Simulation of Flight Conditions on a Test Facility for Rocket Engines

W. H. Kitsche
Institute of Space Propulsion
German Aerospace Center
D-74239 Hardthausen, Germany

Abstract

The DLR test facility P5 in Lampoldshausen, Germany looks back on sixteen years of testing the ARIANE 5 main engine VULCAIN on engine level. During this period, the test facility had to fulfil quite various requirements for the engine tests. The principle task of the facility was always to simulate the conditions on the launcher to the VULCAIN engine. The environment and all interfaces of the rocket motor were adjusted to match this target. Most of the conditions during the flight of the rocket were simulated in each test, the pump inlet pressure e.g. Several conditions, the acceleration of the ARIANE 5 boosters e.g., were performed in separate test campaigns where special devices were operated. This article is a feedback of the experience which was made with various systems for simulation.

1. Introduction

P5 is one of the two largest test facilities for *cryogenic rocket engines* in Europe. Together with the almost identical PF50 at SNECMA (prime contractor for the VULCAIN engine), it was erected under CNES contract within the ESA, ARIANE 5 program. Its huge run tanks have volumes of 200 m³ for liquid oxygen and 600 m³ for liquid hydrogen. Both facilities were designed for the ARIANE 5 main engine VULCAIN. The performance of the bench allows tests of 1.5 times the duration of a VULCAIN flight mission and up to 13 minute test time of the VULCAIN 2 at sea level conditions.

2. Description of the Test Facility

In the field of *rocket testing*, the facility P5 covers all types of *static rocket system tests* [4] with complete propulsion system and simulated rocket operation, establishing full combustion under nominal and off-design conditions [2].The basic purpose of such a facility is to have a test rig on which a hot run with the rocket engine can be performed. If only this fundamental request is considered, there are already a large number of subsystems, devices and components necessary to permit a hot run. Structurally, the test facility (Fig. 1) can be divided into the following sections:

- building
- test cell
- propellant supply
- secondary supply system
- measurement and control facilities.
- safety system

The concrete structure of the 65-meter high tower-like building accommodates and protects the facility rooms. On the tower itself, a steel structure with facade provides space for the oxygen tank. Joining the tower on the side is a shaft to accommodate the liquid hydrogen tank. The operation rooms and the propellant tanks are separated and protected from the test cell by an approximately two-meter thick wall. The test cell accommodates the engine and provides the necessary interfaces for supply, control and measurement systems. A rigid thrust frame supports the engine thrust. The floor of the test cell is closed by an octagonal slab, which is opened during the tests. A jet guide tube and a following jet deflector guarantee a safe deflection of the engine's exhaust jet up and away into the open air.

The VULCAIN engine uses liquid hydrogen (LH2) and liquid oxygen (LO2) as propellants. The tanks have a capacity of 600 m³ liquid hydrogen at a storage temperature of 20 K and 200 m³ liquid oxygen at 90 K. The oxygen tank is located on the top of the concrete tower at a height that corresponds to the geometric conditions of the launcher ARIANE 5. During the test, the liquid propellants in the tanks are conveyed by the vacuum-insulated pipes to the engine turbo pumps in the test cell by means of pressurising the tanks with gaseous hydrogen and gaseous nitrogen, respectively. The propellant tanks are filled during the preparation phases from the propellant depot, which is connected to the test facility through vacuum insulated pipes. In addition to the propellant supply, both the engine and the test facility systems have to be supplied with various gases (nitrogen, hydrogen, helium and propane) at different pressures (up to 70 bars) and corresponding flow rates (up to several kilograms per second). The necessary gas supply systems are integrated in the test facility and are used for various purposes (e. g. pneumatic valve actuators, tank pressurisation, purging, inerting). Furthermore, cooling water is supplied to the jet guide tube and jet deflector at 2700 litres per second from the water tanks through a pipe of one meter in diameter which is routed to the bottom floor of the test facility. The measurement and control building at a distance of about 160 m houses the system for measurement, control and automatic control for test facilities. The building contains the process computer NORSK DATA, magnetic tape recorders and the central control equipment with closed circuit television, intercom and central timer for test facility. The *signal conditioning equipment* for the test facility, together with computer periphery equipment is also installed in the control building, it has a capacity of 608 acquisition channels up to 125 Hz and 96 channels up to 20 kHz. The facility is covered by a network of detectors for hydrogen and oxygen gas concentration. Also a detection system for fire is installed. The detectors are linked to a fire fighting system (sprinklers) and to an alarm system with horns, flashlights and programmed announcement for loud speakers. The sprinklers are installed in the test cell, at the hydrogen tank, at the oxygen tank and at the vacuum insulated lines. In these areas, only *exproofed* electrical equipment is allowed. The tower of the buildings is protected against penetration of gases by an overpressure of approximately 13 Pa as a function of the externally fed air condition. Three powerful water guns which are remotely controlled are installed around the facility.

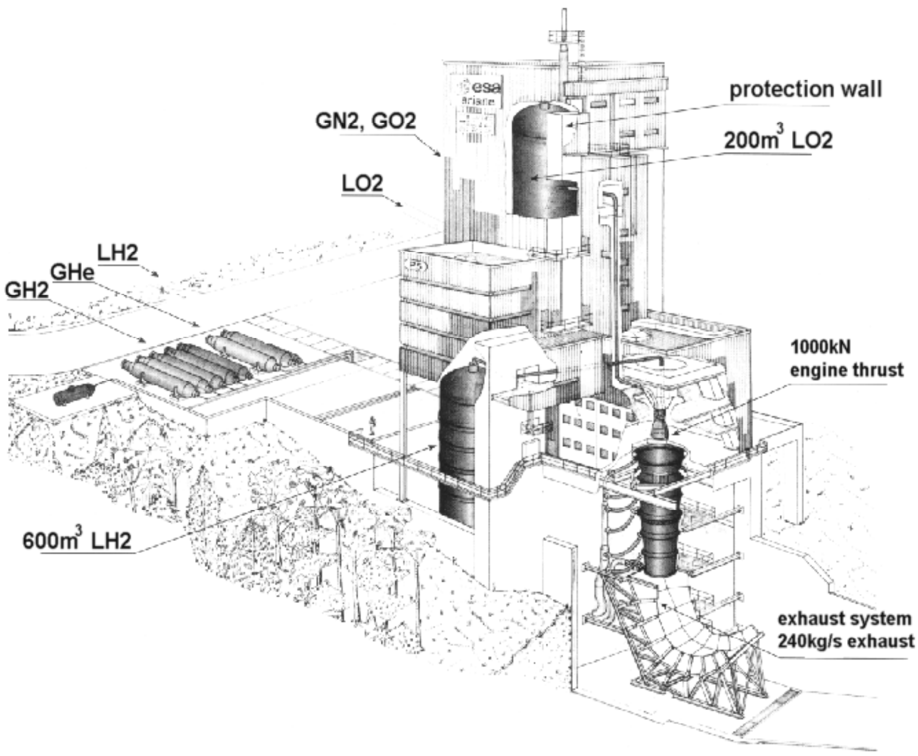

Figure 1: Test Facility P5

3. Simulation of Flight Conditions

A basic requirement to the test facility is to apply flight conditions for the tested VULCAIN engine as far as possible. It is mandatory that all interfaces between the bench and the engine are adjusted to the same values as on the launcher. Furthermore, the evolution of interface parameters versus time is regulated according to the evolution during flight.

3.1 Pump inlet pressure profile

Before the start of the launcher, a sufficient pressure at the inlet of the rocket engines turbo pumps has to be established. During lift off this inlet pressure (Fig. 2) suddenly jumps up and increases furthermore during flight due to the increase of acceleration. The pressure loss in the feed line slightly inhibits this pressure increase, but it becomes really significant when the launcher has powerful boosters as e.g. the ARIANE 5.

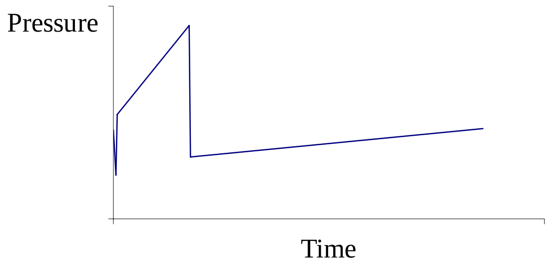

Figure 2: Principle Pressure Profile at the LO_2 Pump Inlet during Flight

Up to the ignition of the engine, the same procedure as on the launcher is followed on the test facility, but in order to simulate the conditions during flight the pressurisation of the run tank has to be adapted. To obtain the requested pressure profile, a powerful pressurisation system (Fig. 3), an effective depressurisation and a fast throttle in the feed line are necessary.

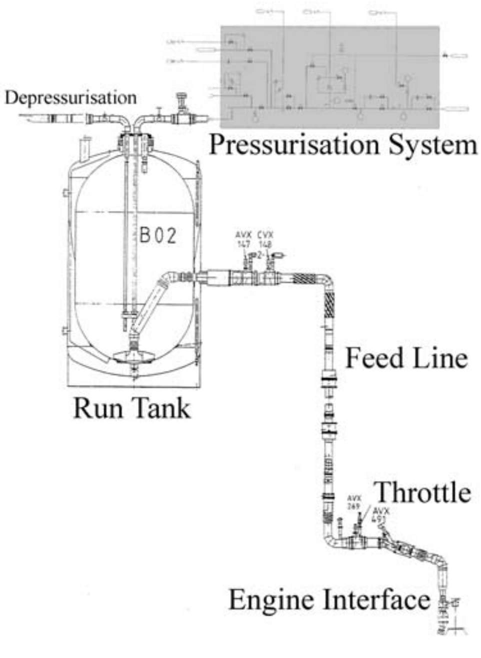

Figure 3: Liquid Oxygen Supply of the VULCAIN Engine

The pressurisation system for the tank on the launcher maintains a certain pressure p_{TL} while the tank runs empty during flight. At the inlet of the rocket engine the pressure p_I is

$$p_I = p_{TL} + \Delta p_{hyd} - \Delta p_{dyn} \qquad \textbf{(1)}$$

Where Δp_{hyd} is the hydrostatic pressure due to the difference of height between tank and engine, Δp_{dyn} is the pressure loss in the feed line.
On the test facility P5 the feed line has the same design as on the launcher, especially the same length. In order to obtain the same inlet pressure on the bench, here the tank pressure p_{TB} has to be higher compared to the launcher.

$$p_{TB} - p_{TL} = \rho \; a \; l \qquad \textbf{(2)}$$

This difference depends on the acceleration a during flight, the density ρ of liquid oxygen and the length l of the feed line, its value increases up to 14 bar. This pressure concerns the whole run tank and for that reason it is very strong and heavy and hence it got its name *battle ship tank.*
On a test facility running on liquid hydrogen, it is preferable to use pneumatic actuators (e.g. N_2 driven) for the valves. For the fast throttle in the main feed line the performance of a pneumatic actuator was not sufficient, therefore a hydraulic actuator with high opening/closing speed was chosen.
With the normal pressure relief valves the depressurisation was not fast enough, therefore an additional relief valve of 250 mm diameter was installed.
Figure 4 shows the pressure at the inlet of the rocket engine. Clearly visible is the pressure drop after ignition, during start up and the sudden pressure increase when the throttle fully opens. The real effect on the launcher (acceleration) means less disturbance than the simulation (fast opening of the throttle) and hence we can consider that the test on the bench sufficiently reveals the behaviour during this phase.

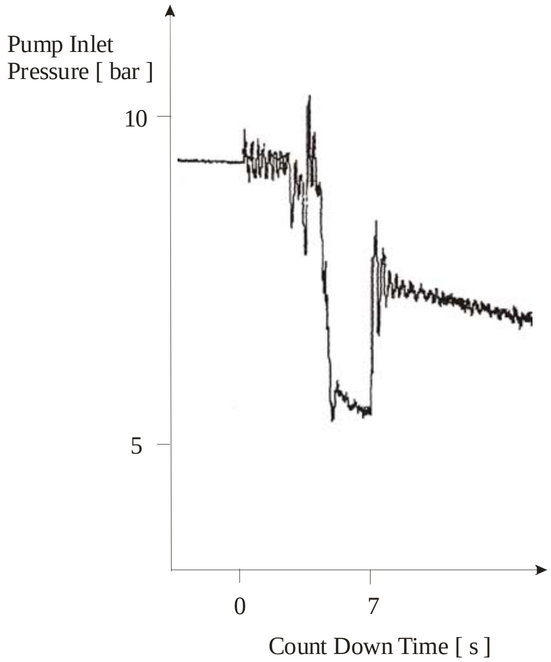

Figure 4: First Phase of the Engine Hot Run

The inverse event occurs two minutes later, during shut down of the ARIANE 5 boosters. The inlet pressure of the main engine drops drastically. Figure 5 shows the simulation of this pressure drop on the test facility.

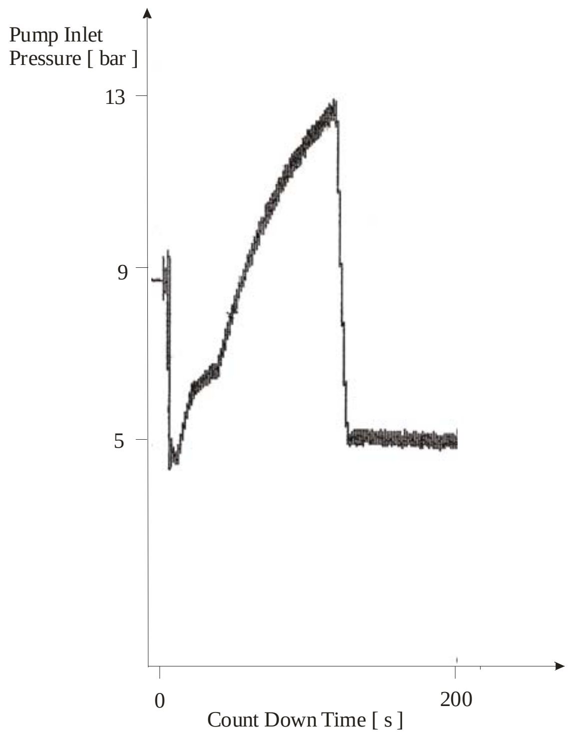

Figure 5: Pressure Drop at the Inlet of the Oxygen Turbo Pump during Simulated Booster Shut Down

No cavitation was observed, the water hammer and oscillation were never critical for the engine. Hence, neither the simulated ignition nor shut down of the boosters had a critical impact on the operational behaviour of the rocket engine or its components.

3.2 *Pogo* Oscillation

Since large cryogenic launchers are applied, the rocket scientists have to face the phenomenon of *pogo* oscillation [3]. The liquid oxygen in a long feed line of a rocket engine tends to show this oscillation when the evaporation creates gas bubbles in the line. The effect is well known and a simple damper (Fig. 6) can reduce the oscillation.

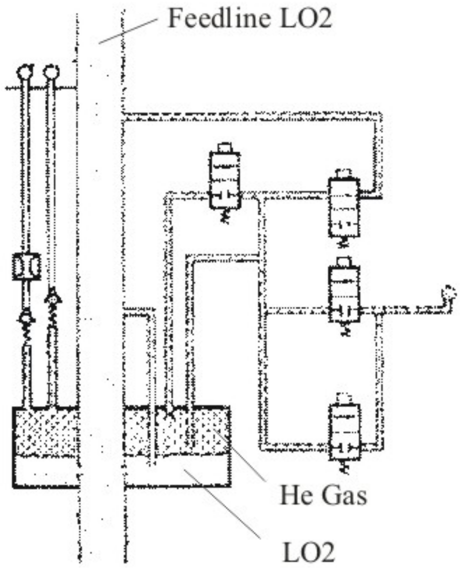

Figure 6: Damper for *Pogo* Oscillation

However, the effect does not always occur. To prove the effectiveness of the damper, an oscillation is generated with an additional hydraulic device. The first tests on the facility P5 were performed with a strong feed line, double walled and vacuum insulated. This feed line for liquid oxygen had no damper. Later on, the feed line was replaced by a flight line, insulated with hard foam, with the original design for flight, including a system to damp *pogo* oscillation.
Oscillation with strong amplitudes can be expected directly after engine shut down (Fig. 7). The flight line has in principle the same behaviour but of course the oscillation dies down a bit faster.

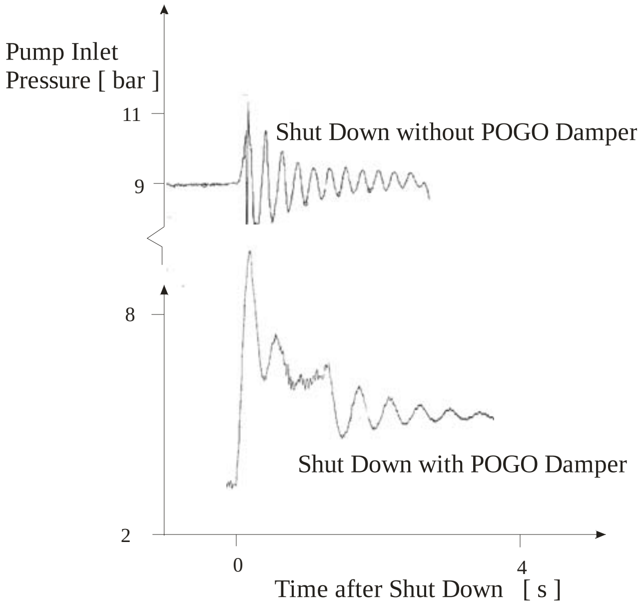

Figure 7: Oscillations in the Feed Line after Engine Shut Down

After it was proved that the oscillation after shut down, meaning after a sudden pressure **increase**, were not critical, the oscillation after a sudden pressure **drop** were studied (Fig. 8). A pressure drop means always a change in direction of the vapour pressure and this might induce the risk of evaporation in the feed line. Meanwhile a system (hydraulic piston) to generate oscillation was connected to the feed line and it was activated after the simulated booster shut down.

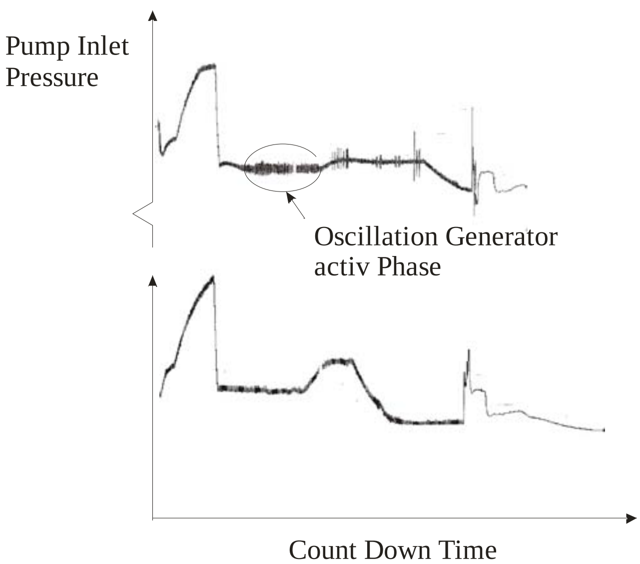

Figure 8: Hot Run with Oscillation Generator (upper Curve) and without Generator (lower Curve)

The oscillation is of course stronger when the generator was applied, but it died down directly after the generator was stopped and no critical excitation occurred while the generator was running.

3.3 Acoustic Load

Another condition due to the booster operation during the first two minutes of flight is the acoustic load caused by the booster jet. The main engine in the middle has to suffer this enormous noise and it was the question whether all components including tiny lines, cables and plugs would bear this load without failure.
The required sound level was higher than the performance of the acoustic chambers available in Europe, hence the idea was to use the VULCAIN itself as the acoustic source and to trap the sound in a casing (Fig. 10) around the engine, made of strong steel plates.

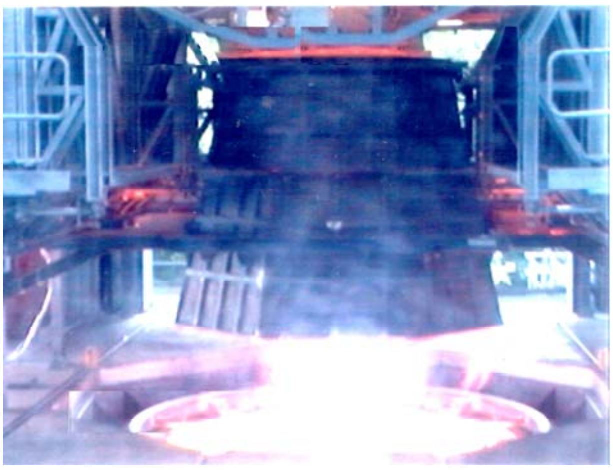

Figure 10: Acoustic Panels around the VULCAIN

The strong steel panels reflect the sound to the engine, where it is reflected again and permanently more noise is produced.
In these tests the influence of the acoustic load to a **running rocket engine** was studied and it was considered to be a much better simulation of the flight conditions than it could have been in an acoustic chamber.
No failure of any engine component or negative impact to its function was observed.

3.4 Load Simulation

The test facility P5 has further systems to simulate flight conditions and was temporarily modified to perform tests with conditions which are a challenge to simulate. The most sophisticated case was a *load simulation device* (LSD) to scrutinise the load on the engine nozzle in high altitude. It is described in detail by A.Haberzettl & alii [1].
During flight the ambient pressure around the nozzle permanently decreases, hence the load on the nozzle increases, the simulation of this load became subject of a test series. The launcher reaches supersonic velocity while it is still in the atmosphere. Even before reaching *Mach 1* the complex flow field around the launcher including the engine has regions with sonic shocks. Furthermore, the flow is not steady and accordingly not the shock waves. The effect of moving, appearing and disappearing shock waves causes a buffeting to the structure and is named after this, the *buffeting effect.* The simulation of this dynamic effect was beyond the possibilities of a test facility. The only thing which was done to get certain knowledge of this effect to the engine was to introduce a force to the exit of the nozzle by a hydraulic piston. The force was constant and only in the order of the forces expected during flight.
Normally, a rocket engine for the first stage is tested at sea level conditions only. Altitude facilities with vacuum test cells are typical for upper stage engines. Hence there was no facility available to test the VULCAIN 2 at altitude conditions when a failure of this engine occurred during its first flight.
The investigation after the failure of the ARIANE 5 flight n° 157 identified a weakness of the nozzle extension to be the origin of the problem. It was known before that the load during flight, especially at high altitude is higher than at sea level, but the load was underestimated and therefore the nozzle had to be replaced by a stronger one. To qualify the new design, a special test campaign was performed which was concentrated on the behaviour of the new nozzle. Therefore, the facility P5 was equipped with a casing around the nozzle and a suction system to reduce the pressure around the nozzle. The main part of the suction system was an ejector driven by nitrogen. The tightness and fast depressurisation were a particular challenge when this device was used. Also in these tests the conditions on the launcher were to be copied as far as possible. Therefore it was requested that the nozzle is not disturbed in its thermal

behaviour due to the load simulation device. Hence it was necessary to consider a cooling system for the casing around the nozzle from the beginning of the design on (Fig. 12).

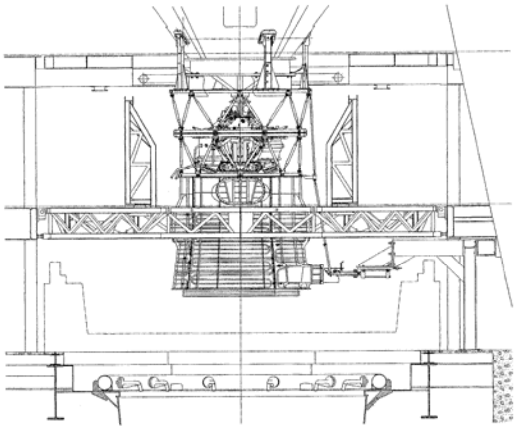

Figure 11: Test Cell with *Load Simulation Device* (LSD)

To reach a load equivalent to the load during flight, a pressure of 200 mbar in the casing was requested. The request was not only to reach this point, but also to perform a specified profile of pressure reduction versus time. Therefore the suction system was planned with two regulation valves of different diameter. To create a requested sudden recovery of ambient pressure at shut down, the casing was equipped with burst discs, busting after ignition of small detonators.
The casing of the device was connected by a lattice ring (Fig. 11) to the steel structure of the bench. The top and the bottom of the casing had a sealing to close the cavity for maintaining low pressure inside.

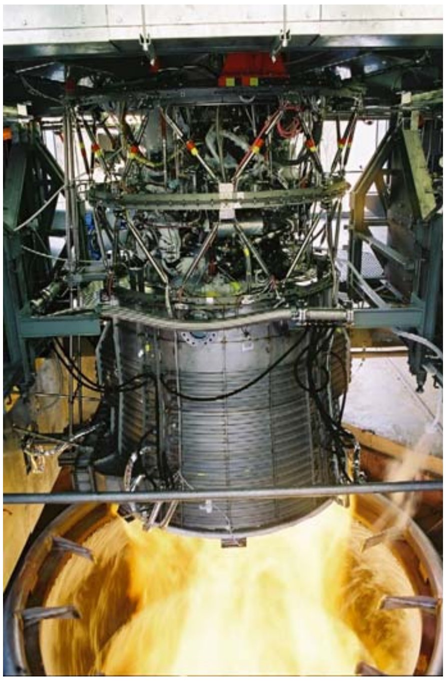

Figure 12: Vacuum Casing of the *Load Simulation Device* (LSD) with Water Cooling during Hot Firing

The sealing had to be flexible to allow the normal move of the nozzle during a hot run. It had to be resistant to fire and strong enough to bear the static and dynamic forces during test. As material a texture of fiberglass was chosen. A particular problem was the fixation of the sealing which needed stepwise optimisation. A remaining leak rate across the sealing was considered and measured in the first reception phase of the LSD. Moreover, the leak raised another

problem, the leak might have had a fraction of hydrogen in air, and therefore attempts were made to adapt the bench measurement systems to measure a hydrogen leak at low pressure.
At the end of the reception phase, the characteristics of the suction system including the influence of the leak flow was known (Tab. 1).

Table 1: Performance of the LSD Suction System

Suction pressure in the vacuum casing	200 mbar
leak ratio into the casing	3 kg/s
driving mass flow of the suction system	14 kg/s GN_2
driving pressure of the suction system	40 bar
suction pressure at closed suction line	14 mbar

In the final reception of the system, the ejector was driven with 39.6 bar and created a vacuum of 9 mbar before the suction line was opened. This value increased to 115 mbar when the valves opened to adjust 300 mbar in the casing of the LSD. After 58 seconds, the leak ratio increased but the system maintained the value of 300 mbar. After the LSD had its *go for test*, it was used during hot runs with a lowest pressure of 216 mbar around the nozzle extension.
After this test and the following inspections of the test material, the improved nozzle was validated for flight and the ARIANE 5 ECA could return to mission.

4. Conclusion

Within the flight qualification of a rocket engine, test data collected on a test facility are only representative if the constitutive conditions during flight are carefully simulated. A good test plan, available early, allows to consider the required subsystems for simulation in the design of the test facility. Adequate modifications of the test facility can always adapt the performance of the facility to reach a high level of compatibility between flight and test conditions. However the simulation is limited to a certain extent where only the maiden flight can give an answer. This flight normally raises new questions and here again the test facility is needed to provide a program to assure the technological success of the flight hardware.

5. Acknowledgements

Thanks goes first of all to the test team of the P5, only their elaborate work made so many successful tests possible. The author would also like to thank his colleagues from the engine manufacturer SNECMA for the outstanding cooperation, his colleagues from the DLR engineering department and A.Haberzettl (head of LSD work group) for their support in the LSD work group.
The greatest honour is due to god, who gave us all the ability and the opportunity to do this thrilling work without any serious incident.

References

[1] Haberzettl, A. et alii VULCAIN 2 Flight Load Simulation Device. *EUCASS European Conference for Aerospace Sciences*, Moscow 2005

[2] Hujeux, C. and Kitsche, W. Evolution of the Rocket Engine Testing Process. *AAAF Association Aeronautique et Astronautique de France,* Versailles 2002

[3] Martin, Richard E. Atlas II and IIA Analyses and Environments Validation, *Acta Astronautica* Vol.35, No12, 1995

[4] Sutton, George P. Rocket Propulsion Elements, John Wiley and Sons, New York, 1986

This page has been purposedly left blank