10 YEARS OF SUBSCALE TESTING AT P8 TEST FACILITY LAMPOLDSHAUSEN

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ABSTRACT

A sound test logic is the key to success of any full-scale development program. Subscale testing at representative conditions plays an important role in maturing the risk from the early design phase on. It is generally recognized that subscale data are crucial for analytical model development and verification. To support these engineering disciplines at Astrium, a stock of different subscale test hardware has been built up over the past 10 years which is based on a 40 kN combustion chamber workhorse. Past experience has shown that this size is a reasonable compromise between the cost and effort to be spent on designing, manufacturing and testing such hardware and the representativity and usefulness of the data and results to be obtained from scaled approaches.

Over the years, various types of subscale injectors, combustion chambers and nozzle extensions have been developed that can be combined in a modular manner depending on the problem or physical phenomenon of interest. While the injection heads allow for a fast exchange of configurations comprising element type, number, pattern, wall spacing, propellant type, etc, the different combustion chambers enable to adopt various chamber lengths, cooling circuits, and nozzle extensions that are attached at well specified interfaces.

This paper gives an overview on the wide range of technologies investigated with the different sets of injector, chamber, and nozzle hardware. Most of the tests have been conducted at the research and technology test bench P8, Lampoldshausen. The paper also outlines the underlying test philosophy adopted by Astrium with the aim to obtain a maximum of information from each test at an acceptable level of risk.

NOMENCLATURE

CH4	Methane	LOX	liquid oxygen
DLR	German Aerospace Centre	MCC	Main Combustion Chamber
ESA	European Space Agency	NE	Nozzle Extension
FSCD	Flow Separation Control Device	TBC	Thermal Barrier Coating
LH2	liquid hydrogen	VAC	Volvo Aero Corporation

INTRODUCTION

During the development of any new liquid rocket engine, fundamental issues concerning the design of thrust chambers have to be solved. These issues aim among others at an optimum design of the injection system, the layout of coolant circuits, or the characterisation of nozzle extensions covering the full operating domain from engine start-up at ambient conditions thru ascent to outer space.

Within the past 10 years, Astrium has conducted numerous test campaigns at the research and technology test facility P8, operated by the German Aerospace Centre (DLR) at Lampoldshausen, in order to establish a sound data base for deepening the fundamental understanding of the processes influencing the design and operation of liquid rocket thrust chamber systems. This data base is vital in bridging the gap between early cold flow experiments and late hot firings employing full-scale hardware [1], [2]. Beyond, it supports the understanding of physical phenomena to be treated in the design phase of a development program.

The ability to transfer any experimental results form subscale to full-scale is strongly influenced by similarity considerations. The design of a subscale hardware not only has to facilitate the operation at relevant conditions in terms of mixture ratio and chamber pressure, it also has to take into account the need to provide similarity in terms of Reynolds- Mach- or geometrical analogy. If these prerequisites are

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properly met, subscale testing can provide valuable information for different fields of application. The data can be used to validate and improve analytical and numerical models describing the underlying physical phenomena of interest. Fundamental processes addressing for instance propellant thermo-hydraulics, mixing and combustion, structural wall heat transfer and cooling, material compatibility, as well as supersonic flow evolution in nozzles can be reliably studied in a suitable subscale environment. In doing so, the risk and the cost of late design modifications can substantially be reduced at an early stage within any development program.

Structure of Paper

The present paper is structured into three main sections describing several key aspects of Astrium's subscale testing experience. Firstly, a brief retrospection is given on oxygen / hydrogen test activities starting on the P59 test facility (Ottobrunn, Germany) up to nowadays P8 test facility (Lampoldshausen, Germany), where all current subscale hot firings are meanwhile performed. Focus is put on the P8 bench, which is shortly introduced from the early beginning to its actual state. Secondly, the in-house subscale test philosophy is outlined in more detail balancing efficiency vs. complexity and accepting higher risk levels in favour of an increased data output. Finally, an insight into the hardware stock and a brief overview on the performed R&D tests of the past decade is given.

P8 TEST FACILITY, DLR, LAMPOLDSHAUSEN

Astrium, site Ottobrunn, started its subscale testing of thrust chambers within the Vulcain engine development program. In '85 and '86 a total of 45 hot tests were performed at the P59 test facility. This facility was originally used for HM7 full-scale testing. It was later adjusted for testing the Vulcain LOX turbopump [3]. From 1996 to 1997 various subscale hot firing campaigns were conducted supporting the Vulcain 2 thrust chamber development. End of the 90's, the P59 facility was closed down and all subscale test activities were transferred to the European P8 test bench in Lampoldshausen [4], [5], jointly established by a German-French team consisting of DLR, CNES, Astrium, and Snecma.

The P8 with its two largely identical test positions was originally designed for research and technology testing with only LOX/H2 propellants (see Figure 1). The LOX and LH2/GH2 high pressure propellant system is capable of providing pressure levels up to 360 bar at the test specimen interface. A de-ionized water system supplies up to 50 kg/s coolant at 200 bar. The maximum mass flow rates are about 14 kg/s for LOX, 1,8 kg/s for GH2 and 3 kg/s for LH2 in chamber pressure domains up to 170 bar. High precision regulation valves, operated under closed loop control, ensure precise propellant and coolant mass flow rates. Recently, the P8 was extended by DLR adding a gaseous methane supply system consisting of pressure bottle packs (200 bar). In 2008, Astrium designed and implemented a modification to the CH4 feed system. A high pressure gaseous CH4 supply system (400 bar) was installed at the P8 in the frame of the ESA FLPP program to enable complementary LOX/CH4 staged combustion tests [6], [7]. This facility extension was specified by Astrium and built by Krytem GmbH, Germany.

Figure 1: Research and technology test facility P8 (DLR, Lampoldshausen).

ASTRIUM TEST PHILOSOPHY AT P8

Definition of Test Objectives

The first mandatory step towards rocket components' testing is the definition of test objectives. From experience point of view test engineers know that the question about stringent test objectives is sometimes unpopular. However, only the distinct definition of clear test objectives actually enables the preparation of a proper hot test program including iteration steps for adaptations. Based on these test objectives the principal strategy is chosen, e.g. whether a fast screening approach is to be pursued or a complex test campaign with highly interacting components.

Principle Strategy and Approaches

Two types of testing are to be distinguished in principle. There is the "screening" approach where mainly basic information is of interest that has to be collected in a very fast and efficient way. The objective is to identify key differences between two concepts selecting the better or most promising one for the next loop of tests.

A second approach is the so-called "verification" approach which aims at characterizing a well defined, specific hardware set-up within a given operational envelope. In such tests, the accurate prediction of a response surface, e.g. combustion efficiency evolution within a specific envelope might be of interest. This type of tests usually results in a complex hardware set-up being as representative as possible for a later full-scale application.

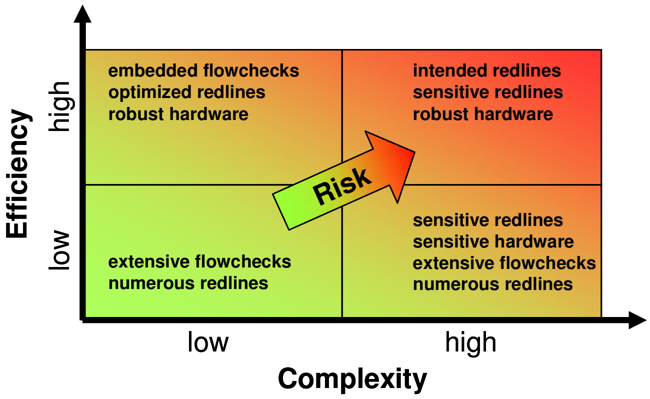

Figure 2: Test output vs. hardware / bench complexity and operation measures with associated risk of test aborts.

In any case the test strategy has to be carefully chosen, taking into account the hardware and test facility complexity, managing an acceptable risk and budget for maximizing the amount of test results and quality. Figure 2 illustrates a principal matrix comprising the desired test output or efficiency of testing vs. the test set up complexity and its link to the associated risk. The separated fields contain measures to ensure safe test operation, but also to increase the data output. In return, of course, a higher risk of encountering a test abort is to be accepted.

Rationale for the "screening" approach

Taking the decision towards fast and efficient testing, the following bullets highlight some of the key ideas:

- modularity, flexibility
- low cost components
- fast reaction on results (modification of hardware)
- higher risk allowed
- intended redlines
- pre-flow-checks within hot run sequences

This kind of testing often implies unexpected results that might affect the further proceeding in the campaign. Therefore modular hardware and low cost components with a maximum grade of flexibility have been developed in the past which can be reused many times in different combinations and/or variations. This modular hardware design allows for exchanging components very easily and thus for a quick modification of single components even during a test campaign. Due to the large number of existing hardware components a standard test campaign can be set-up and conducted on a short term basis.

Typically a higher risk is allowed as long as it is justified by a faster and larger output of test results. In this context a higher risk does not mean to challenge the damage or loss of the hardware. Instead it means to accept test aborts due to undesired conditions or "intended redlines". In very special cases, however, the damage of components might be accepted.

The concept of "intended redlines" means that the activation of a specific redline is actually expected and the test is run as long as the signal for activation is not obtained. Usually the test duration is increased until, for example, the test facility might run out of either propellants or coolant. These redlines are then defined to protect the test facility and specimen from unpredictable test conditions and lead to an automatic shut-down of the test employing a standard run-down sequence.

Another approach to enable the quick step into hot firings is the definition of embedded flow-checks. In case a well known hardware is applied and only little information is to be acquired, it is more efficient to directly step into a hot test by defining a special lead sequence that checks exactly the same topics that a flow-check would do. In case everything works as expected the sequence continues with the hot test. Otherwise the test is stopped. This test philosophy is certainly applied only as long as there is no critical safety issue identified. This procedure has been found to be very efficient especially for small test campaigns with known hardware characteristics.

Rationale for the "verification" approach

This type of testing is typically employed for complex test set-ups emphasizing the following ideas:

- extremely complex test set-ups
- expensive components
- lowest possible risk
- large data output aimed for
- limits of test facility reached (intended redlines)
- secondary test objectives included

In many cases very complex test set-ups are required to achieve the desired test objectives. This complexity is usually driven by the desired level of representativity allowing for a suitable scaling and modelling of the observed phenomena. Often test facility modifications or adaptations are mandatory. Due to the capabilities of the P8 test facility and its design with two identical test cells, modifications are often possible without too much of an effort. When very complex and expensive hardware is applied, all measures are taken to minimize the risk of hardware damage or test aborts. Therefore all operational parameters are checked in detail by dedicated flow checks before hot firing admission. Additionally, redlines for hot tests are defined more sensitive at the beginning of a campaign when new hardware is used. During the test campaign, when experience with the hardware is gained and the behaviour is well understood, redlines might be adapted and defined less sensitive in order to increase the robustness of the tests avoiding undesired as well as unnecessary test stops. Often the approach of intended redlines or embedded flow checks is applied as well as a carefully trade of any potential risks.

OVERVIEW ON HARDWARE STOCK AND TECHNOLOGIES TESTED

Injector Technology

Table 1 gives a brief overview on the injection technologies already tested. The table is completed by a list of the test objectives and related parameters of interest. The various campaigns comprise R&T tests partly co-funded by the German space agency DLR in the frame of national programs, but also 100% in-house activities as well as test campaigns undertaken in the course of European technology and engine development programs. In the following some of these test campaigns are highlighted and explained in more detail.

Objective	Injector Hardware: Integral Open Cycle	Integral Expander Cycle	Modular Open Cycle	Integral Staged Combustion	Cooled Faceplate and Igniter Ring	Film Cooling Injector
Performance, C*	X	X	X	X		X
Wall Heat Flux	X	X	X	X	X	X
Injection Element Type			X			X
Effect of Film Cooling	X		X			X
Injector Pattern			X	X		
Number of Injection Elements			X	X		
Faceplate Heat Load			X	X	X	X
Type of Faceplate / Cooling					X	
Fuel Temperature		X	X	X		
Baffle Elements			X			
Injector Thermal Behaviour			X	X	X	X
H2 / CH4 Injector Behaviour			X	X	X	
Low Frequency Oscillations	X			X		
Injection Velocity Ratio	X	X	X	X		
Recess Length	X	X	X	X		
Element-Wall-Distance	X		X			
Margin Testing			X	X		

Table 1: Matrix of injector hardware and associated test objectives.

Development Driven Injector Screening Tests

Extensive technology and development test campaigns were performed comprising open cycle injection elements of various types and sizes as well as expander cycle elements. The subscale tests were mainly conducted with a standard 19 element injector head (Figure 3) employing a calorimeter combustion chamber (80 mm diameter, contraction ratio of 2,5). The main objectives typically address the optimization of the combustion performance and the determination of the wall heat flux evolution along the chamber axis depending on the individual injector configurations. Complementary objectives are often added aiming at propellant conditions, material investigations, or specific heat transfer issues such as film cooling, etc..

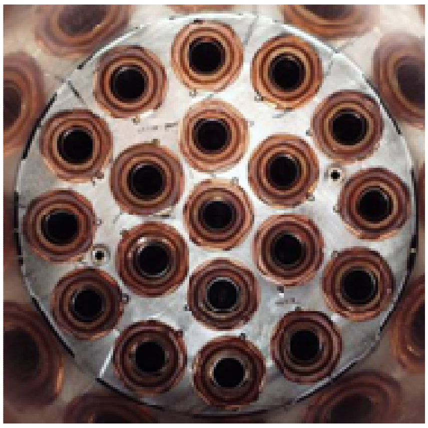

Figure 3: Standard modular 19 element Injector head - steel face plate with film injection slots mounted.

During development programs usually a screening approach is performed varying main design parameters in order to identify the best or most suitable concept. Thermal and hydraulic characteristics that are evaluated from those tests are then implemented in analytical and numerical models enabling a refined full-scale design.

Element Loading and Pattern

Within this group of technology tests the effect of element mass loading and pattern on combustion efficiency and wall heat flux distribution is of interest. In addition to this, the face plate is usually equipped extensively with thermocouples to gain sufficient information on face plate surface temperatures and heat fluxes. All tests are typically performed with the same combustion chamber set-up. In the course of different R&T projects, various types of injector sizes and corresponding propellant mass loadings have been tested in the past featuring 7, 12, or 15 injection element patterns as shown in Figure 4.

Objectives:

- reduction of no. of injection elements
- optimization of performance
- determination of wall heat flux distribution and wall compatibility
- face plate heat load
- effects of no. of injection elements

Parameters:

- injection element type
- injection velocity ratio
- recess length variation
- no. of injection elements and pattern

Figure 4: Injection element patterns - 15 element pattern (left), 12 element pattern (middle), and 7 element pattern (right, shortly after shut down showing face-plate icing).

Injection Temperature

The fuel injection temperature is a key parameter known to affect the propellant preparation inside the combustion chamber. For hydrogen the injection temperature is typically around 100 K for an open cycle gas generator engine like Vulcain or Vulcain 2. For a closed expander cycle engine like Vinci, the hydrogen injection temperature is much higher, e.g. around 220 K. By supporting the Vulcain and Vinci thrust chamber developments injection elements were designed and tested involving hydrogen temperatures from 100 to 270 K at similar injection momentum ratios. Further technology tests in this domain were performed with GH2 injection at ambient temperature, e.g. around 300 K, to investigate the impact of elevated propellant temperature on combustion performance and associated heat flux distribution along the combustion chamber wall.

Staged Combustion Injection (performed with H2 and CH4)

The most complex injection technology tests up to now were performed in 2008 mastering a representative staged combustion injection with liquid oxygen and hydrogen. In 2009 similar tests were performed with the propellant combination liquid oxygen and methane. These campaigns were conducted in cooperation between Snecma and Astrium within the frame of the Future Launcher Preparatory Program, FLPP, funded by the European Space Agency ESA [6], [7]. Snecma was responsible for the pre-burner while Astrium took charge of the overall set-up on the P8 including feed lines, main injector, and main combustion chamber as well as of the coordination and execution of the staged combustion test campaigns.

Objectives:

- verification of injection element functioning
- thermal conditions inside the injector
- investigation of coupling effects and low frequency oscillations
- optimization of performance
- determination of wall heat flux evolution
- determination of face plate heat load
- margin tests (only CH4 operation)

Parameters:

- face plate cooling
- modified injector for margin tests
- recess length variation
- injection velocity ratio

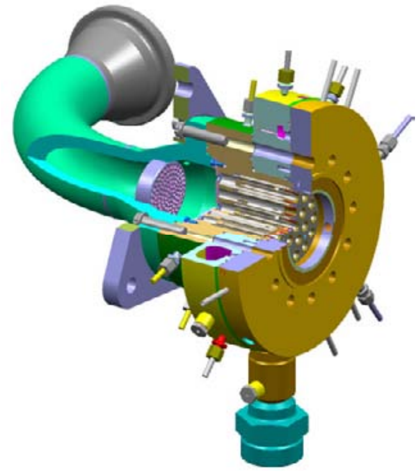

Figure 5: Subscale staged combustion injector.

Combustion Chamber Technology

The main modular combustion chamber hardware stock is summarised in Table 2 in line with its design purpose and objectives. Some typical pieces of this hardware stock are shown in the Figures 6 to 9.

	MCC Hardware					
Objective / Parameter	**Capacitive**	**Calorimeter**	**Integral**	**Segmented [8]**	**Modular Liner Monoblocks**	**Elastic Liner**
Performance, C*		X	X		X	
Axial Wall Heat Flux Evolution		X		X		
Global Heat Flux		X	X		X	X
Effect of Film Cooling		X	X			
Margin Testing	X					
New Start Up Sequences	X					
Risk Mitigation	X					
H2O cooling		X	X	X	X	X
LH2 cooling			X	X	X	X
L* variation by hardware combination		X	X	X	X	X
Liner Life Investigation						X
Hot gas wall contour variation		X			X	
PLD, APS, VPS thermal barrier coating [8]				X		

Table 2: Matrix of chamber hardware and associated test objectives.

Calorimeter Combustion Chamber

The calorimeter combustion chamber is the workhorse for most of the injector tests. It has a modular design that allows for replacement of a cylindrical section and a throat section. It comprises 11 individually water cooled cylinder segments and 9 individually cooled throat segments. Each segment has a varying number of circumferential cooling channels. The chamber diameter is 80 mm and the throat diameter is 50,6 mm. The combustion pressure limit for this hardware is around ~ 120bar. Furthermore, the interfaces between barrel and throat section as well as towards the injector head are designed in a way that the cylindrical section can easily be elongated by up to 6 axial cooled sections or so-called monoblock liners. As a result, different characteristic chamber length L* can easily be realized. Figure 6 illustrates this chamber hardware together with a set-up schematic providing four additional axial segments mounted between calorimeter cylinder and throat section. In total four cylindrical sections and two throat sections have been built and exposed to an accumulated hot firing test time exceeding 6000 sec.

Figure 6: Calorimeter Combustion Chamber - cylinder section (left), throat section (middle), and elongated calorimeter CC for L* effect analysis on performance and wall heat flux evolution.

Integral Combustion Chamber

This combustion chamber was built as a single piece with axial cooling channels to allow for high pressure testing. It is designed for chamber pressures up to ~170 bar which was successfully demonstrated during the staged combustion demonstrator tests performed at the P8 in March 2008 with LOX / H2, and early this year with LOX / CH4. Two hardware sets exist which are optionally water or liquid hydrogen cooled. Together, they have accumulated a hot firing time of 3250 sec. Both combustion chambers are still in excellent condition. Figure 7 shows the chamber liner together with a picture taken during a staged combustion hot run at the P8 bench.

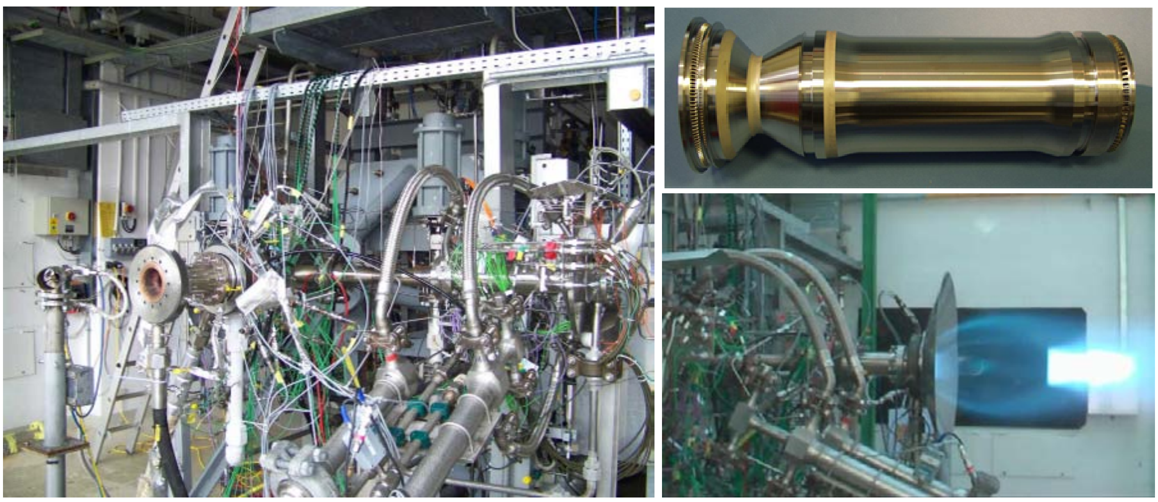

Figure 7: High pressure test of integral chamber in LOX / CH4 staged combustion configuration (left, bottom right), liner hardware (top right).

Contoured Liner with Ribs

In the course of expander cycle engine technology preparation, the controlled enhancement of the hot gas to coolant side heat transfer has driven the development of a liner with cryogenically cooled ribs. Figure 8 shows a 3D-illustration of the modular hardware set-up together with the liner after hot firing. Heat load enhancement was found to range in the order of 30% for this configuration. No significant wall degradation effects were observed after an accumulated test time of 15 cycles and 390 sec [8], [9].

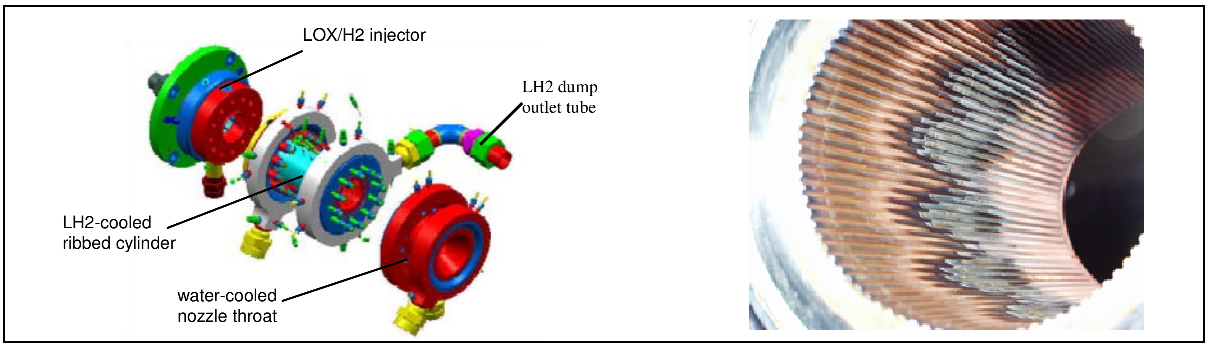

Figure 8: Ribbed combustion chamber - 3D-schematic of test set-up (left) with liner status after 15 cycles and 390 sec hot run time (right).

Figure 9: Combustion chamber hardware - elastic liner (left), modular liner monoblocks [10], [11] (middle), axial cooled chamber segments [8], [12] (right).

Nozzle Extension Technology

In the past also numerous nozzle subscale tests were performed in order to investigate nozzle flow issues and phenomena such as supersonic heat transfer, film cooling, condensation, as well as flow separation and shock patterns. Table 3 gives an overview on the different technologies that were hot tested at the P8 facility.

Ceramic composite (C/SiC) materials are being developed as a promising technology for significant mass reduction of high area ratio nozzle extensions. In that frame a radiation-cooled ceramic subscale nozzle extension was designed to demonstrate the material's thermal and mechanical capabilities at representative ground stage operating conditions. Additionally, the flow field evolution in the expansion regime was investigated in further detail [1], [9]. The potential of this technology was impressively demonstrated by operating the ceramic nozzle at chamber pressures up to 80 bar at varying structural and thermal loads (see also Figure 10). Valuable data were gained for modelling the transition from free shock separation to restricted shock separation enabling a better understanding of the related thermo-mechanical loads under such extreme conditions [13], [14], [15].

In 2001, the three partners Volvo Aero Corporation, DLR, and Astrium agreed to jointly undertake the "Calorimeter Nozzle Program" with the aim to enhance the design models for nozzle pressure evolution, supersonic wall heat transfer, and side-load characteristics. Several hot fire test campaigns were successfully conducted in 2003. The results of this activity also served as a contribution to the European FSCD working group studying flow separation and side-load behaviours in rocket nozzles. Objectives, test hardware, and outcome of this program are described in more detail in [14], [16], and [17].

More recently, ablative composite materials were investigated as a low-cost substitute for dump-cooled nozzle structures today employed on the Vulcain engine family. Figure 11 shows this particular hardware set-up comprising the calorimeter chamber with ablative nozzle before, during, and after hot firing.

Objective / Parameter	NE Hardware: Tube Wall †	C/SiC Composit	Ablative Composit	Calorimeter	NE Skirt ‡	Cu Monoblock Cone
Flow Separation Characterisation		X		X	X	
Material Characterisation	X	X	X			
Axial Wall Heat Flux Evolution		X		X	X	
Global Heat Flux	X			X		X
Effect of Film Cooling	X			X	X	
Side loads					X	
Phenomenology, Data Base Generation			X			X
LH2 cooled	X					X
GH2 cooled				X	X	
H2O cooled				X		
Ablative cooled			X			
Radiation Cooled		X			X	
Film cooled	X			X		
Water Condensation						X

Table 3: Matrix of NE hardware tested and associated test objectives

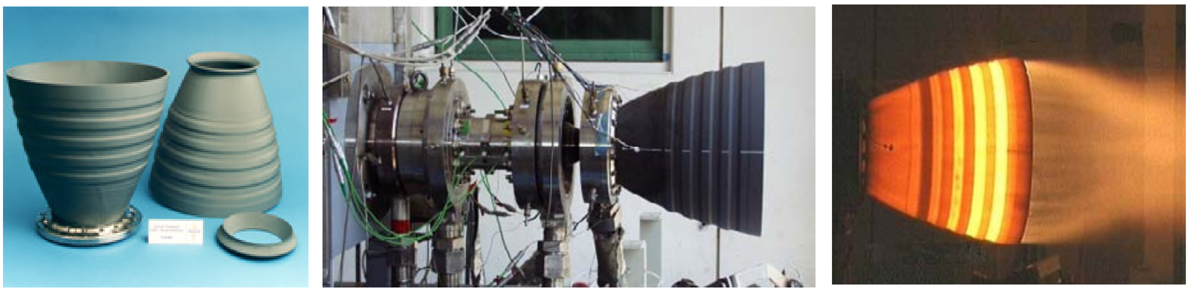

Figure 10: Ceramic nozzle extension - after manufacturing (left), mounted at bench (middle), and during hot gas operation featuring restricted shock separation (right).

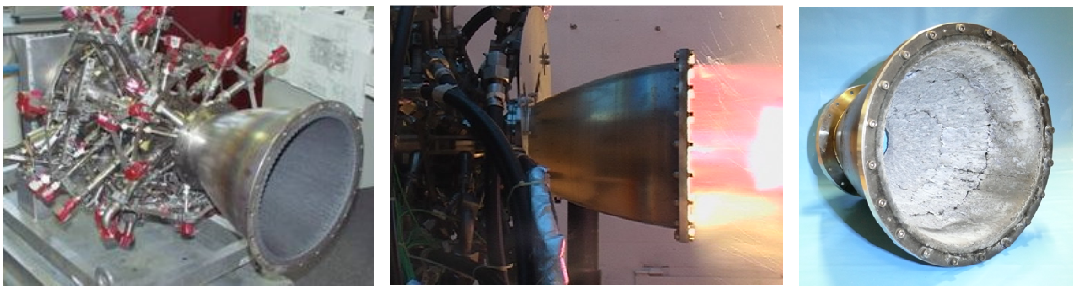

Figure 11: Ablative nozzle extension – hardware set-up prior to installation at the P8 bench (left), during hot firing (middle), and after testing (right).

† Tube Wall Nozzle Extension manufactured and supplied by Volvo Aero Corporation
‡ Nozzle skirt and GH2 actively cooled base nozzle with film layer manufactured and supplied by VAC

CONCLUSION & OUTLOOK

The information published within this paper has tried to illustrate the important role of subscale testing for basic research, technology development and design verification in the field of rocket thrust chamber systems covering advanced injectors, combustion chambers, as well as different kind of nozzle extensions.

Over the past 10 years, many physical phenomena related to rocket engine, and more specifically to thrust chamber technology have been studied in detail employing a huge variety of different hardware sets. Among the most important ones is the interaction of the injector design and propellant state with the performance and wall heat transfer evolution in combustion chambers, a crucial prerequisite for instance in regard to a successful design of a rocket motor's structural life. In addition to this, specific flow situations were investigated such as condensation effects along overcooled walls, shock transition, or separation of overexpanded flows in high area ratio nozzles. The results delivered form all these tests have successfully demonstrated to support a wide range of scalability issues.

Beyond this, subscale testing can easily enable the proof of concepts and the comparison of different engineering approaches to master challenges in rocket engineering. The data recorded during specially tailored tests are of key importance for the design engineers to improve the capability of their predictive tools as basis for a reliable and efficient layout and design of rocket engines.

The complexity of the systems tested at P8 has been increased step by step over the years. The current hardware stock and the layout of the test facility allows for the application of different fuels (LH2, GH2, GCH4) and coolants (LOX, LH2, GH2, H2O) with multiple test set-ups that can be adapted to meet the requirements of future technology and development programs.

The application of state-of-the-art intrusive and non-intrusive diagnostics at the P8 paved the way to constantly increase the quality of the data recorded. The lessons learned from such testing are continuously transferred to full-scale programs.

The test procedures which are applied at the P8 have been optimized in the meantime for a maximum gain of information at an acceptable risk of test aborts. Flow-checks embedded within the nominal hot firing sequence give the potential to record additional data without extra cost; intended redlines maximize test time and allow to collect more data within a single test.

Today, the advanced programs test team at Astrium is prepared to deliver data and information for nearly any question regarding the operation of a rocket thrust chamber system with high degree of flexibility and on a short term basis.

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