SIMULATION OF ENVIRONMENTAL FLIGHT CONDITIONS BY ADVANCED ALTITUDE SIMULATION

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1 Abstract

New developments like advanced nozzles or the unexpected events of the ARIANE flight drive again the question how to qualify rocket engines and propellant systems for the flight and how to generate data bases for the verification of the functional models. It's getting more and more necessary to test rocket engines and nozzles closer to original flight conditions. For the main stage engines it's the transition from sea level conditions up to altitude conditions and for upper stages and satellites propulsion it's high altitude conditions.

Today altitude simulation is primarily the testing of rocket engines in vacuum and simulated thermal environmental condition. For the verification of the VULCAIN II nozzle loads first time a load simulation device was designed to simulate the transient ambient pressure during flight from 1 bar to vacuum. The simulation was mainly to verify the loads of the hot nozzle in changing ambient pressure conditions down to vacuum. An additional device simulates the loads of buffeting by the introduction of mechanical forces to the nozzle during test.

At the Institute of Space Propulsion there is an engineering project for advanced altitude simulation with test conditions more closely to the flight. The objective is to develop the necessary technologies primarily for the verification of nozzles loads and flow conditions of the nozzle. There are 3 main requests to the advanced altitude simulation:

1. Hot gas conditions like VULCAIN II.
2. Variable, adjustable ambient pressure down to vacuum.
3. Surrounding flow of the nozzle.

The paper gives a short overview of the current status of the advanced altitude simulation.

2 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.

To maintain the experience of the test facility engineering and to improve the altitude simulation especially the development of rocket steam generators and the simulation of flight conditions the department of engineering was founded in 1996 within the institute of space propulsion.

In 1998 the P6.2 test facility was developed and erected for the improvement of the altitude simulation and for basic research in flow separation of over expanded nozzles. The main task was the development of an altitude simulation with variable pressure conditions. The pressure should be regulated from $p = 1$ bar at sea level down to $p < 10$ mbar in altitude. The objectives were the investigation of flow separation and transition phenomena of nozzles like dual bell or plug type nozzles.

Due to the experience with the Load Simulation Device tests of the VULCAIN II engine and the altitude simulation of the P6.2 the decision are done to do further investigations in technologies for advanced altitude simulation testing close to the flight. Additionally the work done in the field of flow separation control device at the P6.2, the general basic research and development work for new advanced nozzle designs and the investigations in the environmental flow conditions of the ARIANE 5 specially the tail of the launcher, an Engineering Project "Advanced Altitude Simulation P8" started at the Space Propulsion Institute of DLR Lampoldshausen. The task is to design and develop the technologies of a flight simulation for rocket engines at the test facility P8.

3 Simulation Requests and Specifications

The requests for the Advanced Altitude Simulation 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 specification are the launcher conditions and the test facility P8.

The goals are the investigation in nozzle and test technologies detailed as follows:

Nozzle:

- Verification of the interaction between internal and external flow
- Qualification of mechanical and thermal loads driven by the ambient conditions and the flow interaction
- Verification of modelling and codes
- Verification of transient internal flow conditions and side loads

Test technologies:

- Simulation of variable and adjustable ambient pressure within a vacuum cell by supersonic diffuser
- Simulation of the surrounding flow conditions
- Special Diagnostic and Measurements techniques like flow visualisation and the side load measurements

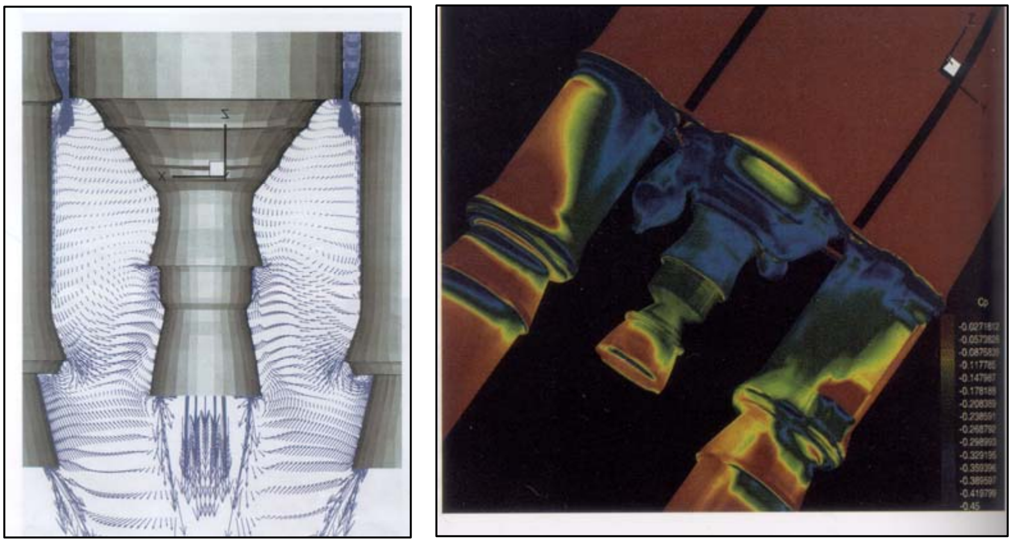
3.1 Flight Conditions ARIANE 5

The basic flight conditions of the ARIANE 5 [R1] for the VULCAIN engine are:

- Ignition and Start up of the VULCAIN engine at sea level conditions (1 bar ambient pressure, 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, aero-acoustic loads, acceleration loads, buffeting loads)
  - Transonic phase (altitude about 7 km, ambient pressure about 400 mbar, velocity about M = 1)
  - Maximum acceleration (altitude about 39 km, vacuum conditions, velocity about 1600 m/s)
- Shut down of the booster (altitude about 65 km, vacuum conditions, velocity about 2000 m/s)
- Shut down VULCAIN (altitude about 140 km, ambient pressure 10^{-6} mbar, velocity about 7600 m/s)

CFD calculations [R2] 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.

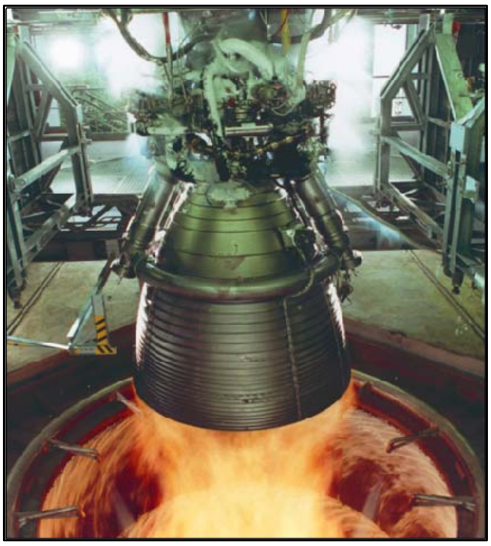
Fig. 1: CFD Calculation after body of the ARIANE launcher



3.2 VULCAIN II

The VULCAIN II is the main stage engine of the ARIANE 5 launcher built by SNECMA Moteurs “Fig 2”. The principle specifications [R3] are mentioned in table 1.

Fig.2: VULCAIN II at test facility P5



Tab. 1: Specifications VULCAIN II

Technical specifications VULCAIN II

General	
Total thrust (vacuum)	1 350 kN
Specific impulse (vacuum	433 s
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

Additional requests are given by the chamber geometry and cooling behaviour (dump cooling and turbine gas injection).

During start up at sea level the nozzle flow is over expanded close to the limits of flow separation. During flight the ambient pressure decreases to vacuum. The thrust increases to vacuum thrust of 1350 kN. Additional structural loads primarily for the nozzle are coming from flight control operations like Gimballing and loads like buffeting of transonic conditions.

The flight loads was verified by a Load Simulation Device during ground testing. The loads of the vacuum conditions and buffeting were realised by a suction system to maintain low pressure conditions at the nozzle outside and by mechanical forces introduced to the nozzle surface. The variation and justification of the pressure was done by a nitrogen ejector system and a regulation valve in the suction line. The pressure characteristic was very close to the flight profile.

3.3 Launcher Conditions ARIANE 5

Due to the geometrical situation of the ARIANE 5 launcher at the launch pad “Fig 3” [R4] 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 realised of $\varepsilon = 100$ maximum with the VULCAIN II.

Fig.3: ESC-A at the launch pad

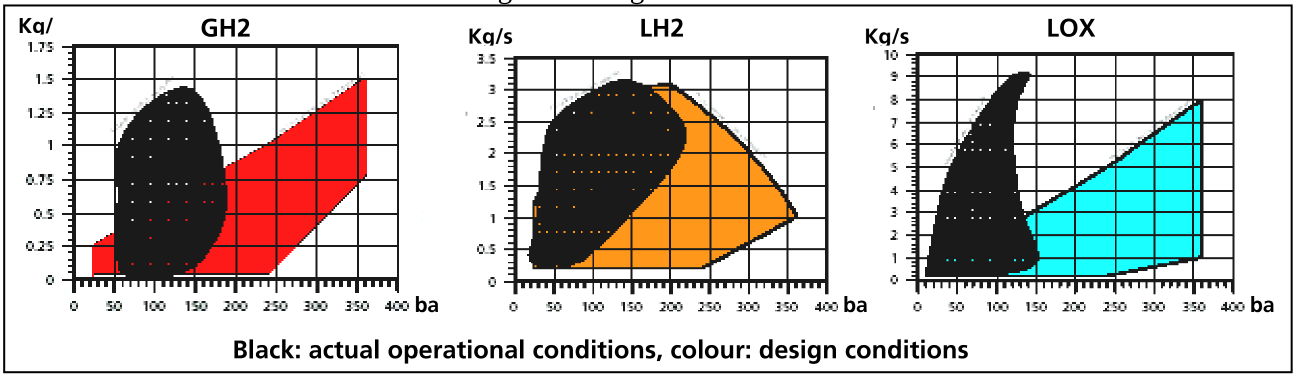
3.4 P8 Test Facility

The P8 “Fig.4” 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 combustion research.

Fig.4: Test Facility P8

The feeding conditions are high pressure supply for GH2, LH2 and LOX “Fig. 5”.

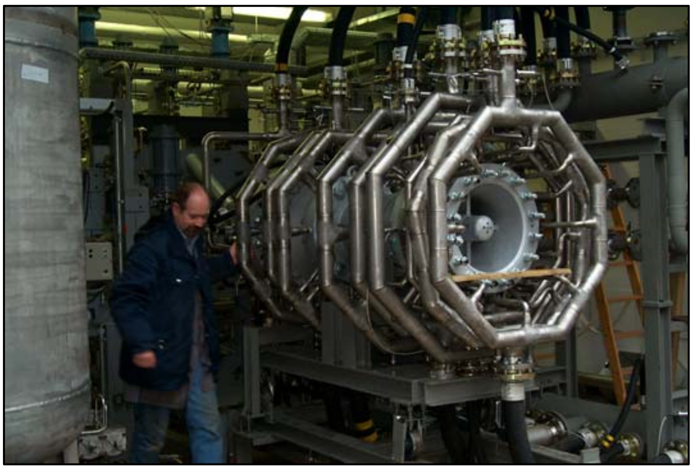
Fig.5: Feeding Conditions P8



Black: actual operational conditions, colour: design conditions

Subscale combustor of 50 mm and 80 mm chamber diameter are successful operated at P8. With the 50 mm combustor the self sustaining subscale centre body diffuser of the P4.1 VINCI altitude simulation was tested “Fig. 6” with the same test conditions like VINCI (ROF = 6, Pc = 60 bar, H2/O2 combustion).

Fig. 6: Hot gas Model Centre Body Diffuser P4.1



3.5 Specification Advanced Altitude Simulation P8

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

Hot Gas Conditions:

- Scale to VULCAIN II about 1 to 8-10.
- 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

Nozzle:

- Exchangeable nozzle configurations (VULCAIN II like, Dual Bell nozzle, extensible nozzle, etc.).
- Expansion ratio of 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 and 100 mbar
- Surrounding flow conditions of maximum Mach number M=2
- Flow conditions with air (after burning with hydrogen rich gases, interaction of the internal and external flows, etc.)
- Radiation conditions (heat shield, thermal simulation)

Test Conditions:

- Diagnostics and visualisation of the flow
- Thrust and side load measurement
- Test time T > 30 s steady state,
- Different operational points during test

4 P6.2 Cold Gas Test Facility

The test position P6.2 has been developed and erected in the field of gas dynamic studies in cold gas conditions. The objectives for P6.2 are basic research in altitude simulation for rocket engines and in flow separation phenomena of advanced nozzles. A special task for the P6.2 facility is the simulation of transient environmental pressure conditions similar to the flight conditions of a launcher during lift off.

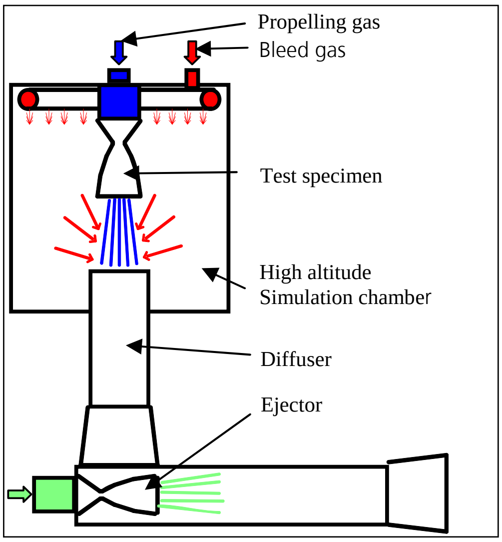
4.1 Principle of P6.2

The P6.1 “Fig. 7” consists of a vacuum chamber combined with exchangeable super- or subsonic diffusers and optional an ejector system.

Fig.7: Test Bench P6.2

The principle “Fig. 8” allows the regulation of the pressure inside the vacuum chamber depending on the behaviour of the diffuser, ejector and the bleed gas injection. The pressure can be adjusted between 1 bar and <10 mbar.

Fig. 8: Principle P6.2



The P6.2 conditions are mentioned in table 2.

Tab 2: P6.2 Conditions

Conditions	**Description**
Supply system	N2 cold gas, m ≈ 2.8 kg/s (optional 4.2 kg/s), pressure regulated from 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

The characteristic of the pressure inside the vacuum chamber (fig. 2) can be controlled with respect to the requested profile, parameters are:

Diffuser characteristics:

- Sub sonic diffuser (1 to 0,5 bar) or super sonic diffuser (1 to 0,05 bar)
- Different types (Tube Diffuser, Second Throat Diffuser, Centre Body Diffuser)

Geometrical conditions:

- Distance nozzle to diffuser inlet, gap between nozzle and diffuser, volume of the vacuum chamber, etc.

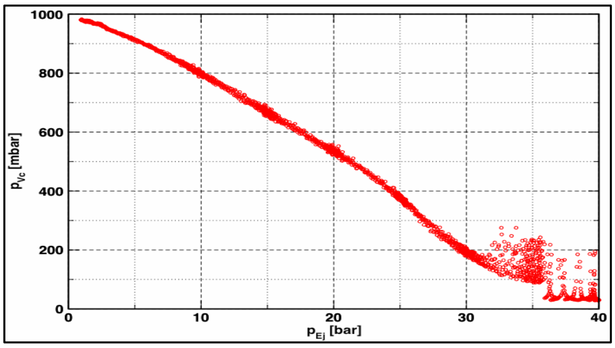
Additional conditions:

- Extractions of boundary layers, use of ejector stages, bleed gas characteristic and conditions.

4.2 Regulation of vacuum pressure

One possibility to regulate the pressure inside the vacuum chamber P_{Vc} is the variation of the ejector supply pressure P_{Ej}. 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 “Fig. 8”. In these regions the vacuum chamber pressure can be regulated directly.

Fig. 9: Vacuum Pressure with Ejector System



An adapted PID regulation is used for this operation. The valve opening S_{valve} is calculated directly (1).

$$S_{valve} = S_{valve}(t_{-1}) + G_0 e(t) + G_1 e(t_{-1}) + G_2 e(t_{-2}) \qquad (1)$$

The function $e(t)$ is depending on the set point deviation and G_0, G_1 and G_2 are PID parameters (2):

$$
\begin{aligned}
G_0 &= K_R\left(1+\frac{T_D}{T}\right) \\
G_1 &= -K_R\left(1+\frac{2T_D}{T}-\frac{T}{T_I}\right) \qquad (2) \\
G_2 &= K_R\left(\frac{T_D}{T}\right)
\end{aligned}
$$

The parameters where determined experimentally and depends on the reaction time of the regulation valve as well as on the fluid system. The error function $e(t)$ (3) is calculated with the set point deviation and a function of depending of the real value, where p_{sp} is the pressure set point.

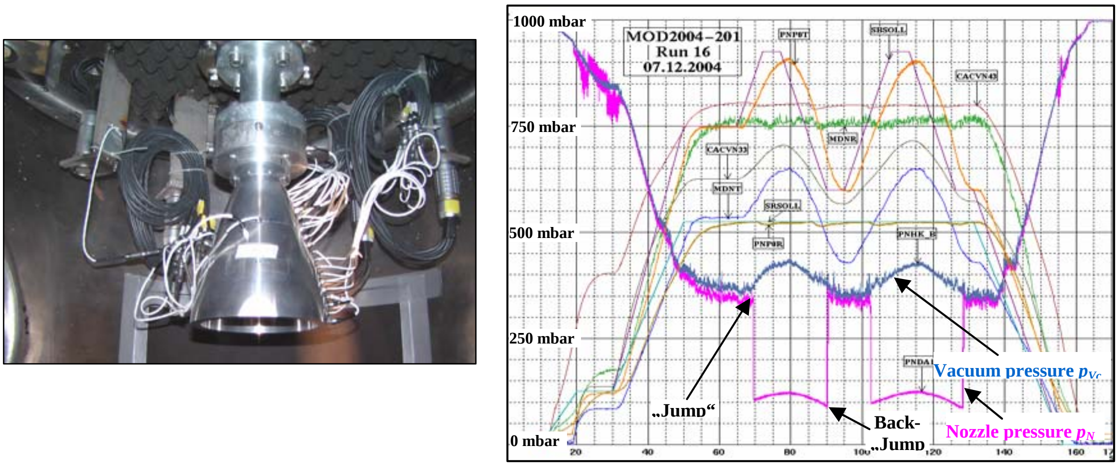
$$e(t) = -\frac{(p_{sp} - p_{Vc})}{C + p_{Vc}} \qquad (3)$$

The constant C was also experimentally determined. The closed loop regulation fails at pressure values p_{Vc} below 200 mbar. These points can only be reached by an open loop regulation of the ejector supply pressure p_{Ej}.

The P6 altitude simulation with ejector supply pressure regulation allows vacuum pressure adjustment with an accuracy of 3% relating to a pressure of 1 bar also with mass flow starting from the test specimen.

With the new regulation loops a test campaign for a dual bell nozzle “Fig. 10” was 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. 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 nozzle was tested without diffuser. Only the ejector system was used. The flow “jumping” of the nozzle was driven by increasing of the supply pressure. The “jumping” behaviour was as expected without direct “back jumping“.

Fig.10: Dual Bell Cold Gas Tests

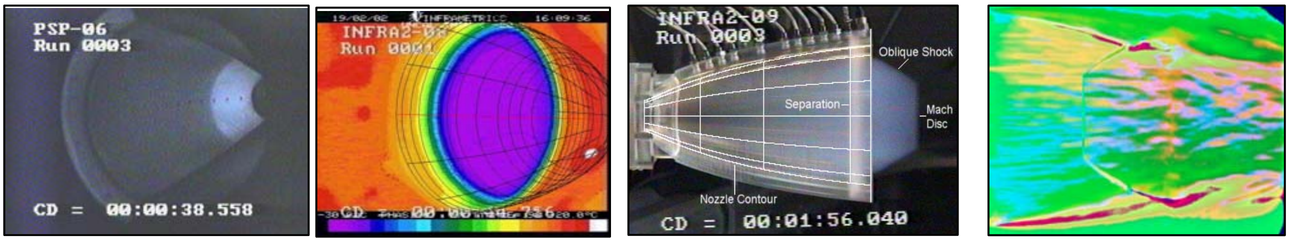


5 Current Status of the Advanced Altitude Simulation P8

The Engineering project of the advanced altitude simulation P8 starts in November 2004. 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.

Additionally different visualisation techniques "Fig.11" are in verification 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.

Fig. 11: Visualisation Techniques



PSP IRT BFF Schlieren

Status of hot gas generation and nozzle:

- The requirements are verified and influences to the sub scale combustor and nozzles are studied.
- 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 modelling of the heat transfer and verification of existing methods are done.
- 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.

Status of flight simulation:

- The requirements are verified and there is a first basic configuration with a self sustaining super sonic diffuser for the recompression of the nozzle exhaust jet. On of the deeper investigations is the cooling behaviour 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. In a first step the principal should be demonstrated on a small scale at the cold gas test facility P6.2.
- The pressure will be adjusted variable by two possibilities
  - Regulation of the suction pressure of the ejector demonstrated with the Load Simulation Device for the VULCAIN II nozzle or the P6.2 altitude simulation.
  - Regulation of the "bleed gas" mass flow like demonstrated on cold gas test facility P6.2.
- The principle contour of the test set up is defined according the ARIANE 5 after body as an input for the subscale combustor.

6 Conclusion

With the experience of the loads simulation device for the VULCAIN II nozzle and the altitude simulation at P6.2 there are first techniques to simulate flight conditions. For development of new advanced nozzle designs and materials test conditions very similar to the flight are essential. The verification of the calculations and modelling 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.

7 References

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