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Advanced Nozzle Testing in Flight Conditions

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The development of advanced nozzles for main stage engines is one of the potential to increase the performance of a launcher. The transition from sea level conditions at the launch pad up to high altitude conditions during flight requires special nozzles designs for maximum thrust. To test advanced nozzles the flight conditions has to be simulated. There is a project in cooperation between the Engineering and the Research department at DLR test center for advanced altitude simulation with flight like test conditions. The objective is to develop the necessary technologies primarily for the verification of nozzles loads and flow conditions. Main requests are simulation of the thermal loads by hot gas, variable and adjustable ambient pressure and the surrounding flow conditions.

Nomenclature

AAS P8	= **A**dvanced **A**ltitude **S**imulation P8	*M*	= Mach number
ARIANE	= European Launcher	*PIV*	= Particle Image Velocimetry
BOS	= Background Oriented Schlieren	*ROF*	= Mixture Ratio Propellants
DLR	= German Aerospace Centre	*VULCAIN*	= ARIANE 5 main engine SNECMA Moteur
FSCD	= Flow Separation Control Device		

I. Introduction

FROM the very beginning in the 1960s, DLR Lampoldshausen has been involved in all European launcher programs and one of its main tasks has always been high altitude testing of rocket engines. For basic research how to generate test conditions more closely to the flight loads and for the basic research in advanced nozzles the P6.2 cold gas test facility was developed in 1998. The increasing impulse (Figure 1) of advanced nozzles like dual bell nozzles is one of the potential to increase the performance of a launcher.

The main task was the design of an altitude simulation with variable pressure conditions during test. Today the pressure is regulated from p = 1 bar (sea level conditions) down to p < 10 mbar (altitude conditions). The objectives are the investigation of flow separation and transition phenomena of nozzles like dual bell or plug type nozzles done in the field of flow separation control device (FSCD).

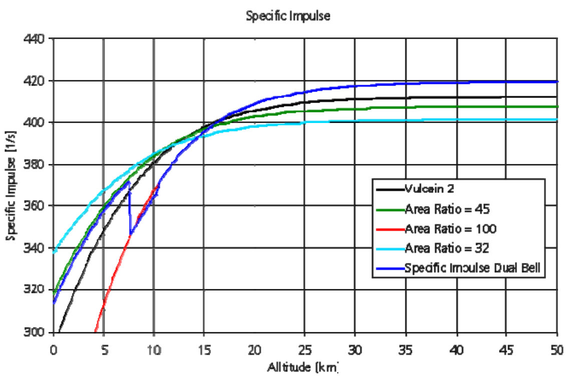

Figure 1: Specific Impulse Nozzles
Nozzle research, technology department

Driven by the experience with the Load Simulation Device tests of the VULCAIN II nozzle at the test facility P5, the investigations in the environmental flow conditions of the ARIANE 5 launcher especially the tail of the launcher and with the development of the altitude simulation test facility P4.1 for VINCI engine the decision are done to do further investigations in technologies to create real flight conditions during test. Besides the variable ambient pressure mainly the heat loads, the surrounding flow and the

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dynamical loads has to be generated. The first step for the research in nozzles on subscale level an Engineering Project "**A**dvanced **A**ltitude **S**imulation P8, AAS P8" has started. The task is to design and develop the technologies of a flight simulation for rocket engines at the research test facility P8.

II. Basic Conditions and Simulation Requests

The tests requests for the AAS P8 are based on the flight condition of the ARIANE 5 launcher to have similar nozzle loads and flow conditions. The target is to investigate nozzles on a VULCAIN II - class engine at lower scale. Additional drivers for the test requests come from the test facility P8. The main test requests are:

Nozzle:

- Verification of the interaction between internal and external flow
- Qualification of mechanical and thermal loads
- Verification of modeling and codes
- Verification of transient internal flow conditions and side loads

Test technologies:

- Simulation of variable and adjustable ambient pressure (flight profile)
- Simulation of the surrounding flow conditions
- Special Diagnostic and Measurements techniques for flow visualization and the side load measurements

A. Basic Flight Conditions ARIANE 5

The basic flight conditions of the ARIANE 5 for the VULCAIN engine are:

- Ignition and Start up of the VULCAIN engine at sea level (1 bar, no surrounding flow, acoustic loads, etc.)
- Start up of the booster and lift off (decreasing ambient pressure, increasing surrounding flow, flight control operations, acoustic loads, aero-dynamic loads, acceleration loads, buffeting)
- Transonic phase (altitude ~7 km, ambient pressure ~ 400 mbar, velocity ~ M = 1)
- Maximum acceleration (altitude ~39 km, vacuum conditions, velocity ~ 1600 m/s)
- Shut down of the booster (altitude ~65 km, vacuum conditions, velocity ~2000 m/s)
- Shut down VULCAIN (altitude ~ 140 km, ambient pressure 10^{-6} mbar, velocity ~7600 m/s)

CFD calculations by DLR Göttingen (Figure 2) give an idea of the flow conditions around the VULCAIN II engine during flight. Especially the after body of the launcher influences the direct environment of the rocket engine.

Figure 2: CFD Calculation ARIANE launcher, DLR Göttingen

B. VULCAIN

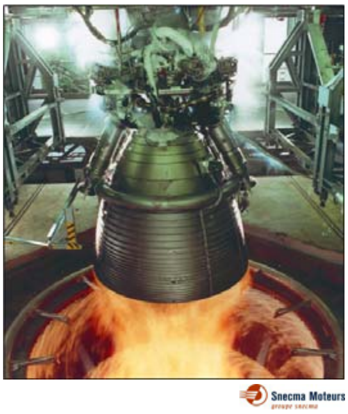


Figure 3: VULCAIN II at P5

The VULCAIN is the main engine of the ARIANE 5 launcher built by SNECMA Moteurs (Figure 3). The principle specifications are mentioned in Table 1.

The conditions for the nozzle are given by the dimensions and cooling behavior (dump cooling and turbine gas injection).

The flight loads of the VULCAIN II nozzle was verified by a Load Simulation Device during ground testing at test facility P5. The vacuum conditions were realized by a suction system to generate low pressure conditions around the nozzle. The variation and justification of the pressure was done by a nitrogen ejector system.

Technical specifications VULCAIN II	
General	
Total thrust (vacuum)	1 350 kN
Combustion pressure	115 bar
Area ratio	60
Overall mass flow rate	320 kg/s
Mixture ratio	7,15
Height	3,60 m
Diameter (nozzle exit)	2,15 m
Specific impulse (vacuum	433 s

Table 1: Specifications VULCAIN II

C. Launcher Conditions ARIANE 5

Due to the geometrical situation of the ARIANE 5 launcher at the launch pad (Figure 4) the dimensions of the VULCAIN nozzle are limited. The arrangement of the exhaust gas guiding system and the dimensions of the launch pad gives a visible expansion ratio to be realized up to $\varepsilon = 100$ with the VULCAIN.

Figure 4: ARIANE 5 Launch Pad

D. P8 Test Facility

The P8 (Figure 6) is a research and development (R&D) test facility operated by DLR on cooperation between the partners SNECMA, EADS-ST, CNES, and DLR in the field of high-pressure, Hydrogen-Oxygen and green propellant combustion research.

Figure 6: Test Facility P8

Subscale combustor of 50 mm and 80 mm chamber diameter are successful operated with Pc > 100 bar chamber pressure at P8.

With the 50 mm combustor the self sustaining subscale centre body diffuser of the P4.1 VINCI altitude simulation was tested (Figure 5). There was the same test conditions like VINCI (ROF = 6, Pc = 60 bar, H2/O2 combustion).

Figure 5: Model Diffuser at P8

The feeding conditions are a high pressure supply for GH2, LH2 and LOX (Figure 7).

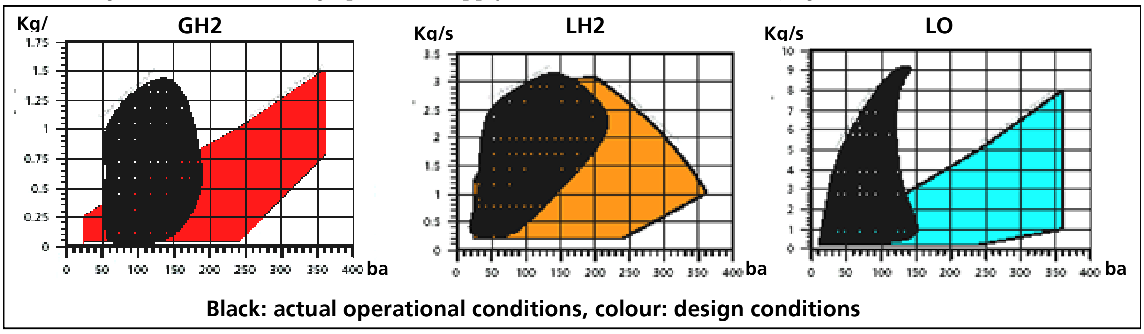


Figure 7: Feeding Conditions P8

E. P6.2 Cold gas Test Facility

The test position P6.2 has been developed in the field of gas dynamic studies in cold gas conditions. A special task is the simulation of transient environmental pressure conditions similar to the flight of a launcher.

1. Principle of P6.2

The P6.1 (Figure 9) consists of a vacuum chamber combined with exchangeable super- or subsonic diffusers and optional an ejector system.

Figure 9: Test Position P6.2

The principle (Figure 8) allows the regulation of the pressure inside the vacuum chamber depending on the behavior of the diffuser, ejector and the bleed gas injection. The pressure can be adjusted between 1 bar and <10 mbar. The P6.2 parameters are mentioned in Table 2.

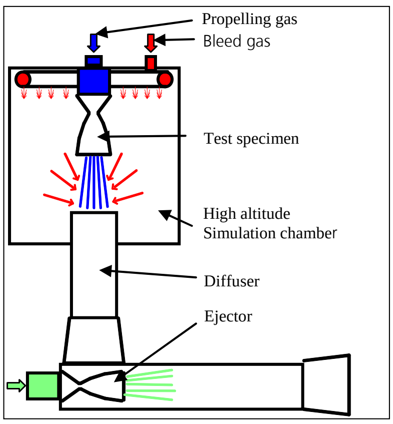


Figure 8: Principle P6.2

Conditions P6.2	Description
Supply system	N2 cold gas, m ≈ 2.8 kg/s (optional 4.2 kg/s), regulated P = 10 – 40 bar (optional 55 bar)
Test time	> 60 s with full flow
Altitude simulation	Vacuum chamber < 10 mbar – 1 bar, adjustable for the research of transition phenomena
Measurement and control system	64 LF channels up to 1 kHz, 16 HF channels up to 100 kHz, 32 digital I/O, 4 GB capacity

Table 2: P6.2 Conditions

2. Regulation of vacuum pressure

One possibility to regulate the pressure inside the vacuum chamber is the variation of the ejector supply pressure. In order to simulate the flight profile a pressure regulation sequence was installed to control the ejector supply pressure and also the vacuum chamber pressure directly within certain limits. In a wide region the vacuum pressure have a static functional dependency of the ejector supply pressure (Figure 10). In these regions the vacuum chamber pressure can be regulated directly.

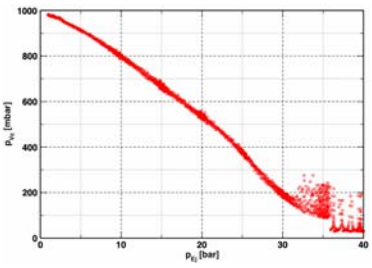


Figure 10: Regulated Ejector

An adapted PID regulation is used for this operation. The valve opening is calculated directly. The P6 altitude simulation with ejector supply pressure regulation allows vacuum pressure adjustment within accuracy of 3% relating to 1 bar.

With the new regulation loops tests for a dual bell nozzle (Figure 12) for the technology department were successfully performed. The objective was the analyzing of the flow transition from the first bell to the second bell without feedback from the altitude simulation.

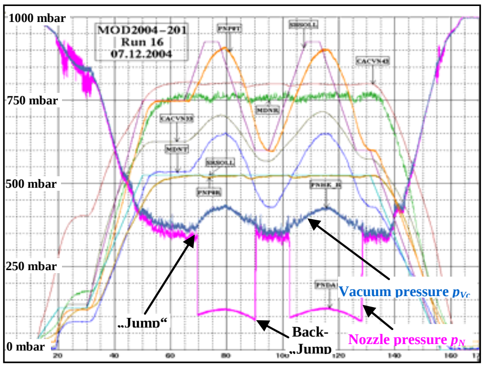


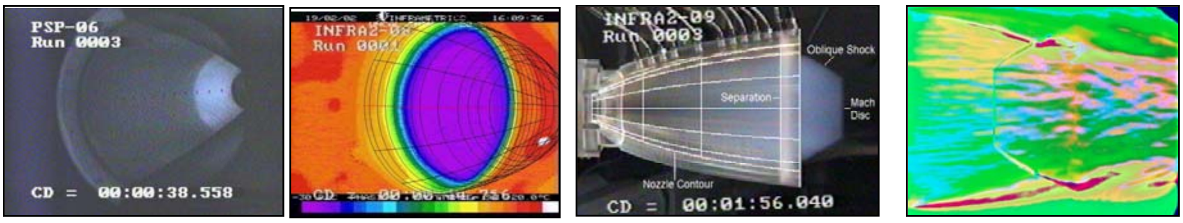
Figure 11: Dual Bell Tests, research department

The flow “jumping” reacts into a strong momentum change, which has to be compensated by the suction system to prevent the direct “back jumping”. The “jumping” behavior was as expected without direct “back jumping“(Figure 11).


Figure 12: Dual Bell Nozzle P6.2

3. Visualization Techniques

Different visualization techniques (Figure 13) are in verification which was developed and used during the nozzle research for the technology department at the P6.2, like Pressure Sensitive Paint (PSP), Backflow Frosting (BFF), Infrared Thermography (IRT) and Schlieren Optic. Actual the methodical of Schlieren optic will be improved for the introduction at P6.2. (see current status).



PSP IRT BFF Schlieren

Figure 13: Visualization Techniques used for the nozzle testing of the technology department

III. Specification Advanced Altitude Simulation P8

The principle specifications of the advanced altitude simulation P8 based on the conditions mentioned before are:

Hot Gas Conditions:

- Subscale Combustor (Figure 14), scale to VULCAIN II is 1 to 8.
- Mixture Ratio ROF = 5 – 7,5
- Chamber Pressure Pc = 150 bar maximum.
- Mass flow m = 6 kg/s maximum.
- Stable combustion and high reliability in the whole operational envelope up to maximum conditions.
- Homogeneous temperature and flow field.
- Thermodynamically and flow characteristics close to VULCAIN II.
- Operational with Hydrogen and Methane.

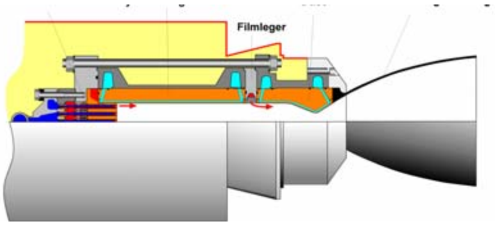


Figure 14: Subscale Combustor
Critical design review Chamber E

Nozzle:

- Exchangeable nozzle configurations, VULCAIN II like, Dual Bell nozzle, extensible nozzle, different materials, etc.
- Expansion ratio of nominal 60, maximum 100.
- Exit Diameter of D = 330 mm maximum.
- H2 dump cooling.
- Turbine gas injection simulation.

Ambient Conditions:

- Variable and adjustable pressure between 1 bar - 100 mbar.
- Surrounding flow conditions of maximum M=2.
- Flow conditions with N2 and air (after burning with hydrogen rich gases, interaction of the internal and external flows, etc.).
- Simulation of radiation conditions (heat shield, thermal simulation).

Test Conditions:

- Diagnostics and visualization of the flow.
- Thrust and side load measurement.
- Test time T > 30 s steady state.
- Different operational points by control loops during test.

IV. Current Status of the Advanced Altitude Simulation P8

The Engineering project of the advanced altitude simulation P8 starts beginning 2005. Two working groups one for the hot gas generation and the nozzle design and the other for the variable and adjustable pressure simulation and the surrounding air flow conditions are implemented.

F. Status of hot gas generation and nozzle:

- Critical design reviews for the subscale combustor and the nozzle are performed.
- Special investigations are done concerning the film cooling, the heat loads and the measurements for the heat loads driven by the mixture ratio up to ROF = 7,5 and chamber pressure up to 150 bar. First verification of the heat loads and static loads (Figure 15) are done for the critical design review, see references.
- Hardware configurations and designs are under verification.
- The first nozzle design will be close to the VULCAIN II nozzle for the verification of the VULCAIN II like test conditions.

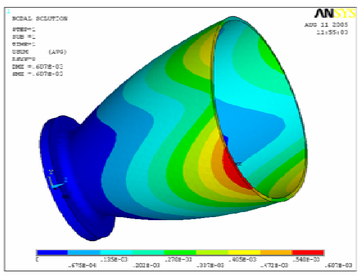


Figure 15: Modal Analysis Nozzle
Critical design review Chamber E

G. Status of flight simulation P8:

The requirements are verified and there is a first basic configuration (Figure 16) with a self sustaining super sonic diffuser for the recompression of the nozzle exhaust jet. On of the deeper investigations is the cooling behavior of the diffuser.

For the air flow around the nozzle an ejector system is in study to maintain the necessary pressure conditions. The air will be sucked from the ambient by an ejector system. Especially the start up of the super sonic flow has to be investigated.

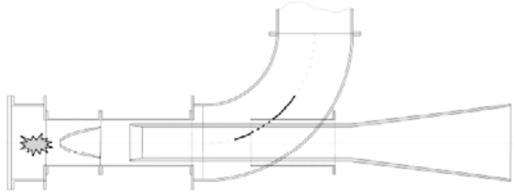


Figure 16: Concept of test set up P8

H. Status of P6.2 Cold Gas Demonstration

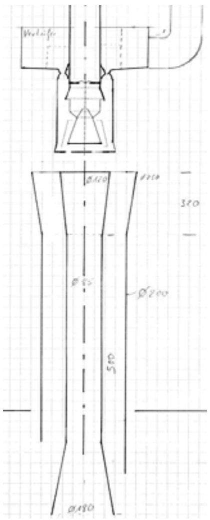


Figure 17: Design P6.2

In a first step the principal design and function will be investigated and demonstrated at the cold gas test facility P6.2.

The critical design review for P6.2 is performed and the test set up is designed (Figure 18).

The nozzle is mounted vertical inside the vacuum chamber. The “bleed gas “is guided by a ring nozzle and glass cylinder to create the surrounding flow conditions. The exhaust jet of the investigated nozzle is recompressed by a diffuser (Figure 17).

The pressure will be adjusted by the regulation of the suction pressure of the ejector or/and by regulation of the “bleed gas” mass flow. These regulation principles are already used and verified.

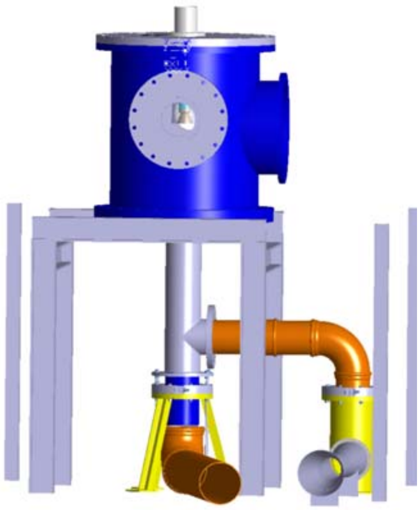


Figure 18: Test Set Up P6.2

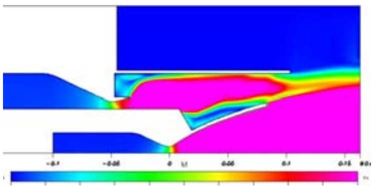


Figure 19: CFD Calculation P6.2

The contour of the circulation area around the nozzle is defined according the ARIANE 5 after body. The verification of the surrounding flow conditions is started by CDF calculations (Figure 19).

To simulate dynamical loads the bleed gas will be stimulated by pressure oscillation.

The existing side load measurement assembled by a ring equipped with strain gauges will be used.

I. Diagnostics

For the visualization of the flow conditions at P6.2 two optical diagnostics are foreseen, the Background Oriented Schlieren (BOS) and the Particle Image Velocimetry (PIV).

The difficulties are driven by the vacuum chamber and the glass cylinder. The two diagnostics will be operated in parallel (Figure 20). The BOS operates with a by modified speckle muster, created by backlight. The PIF needs traces particle visualized by a light sheet and detected by a high velocity camera.

To verify the diagnostics basic experiments and special calibration tests with the glass cylinder are foreseen.

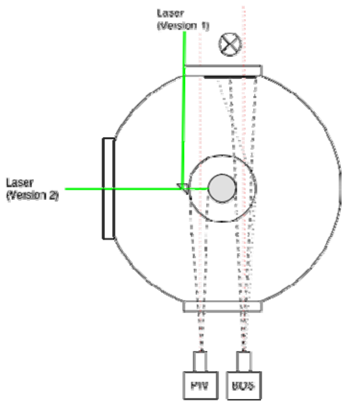


Figure 20: Diagnostics P6.2

V. Conclusion

With the experience of the loads simulation device for the VULCAIN II nozzle and the altitude simulation at P6.2 there are techniques to simulate flight loads. For development of new advanced nozzle designs and materials test conditions very similar to the flight are essential. The verification of the calculations and modeling of the nozzles and to qualify the design itself is the main request during development.

With engineering project of the advanced altitude simulation P8 the necessary technologies will be investigated and prepared for the application at the test facility P8.

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