and to manufacture a special hot gas device for generating a pre-burner gas for main chamber injection. In both cases the same element layout (**Figure 5** and **Figure 6** type **j** elements) philosophy was used, as already applied for open cycle application - reducing the design and manufacturing effort.

Figure 5 Main chamber staged combustion injector head [Ref. 2]

Even in the hot gas device, generating a fuel rich gas, these elements worked satisfactorily (see **Figure 6** and **Figure 7**). Only minor modifications with respect to a main chamber application were implemented, taking into account the very low O2 mass flow. In addition to that, some injection element exit plain related measures were implemented in order to provide a stable combustion within the whole operational range. The tests were conducted using GH2 with a temperature of about 160K. In a second phase an additional mixing ring downstream was installed, verifying its durability and impact on the overall combustion process in terms of temperature field uniformity and combustion noise. The performance of this fuel-rich operating high pressure device (max. pressure ~250bar) was evaluated in stand alone and coupled tests with a 19 element subscale main chamber. The corresponding compositions are depicted in **Figure 5**. The tests of the hot gas device showed a very low noise content within the whole operational domain.

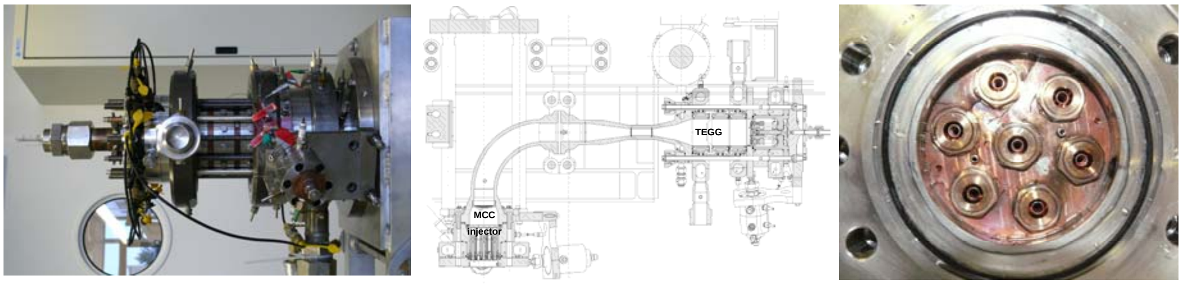


Figure 6 Coupled test configuration PB + MCC

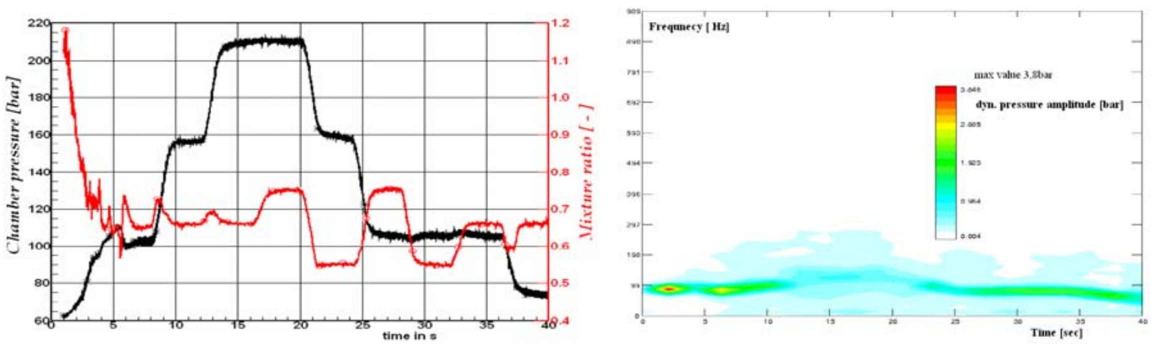


Figure 7 Hot gas device behavior

5 Hydrocarbon injectors

Hydrocarbons like Kerosene, Methane, and MMH are used within a wide thrust range. MMH presents the preferred fuel for small and medium thrust applications used for space missions, due to the hypergolic and storable behavior.
However the really high instability affinity presents the major problem of the most hydrocarbons independently on the applied engine cycle. Especially Kerosene and MMH tend to be the most LF and HF sensitive propellants among the investigated combinations. Based on Astrium-ST experiences [Ref. 3, 6] Methane inclined to be more stable. Several test showed a behavior close to hydrogen, especially at higher temperatures.
The contradicting behavior of stability and performance requires in the most cases an adequate injector design taking not only into account the operational conditions, but also the chamber geometry. Therefore the major challenge is to configure a minimum statically stable injection system without additional damping device like absorbers, in order to get reliable data in terms of performance, heat transfer and life for combustion tool development and future full-scale engine design. Additional damping devices like baffles and absorbers do not eliminate LF and/or HF sources. These measures are only dedicated to suppress oscillations, increasing the stability margin of a system. Due to a missing general design approach with respect to low and high frequency aspects in some cases the design phase involves several loops using test data for adaptation.

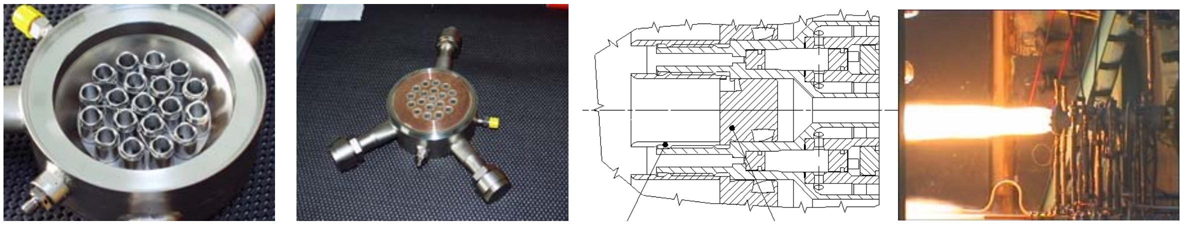
5.1 Open and closed cycle application

The Astrium-ST storable propellant in-house experience is mainly based on the AESTUS and the RS-72 engines using the NTO-swirl/MMH-slot injector configuration (type **g**). In the past the AESTUS injector was already successfully tested using LOX-Ethanol [Ref. 4]. Therefore this element type seems to be also a promising configuration for different future multi-element applications. At present also large efforts are undertaken to investigate closed cycle applications including gas-generators and pre-burner.

5.2 LOX-Kerosene

All experimental LOX-Kerosene activities were conducted within the TEHORA II [Ref. 3] and III [Ref. 5] programs including also fundamental investigations at the TU-Munich. The TEHORA II program was dedicated to investigation of different open cycle injector concepts. Taking into account the positive experiences of the AESTUS like element design also within the RS-72 program the type-**g** element was chosen (**Figure 8**), implementing only some minor modification regarding the O2 swirl. The modifications were mainly addressed to increase the swirl vortex stability keeping the hollow cone injection angle unchanged. An important feature was the abdication of additional O2 trimming orifices-reducing the chamber-feed system decoupling. The whole pressure drop versus the

O2 element was only generated by 45° inclined grooves of the swirl insert. During the subscale tests no LF or HF was observed underlining the potential of this element design.



LOX-dome | face plate | swirl slot element | hot firing

Figure 8 LOX-Kerosene subscale injector head [Ref. 3]

The TEHORA III program was addressed to investigate the same propellant combination related to closed cycle application. Therefore the focus was not only the main chamber injector. In addition at Astirum-ST one pre-burner injector was designed, as shown in **Figure 9**. With respect to a real application, an ox-rich subscale pre-burner concept was chosen. Based on recommendations a two zone injector consisting of a combination of double swirl and jet injectors was chosen. Taking into account the high reactivity of the combustion products (high content of unburned O2) an additional cold film layer was integrated. The second zone was formed by O2 holes at a fixed common angle around the seven double swirl first zone elements. This multi hypoid injection provides a faster mixing in comparison to axial jets.

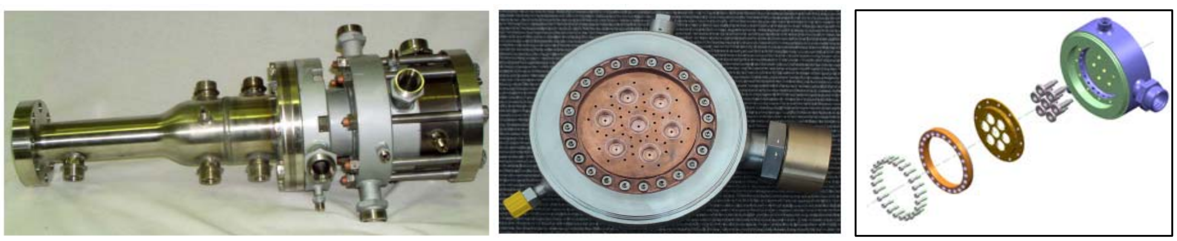
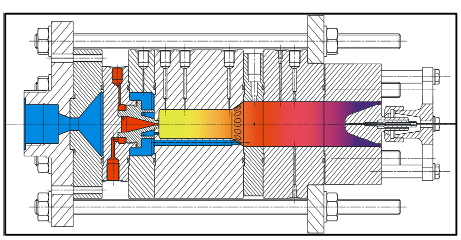


Figure 9 Ox-rich LOX-Kerosene pre-burner [Ref. 5]

In parallel a small GOX-Kerosene combuster (see
Figure 10) for material compatibility testing at the TU-Munich test facility was developed. In this case a stand alone Kerosene swirl surrounded by O2 jets (type **g**) was chosen taking into account the restricted GOX mass flow. In order to guarantee a stable combustion at a very low pressure of about 20 bar a two zone GOX injection was realized. The second zone GOX flow was also used within a first zone dump cooling circuit. Within several test campaigns over 50 tests without any damage and stability problems were performed.



Parameter	Unit	Value
Chamber pressure	bar	20
Total mass flow	kg/s	~0.71
O/F (zone 1)	-	10 - 20
Combustion temperature (zone 1)	K	~2000
O/F (zone 2)	-	70
Combustion temperature (zone 2)	K	~890

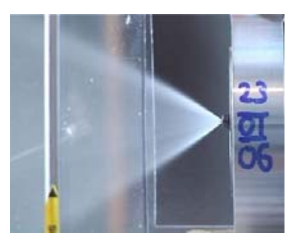


Figure 10 Ox-rich combuster (O/F$_{max}$~100) [Ref. 6, 7]

The main chamber injector developed by Astrium-ST within the TEHORA III was based on a coaxial-jet-swirl injector (type **i**). This concept was chosen due to the lower performance of a simple jet pre-mix element. All elements were pre-characterized during single element tests at the TU-Munich [Ref. 8]. However during the first subscale test a strong longitudinal HF oscillation occurred. In order to modify the injector head, additional single element tests were conducted, including the reproducibility of the same HF oscillation on single element level without additional triggering. These tests were a unique opportunity to improve the general understanding of this combustion phenomenon and to transfer the results between single and multi-element (subscale) configurations.

Based on this detailed investigation a gas swirl was implemented (type **k**), resulting in a significant noise reduction and performance increase, as shown in **Figure 11**.

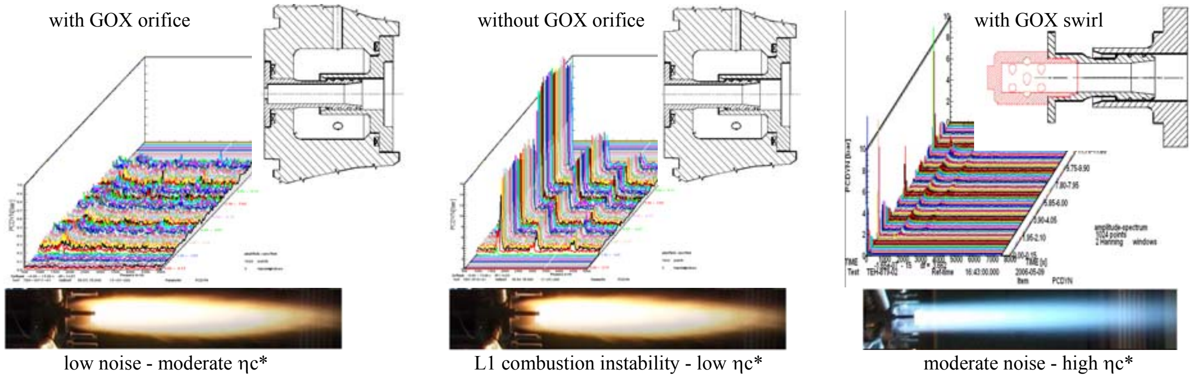


Figure 11 Staged combustion element modification

An up-scaled, modified single element (type **k**) is currently also used for tests with liquid film injection. In order to reach a maximum effective film length a minimum combustion noise (low turbulence) is required. Therefore an additional element adaptation was necessary. Analysis of the internal element flow showed, that the combustion noise is mainly driven by the Kerosene injection. The TEHORA III element was based on 12 inclined Kerosene grooves for swirl generation (**Figure 12**). In a first step additional modifications on the Kerosene side were implemented and tested, but without significant improvement, keeping the fuel-swirl-groove design. Both modifications were dedicated to intensify the mixing process. However the best results were achieved using 2 rows of tangential arranged Kerosene holes instead of inclined groves, keeping recess length unchanged.

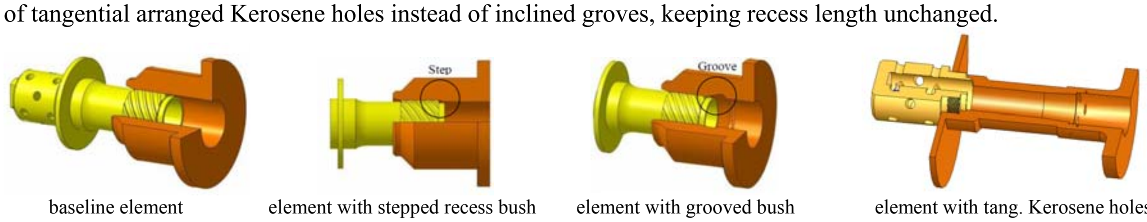
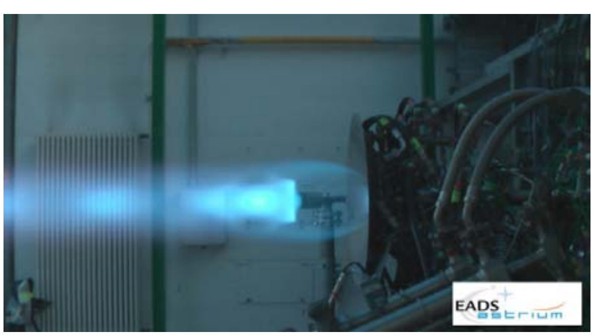


Figure 12 Injection elements used for noise reduction for film cooling investigations [Ref. 9]

5.3 LOX-Methane

LOX-CH4 presents a quite attractive propellant combination in terms of performance and density. Within the FLPP program [Ref. 10] also coupled pre-burner main chamber tests using O2-CH4 were performed focusing only on the main chamber injector configuration (see **Figure 13**). A major objective was the verification of the usefulness of O2-H2 based staged injection elements with only minor changes. Therefore an already existing injector head was used for subscale testing. Taking into account the slightly different behavior regarding the optimum impulse ratio, only the geometry of the outlet section was changed. This was also done with respect to the different pre-burner gas composition, overall mixture ratio and mass flow.



Parameter	Engine Reference Cycle	Sub-scale SC Demonstrator
PB pressure	210 bar	210 bar
PB mixture ratio	0,20	0,20
PB gas temperature	850 K	710 K
PB CH4 inlet temperature	335 K	appro. 280 K
PB O2 inlet temperature	100 K	110 - 125 K
MCC pressure	150 bar	150 bar
MCC mixture ratio	3,5	3,5
MCC CH4 inlet temp.	820 K	710 K
MCC O2 inlet temperature	100 K	110 - 125 K

Figure 13 closed cycle LOX-GCH4 injector testing

The Astrium-ST CH4 activities cover open cycle as well [Ref. 10]. The tested standard coaxial injection elements (**Figure 14** type **j**), based on the hydrogen experiences, showed a very smooth combustion without any appearance of LF or HF. However this test campaign was also used to verify the feasibility of actively cooled baffle elements. In order to reduce the performance loss due to the baffle elements a coaxial-swirl type design (type **i**/**j**) was chosen. The Methane swirl did also improve the temperature conditions of within the protruding element section.

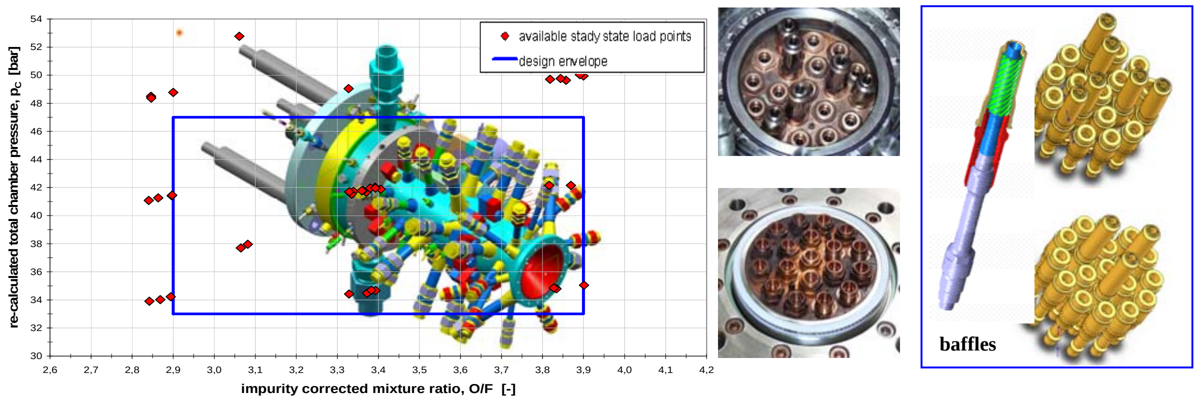
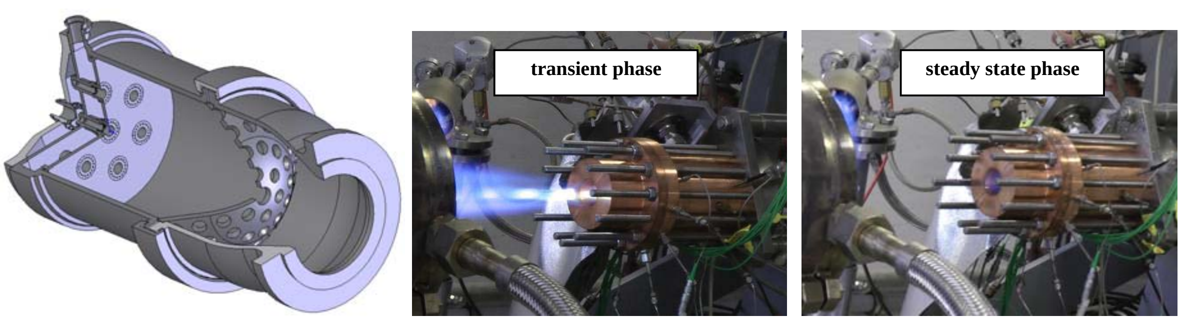


Figure 14 Open cycle LOX-GCH4 injector testing

Another direction presents some preparation work for a preliminary liquid-liquid gas-generator. Due to the fear of higher affinity regarding instability (similar to cold H2 injection), taking into account the low CH4 temperature, special double swirl injection elements (type **k**) were selected. This element type using adequate recess area is also used to form a "hot source". That means the fuel rich driven gas-generator design uses a two zone injection generated via the flat faceplate. The second zone mass flow, needed for temperature balancing, is additionally split into two portions to protect the hot gas wall by a cold film layer. The film layer is integrated in the faceplate to simplify the design. **Figure 15** shows a simplified cut view of a possible multi-element configuration with film/heat sink cooled liner. In a first phase a single element configuration, keeping the main design features, was chosen for hot firing.



possible full-scale layout — single element testing

Figure 15 Gas-generator conceptual design [Ref. 11].

5.4 NTO-MMH

The dedicated MMH-NTO activities at Ottobrunn cover a wide field of possible applications using different types of injection elements like slot/swirl (type **g**), double swirl (type **k**) and pintle (type **l**). Within a small "screening" program a double swirl element was tested (**Figure 16** type **k**) on different combustion chambers performing also contraction ratio and chamber length variations. These tests supplied very informative results regarding the wall temperature evolution using MMH or NTO film cooling.

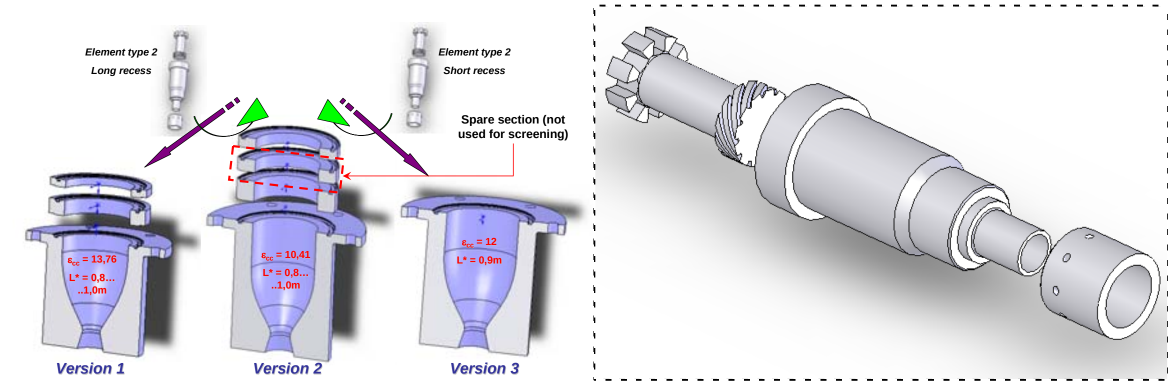
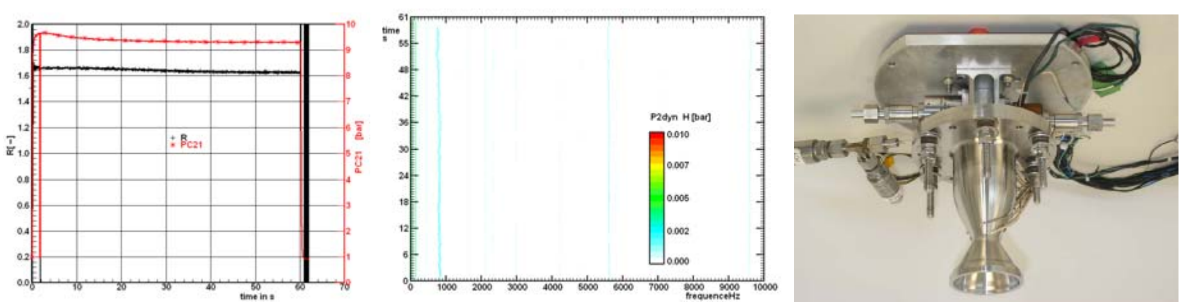


Figure 16 Single element NTO-MMH thruster

Such investigations are also addressed to study the impact of injection element design within a potential operational box on the combustion roughness. The restricted feasibility of damping devices on a single element chamber requires an adequate injection element design, providing a sufficient stability and high performance, keeping the hot gas wall temperature within a permissible range. A typical frequency color map of such a test with a low noise content of a flight like combustion chamber is shown in **Figure 16.**



steady state conditions — combustion roughness — flight-like combustion chamber

Figure 17 Single element NTO-MMH thruster (4231-017

Taking into account the AESTUS and RS-72 as well as the small thruster derived data different types of injection elements are currently under investigation [Ref. 12]. In the frame of the VENUS II and the FLPP Storable programs different elements (see **Figure 18**) were screened on single element -level in terms of performance and stability:

- Variant A: Aestus-scaled element (straight MMH slots- NTO swirl injector - type **g**)
- Variant B: Aestus-scaled element (inclined MMH slots- NTO swirl injector - type **g**)
- Variant C: Double swirl element generated by means of tangential orifices (type **k**).

One or two promising injection element designs will be used in a next phase for further investigation towards demonstrator application. The main scope lies in the development of a highly efficient multi-element injector head design for a 5kN engine demonstrator, which guarantees a stable operation using different propellant injection temperatures. This demonstrator should provide a nominal thrust level of about 5kN at a nominal chamber pressure of 15bar and a mixture ratio of 2.0.

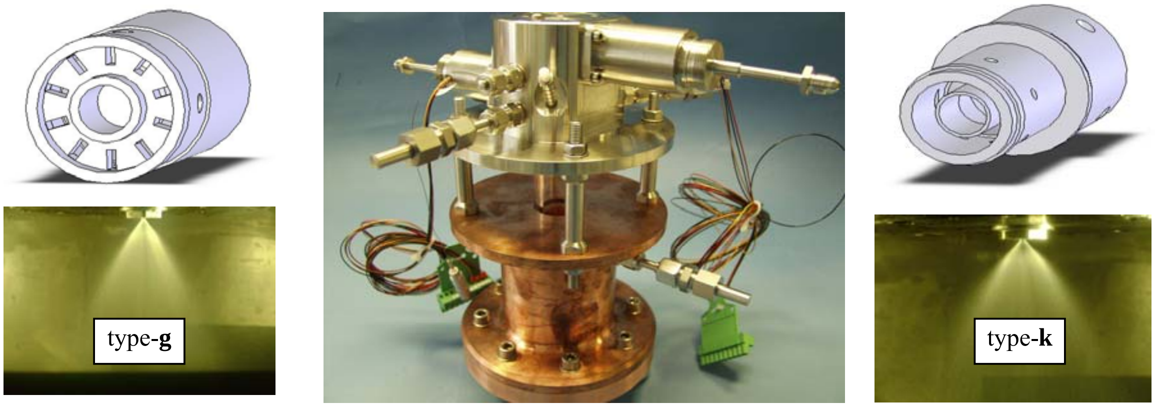


Figure 18 Single element hardware set-up

6 Conclusion

All the introduced activities are used to improve and develop a certain design and qualification procedure including an improved element pre-characterization using a dedicated flow-check facility for hydraulic and spray investigations. A major outcome presents also the improved capabilities to perform a quick and safe pre-selection of adequate types of injection elements with respect to the dedicated application covering the whole in-house spectra of thrust chambers starting with small thrusters at a chamber pressure level of 10bar up to staged combustion application with a chamber pressure of about 250bar. Especially the enlarged field of application covering also fuel- and oxidizer-rich gas-generators and pre-burners presents a new challenge for injector design and simultaneous tool development for heat transfer and combustion prediction.

7 References

[1] G. Hagemann, D. Preclik, L. Brummer, J. Kretschmer, C. Maeding, F. Grauer, O. Knab: *TEKAN 2010 - Thrust Chamber Technologies for Liquid Rocket Propulsion*, 42nd Joint Propulsion Conference, AIAA-2006-4362, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference **&** Exhibit, Sacramento, California, July 9-12, 2006

[2] R. Strunz, F. Grauer, C. Maeding, D. Preclik: *Status of LOX/GH2 Staged Combustion Activities within the Future Launcher Preparatory Programme FLPP,* Space propulsion conference, Kreta, 2008

[3] D. Haeseler, C. Maeding, V. Roubinski, S. Khrissanfov: *LOX-Hydrocarbon Rocket Engines and Thrust Chamber Technologies for Future Launch Vehicle Applications*, IAC-02-S.2.01, 53rd International Astronautical Congress, Houston, USA, October 2002

[4] C. Greene, S. Clafin, C. Maeding: *Non-Toxic Orbital Maneuvering System Engine Development*, AIAA-99-2742, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Los Angeles, CA, 2-24 Jnue, 1999

[5] D. Haeseler, C. Maeding, D. Preclik, V. Rubinskiy, V, Kosmacheva: *LOX-Kerosene Oxidizer-Rich Gas-Generator and Main Combustion Chambers Subscale Testing*, AIAA-2006-5197, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference **&** Exhibit, Sacramento, California, July 9-12, 2006

[6] D. Preclik, G. Hagemann, O. Knab, C. Maeding, D. Haeseler, O. Haidn,, A. Woschnak, M. DeRosa: *LOX/Hydrocarbon Preparatory Thrust Chamber Technology Activities in Germany*, AIAA-2005-4555, 41st Joint Propulsion Conference, Tucson, Arizona, July 10-13, 2005

[7] Soller, S., Wagner, R., Kau, H.-P., Martin, P. and Maeding, C.: *Characterization of Main Chamber Injectors for GOX/Kerosene in a Single Element Rocket Combustor*, AIAA-2005-3750, 41st AIAA/ASME/SAE/ ASEE Joint Propulsion Conference & Exhibit, Tucson, AZ, Jul 10th – 13th 2005

[8] S. Soller, R. Wagner, H.-P. Kau, P. Martin, C. Maeding: Combustion Stability Characteristics of Coax-Swirl-Injectors for Oxygen/Kerosene, AIAA-2007-5563, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cincinnati, Ohio, July 8th to 11th 2007

[9] C. Kirchberger, G. Schlieben, R. Wagner, H.-P. Kau,Ch. Maeding, S. Soller P. Martin: *Design and Commissioning of a Combustion Chamber for Cooling and Material Investigations,* AIAA 2008-5239, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Hartford, CT, USA, July 20th-23rd 2008

[10] A. Preuss, D. Preclik, C. Maeding, J. Görgen, S. Soller, O. Haidn, M. Oschwald, W. Clauss, Y. Torres, J. Sender: *LOX / Methane Technology Efforts for Future Liquid Rocket Engines*, Space propulsion conference, 2008

[11] D. Preclik, C. Maeding, J. Alting, D. Haeseler, S. Soller, V. Roubinski, V. Kosmatcheva, N. Veremeenko: *Astrium - KBKhA: 10 Years of Successful Cooperation on Hydrocarbon Combustion Devices Technology*

[12] R. Arnold, A. Götz, P. Philipp, C. Maeding, G. Obermaier, J.-N.l Caruana: *Technology Development Program for a New Storable Propellant Low-Thrust Engine Demonstrator*, 4th European Conference for Aerospace Sciences (EUCASS), Saint Petersburg, Russia, July 4, 2011 – July 8, 2011

[13] D. Haeseler, C. Maeding, Götz, V. Rubinski, S. Khrissanfov, V. Berezhnoy: *Testing of LOX-Hydrocarbon Thrust Chambers For Future Reusable Launch Vehicles*, AIAA-2002-3845, 38th AIAA Joint Propulsion Conference, Indianapolis, USA, July 2002

[14] C. Maeding, D. Preclik, D. Haeseler: *Recent Investigations on Hydrocarbon Based Fuels for future Propulsion Systems*, 2nd European Conference for Aerospace Sciences (EUCASS), Brussels, 2007