DEVELOPMENT OF P4.1 ALTITUDE SIMULATION FOR VINCI® ENGINE

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1 ABSTRACT

To test rocket propulsion systems as much as possible under operational conditions are one of the main drivers for flight qualification. For upper stage engines the tests in vacuum conditions with fully expanded nozzle defines the essential criteria for altitude simulation test facilities.

SNECMA is developing a new upper stage engine called VINCI®. For the engine tests the existing test bench P4.1 at the DLR test centre Lampoldshausen was adapted to high altitude conditions.

VINCI® is an Expander cycle-type engine with up to 180 kN thrust. An extendable nozzle will give VINCI® a specific impulse of 465 s in vacuum.

The task of altitude simulation consists of creating the test condition within a vacuum cell. This is primarily low ambient pressure of just few mbar. Special operational conditions are linked to the transients during Start-Up and Shut-Down of the engine with respect to the nozzle loads.

Maintenance of the vacuum with running engine is achieved by recompression of the supersonic exhaust jet in a diffuser and the extraction of the exhaust gas by steam jet ejectors.

To provide the large quantities of steam, rocket steam generators with liquid Oxygen and Alcohol are used.

The maximum flexibility is reached by adaptation of the test bench to the different engine configurations and the test conditions. This contents modular systems.

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.

The P4 test facility with two test positions P4.1 and P4.2 was build in the mid-sixties for the ELDO program. In 1973 when the ARIANE launcher program started the P4 was equipped for altitude simulation tests of the VIKING engine with 80 t vacuum thrust.

With the development of the ARIANE 5 the P4.2 was adapted in 1992 to the altitude simulation of the AESTUS upper stage engine.

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

In 1998 the decision was taken to modify the existing test position P4.1 for the VINCI® development tests. Since February 2005 the test bench is operational (FIG. 1).

FIG. 1: P4.1 ALTITUDE SIMULATION

P4.1 is now the larges altitude simulation test facility in Europe.

3 TEST REQUIREMENTS

The VINCI® engine (FIG. 2) will be tested in 3 configurations (Table.1).

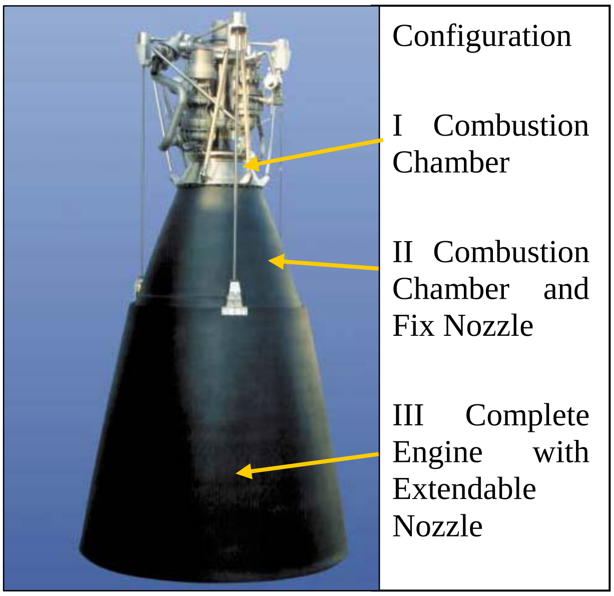


FIG. 2: VINCI ENGINE

VINCI Test Configuration	**Expansion Ratio ε** **Length l [m]** **Exit Diameter Ø [m]**
Configuration I	Combustion chamber ε = 22,3, l ~ 1,4 m, Ø~ 0,7 m
Configuration II	Chamber with the fix nozzle ε = 93, l ~ 2,2 m, Ø~ 1,4 m
Configuration III	Complete engine with the extendable nozzle ε = 243, l ~ 4,2 m, Ø~ 2,3 m

TABLE 1: VINCI® TEST CONFIGURATIONS

The P4.1 test conditions are:

- Vertical test position with maximum test time of 770 s.
- Pressure at engine interface during chill down $p < 200$ mbar.
- Ignition at ambient pressure $p < 60$ mbar
- Start up phase with simulation of in-flight engine start up conditions
- Steady state phase with the operational envelope in vacuum conditions
- Shut down phase with transient conditions considering the maximum nozzle loads
- Ballistic phase and reignition in vacuum conditions.

4 DEVELOPMENT OF P4.1 ALTITUDE SIMULATION

The development of the altitude simulation was done in different phases:

Phase 1: Basic studies and general lay out.

Phase 2: Development of basic components

- Centre Body Diffuser
- Rocket Steam Generators
- Ejector System
- Modular system to different test configurations.

Phase 3: Final lay out of the test bench.

5 STUDIES AND GENERAL LAY OUT (PHASE 1)

The basic studies are performed to define the principal conditions and dimensions of the components, particularly the super sonic diffuser and the dimensioning of the suction system with adapters for the different test configurations.

Centre Body Diffuser: Due to the limited high of the existing P4.1 building a centre body diffuser was chosen with reduced length.

The centre body diffuser has the same behaviour like a second throat diffuser. The supersonic flow is stable down to lower pressures ratios (Hysteresis). The length L to diameter D ratio should be $6 < L/D < 8$ for reduced pressure losses. The second throat is realised by a ring channel around a centre body. The overall length of the diffuser is short because of the reduced hydraulically diameter of a ring channel. The centre body has to be cooled intensively.

The main parameters for the centre body diffuser design were linked to the characteristics of the combustion chamber pressure Pc, the expandable nozzle with the expansion ratio $\varepsilon = 243$, the heat loads and the given dimensions of P4.1.

Suction system: The main parameters for the suction system were linked to the transient pressure conditions during Start-Up and Shut-Down of the engine. The trade-off was between powerful ejectors with high steam consumption for fast transients and a big condenser with high cooling water flow.

Adapters: The adapter for combustion chamber tests is designed as a short diffuser and for Gimballing. The adapter for the fix nozzle replaces the extendable nozzle and guides the exhaust to the centre body diffuser.

Main drivers were:

- Consumption of steam for the sizing of the rocket steam generator plant.
- Ignition and reignition conditions.
- Consumption of cooling water for the sizing of the cooling water plant, the underground storage and the condenser.
- The transient behaviour of the engine requires the supersonic Start and Un-Start of the diffuser at low combustion chamber pressures to prevent the back flow of hot gases.
- Flexibility to adapt the altitude simulation to the test configurations by short notice.
- Reliability of the altitude simulation

The altitude simulation has been achieved by an experienced calculation process. The general way of calculation (FIG. 3) consists of three steps.

Step 1: A forward calculation, to determine geometric parameters from input parameters, represents the first step.

Step 2: The second step is like a cross-check procedure by a backward calculation, receiving the characteristic curve from geometric parameters.

Step 3: Finally in a third step, the sensitivity to parameter-variations is evaluated to check the reliability of the prediction.

To get the required accuracy, the steps are adjusted by experienced loss- and gain-parameters, which depends on type and basic configuration. The result arises iteratively by this way.

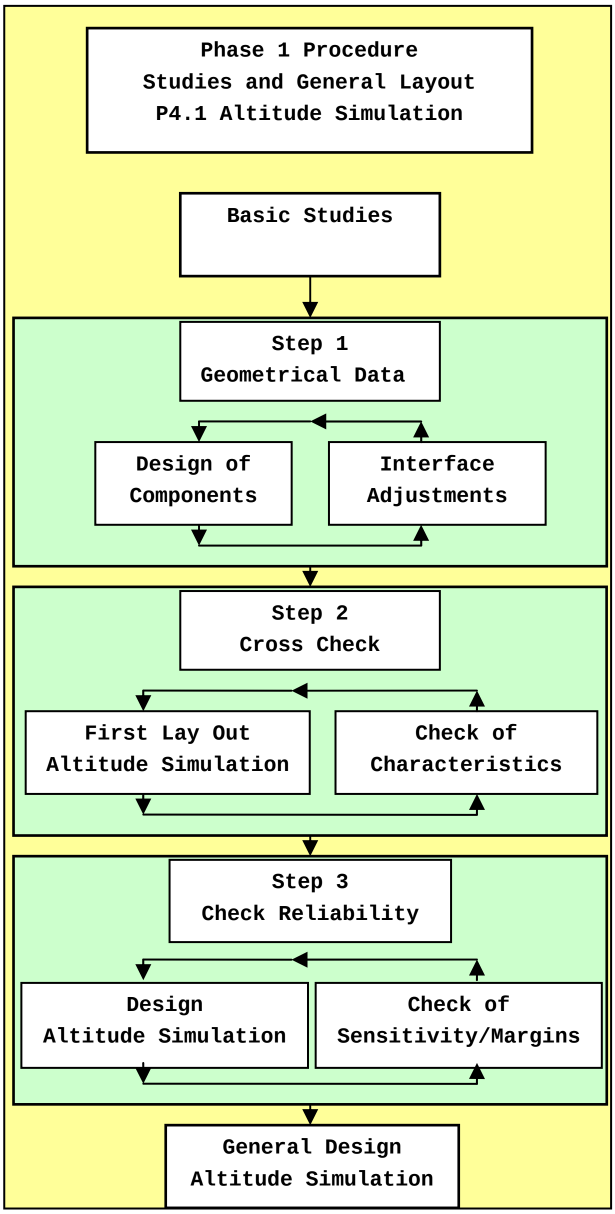


FIG 3: CALCULATION PROCESS

Test Phase	Combustion pressure [bar]	Vacuum chamber [mbar]
Chill down	**-**	**< 40 (< 200 at chill down Interface)**
Ignition	**-**	**25 - 40**
Start Diffuser	**10 – 15**	**< 60**
Steady State	**25 – 80**	**2,5 - 7**
UN Start Diffuser	**10 – 20**	**< 80**

TABLE 2: PARAMETERS ε = 243 CONFIGURATION

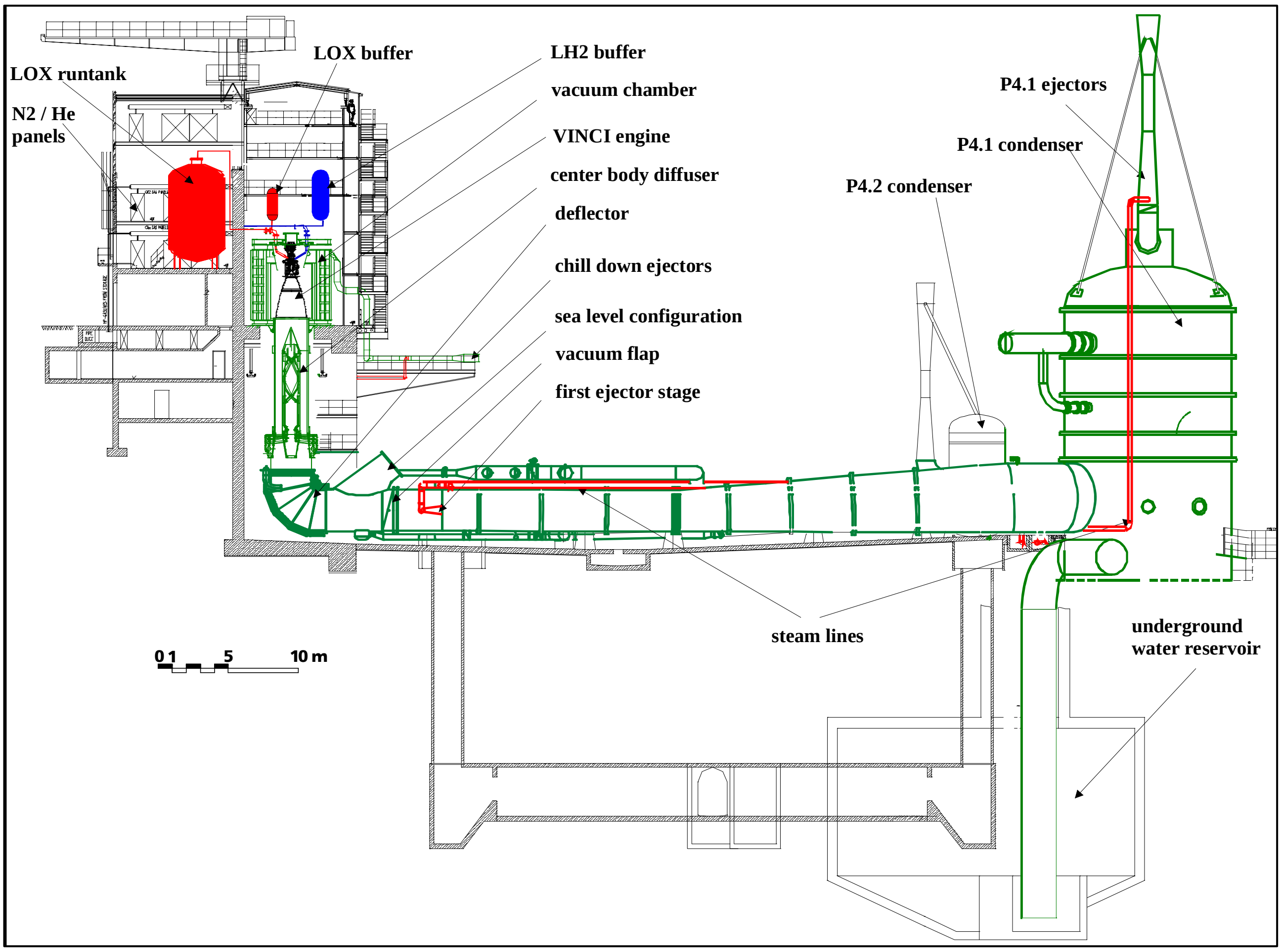


FIG 4: GENERAL DESIGN P4.1

The general design (FIG. 4) is:

- Feed System with run tanks for LH2 and LOX designed for chill down and 770 s hot run.
- Buffer tanks for LH2 and LOX to simulate the dynamical transient feeding conditions of the stage during Start up and Shut Down
- The VINCI engine is vertically mounted inside a vacuum chamber within a thrust measurement device.
- The supersonic exhaust jet will be recompressed inside the centre body diffuser to subsonic conditions.
- The heat loads of the hot gases will be reduced by water injection after the diffuser. All parts up to the vacuum flap are double wall water cooled. The exhaust gases are guided to the first ejector stage by the deflector.
- The first ejector stage maintains the pressure conditions during Ignition, Start up and Shut down against higher pressure of the condenser.
- A big condenser reduces the mass flows to be sucked by the end stage ejector to ambient pressure conditions. The water is routed barometrically to an underground water reservoir maintaining the vacuum pressure inside the condenser.
- The “chill down” ejectors maintain the vacuum simulation during the cool down phase of the engine before ignition.

6 DIFFUSER SUBSCALE TESTING (PHASE 2)

CFD calculations and model tests under cold and hot conditions were performed to verify the heat loads and functional behaviour of the centre body diffuser.

6.1 SUBSCALE DIFFUSER COLD GAS TESTS

The test position P6.2 (fig. 5) has been developed and erected to investigate components for altitude simulation and advanced nozzle designs.

FIG. 5: P6.2 TEST POSITION

The diffuser sub scale tests are done by N2 cold flow conditions with similar Mach numbers.

The objectives were:

- Verification of the basic design
- Investigation of phenomena like engine Gimballing (Fig. 6)

FIG. 6: GIMBALLING

FIG. 7: CENTER BODY DIFFUSER

- Transient studies for supersonic Start and Un-Start conditions.
- Parameter studies of diffuser arrangement (FIG.7).

Different diffusers were tested for basic investigations (fig. 8). The results show a supersonic Start and Un-Start of the centre body diffuser at low ratios of chamber pressure to vacuum pressure. Due to the given dimensions of P4.1 the ratio of diffuser length L to diameter D were chosen to L/D = 5.

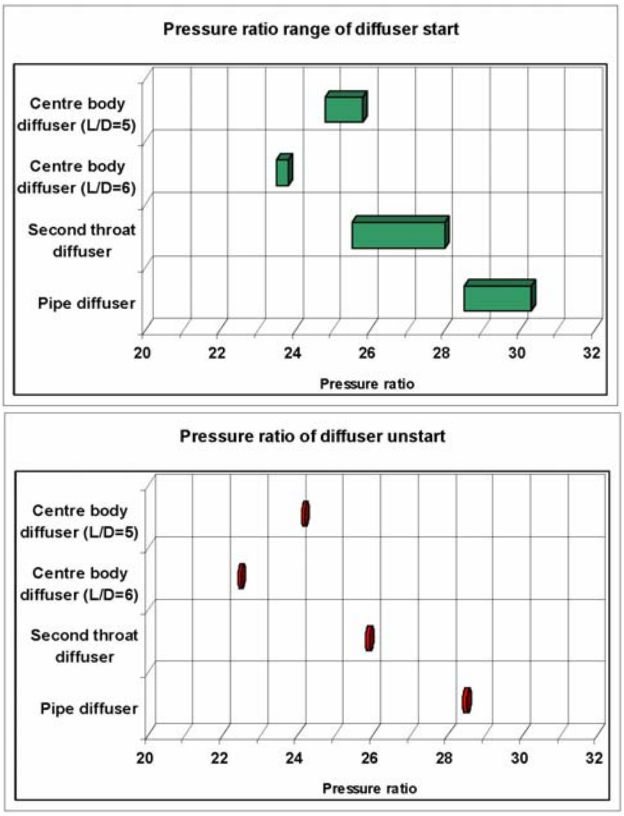


FIG. 8: DIFFUSER STRAT AND UN-START

The verification of the Gimballing shows for the supersonic Start of the diffuser an increasing supply pressure (FIG. 9) from 10 to 18 bar with a gimballed angle from 0°to 7°.

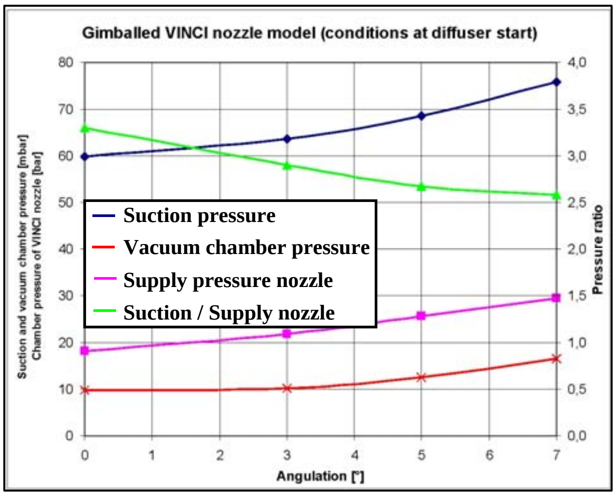


FIG.9: GIMBALLING

6.2 SUBSCALE DIFFUSER HOT GAS TESTS

The hot gas model was tested at the test bench P8 with a H2 / O2 combustion chamber (Table 3). The objectives were:

- Verification of the modelling and design
- Verification of the heat loads
- Verification of diffuser supersonic Start and Un-Start conditions
- Verification of water cooling design parameters

Test Conditions	Parameter
mixture ratio	O/F < 6
Chamber pressure	PC ~ 40 - 60 bar
Mass flow	m = 2.5 kg/s

TABLE 3: HOT GAS DIFFUSER TESTS

The modelling of the subscale model was performed with AeroShape-3D program. AeroShape-3D is an explicit finite volume method of 2.order with an adaptive grid based on the RAM technique (rectangular adaptive mesh). Turbulence is considered by a standard k-ε model.

The supersonic Start condition was estimated to 55 bar chamber pressure and the Un-Start condition to 48 bar (FIG. 10).

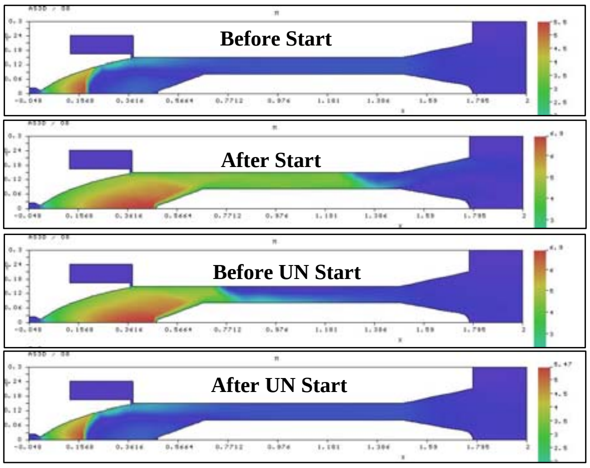


FIG. 10: CFD MODELLING HOT GAS MODEL

The heat flux density (FIG.11) is calculated by the Stanton number and constant wall temperature. The maximum heat loads for the center body (black line) is calculated to q $_{max}$ = 3,5 kW/m². The tube (red line) is calculated to q $_{max}$ = 1,5 kW/m².

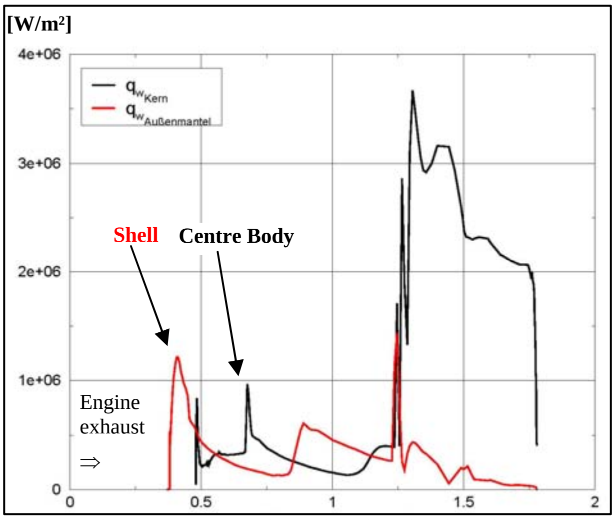


FIG. 11: HEAT LOADS HOT GAS MODEL

The diffuser hot gas model (fig.12) had a scale of ≈ 1: 8 to P4.1. The expansion ratio of the nozzle was ε = 100 with respect to self-sustaining against 1 bar ambient conditions.

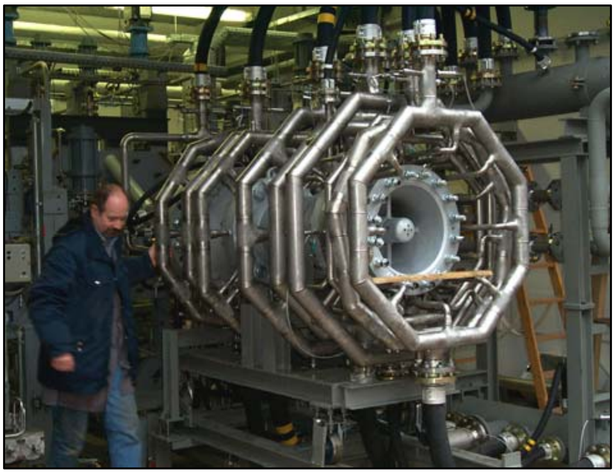


FIG. 12: HOT GAS MODEL

The test results (Table 4) were taken to improve the modeling for the design of the P4.1 diffuser.

- The prediction of the Start and Un-Start condition were quiet good.
- The predictions of the heat loads were under estimated. Especial hot spots with high heat loads were detected but not local measured.
- The vacuum conditions were better than expected.

Generally the design fulfills all requirements but optimization of the water cooling was necessary.

Hot Gas Model	Calculated	Measured
Heat Load Centre Body [kW/m^2]	1200 aver. 3500 max	2180–2600 aver. (caloric measurement) Hot Spots (no local measurement)
Heat Load Cylinder [kW/m^2]	500 aver. 1500 max	660 – 1130 aver. (caloric measurement) Hot Spots (no local measurement)
Chamber pressure for Start [bar]	55	50 - 56
Chamber pressure for UN Start [bar]	48	48 - 50
Vacuum [mbar]	80	40 - 50

TABLE 4: TEST RESULTS HOT GAS MODEL

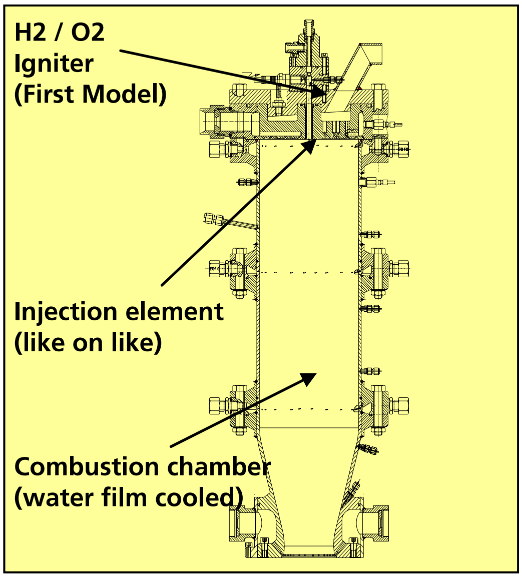
7 STEAM GENERATOR DEVELOPMENT

An altitude simulation test facility for rocket propulsion systems requires for a short time large quantities of steam to operate the ejectors. New rocket steam generators are developed (Table 5).

Year	Steam generator development
1995:	4,5 kg/s sub scale
1996:	28 kg/s sub scale
1997/1998:	10 kg/s P1.0 - satellites
1999/2000:	45 kg/s P4.2 - AESTUS
2001/2002:	16 kg/s P4.1 - VINCI
2001/2003:	55 kg/s P4.1 – VINCI
2004/2005	P4 Steam Generator Plant

TABLE 5: STEAM GENERATOR DEVELOPMENT

The principle is to inject water into the hot gases of a rocket combustion chamber and evaporate the water in a mixture chamber. The rocket steam generators are based on the combustion of Ethyl Alcohol and Liquid Oxygen ignited by H2/O2 Igniter.



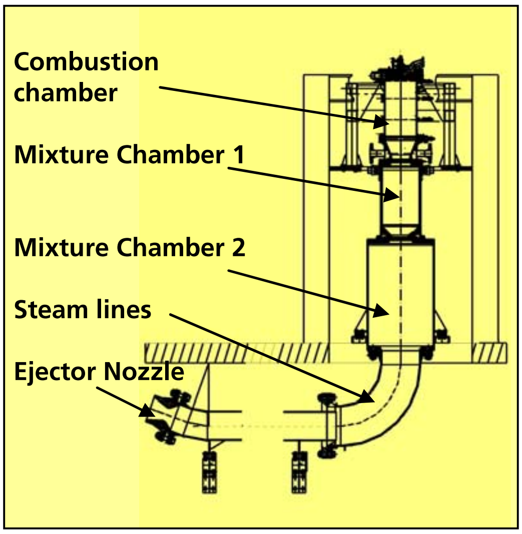


FIG. 13: ROCKET STEAM GNERATOR

The rocket steam generators (FIG. 13) are developed in two modes, the combustion chamber mode like a rocket engine and the steam generator mode with ejector nozzle.

Special investigations were performed on the test position P1.1 for:

- HF Stability (Quarter Wave Tube / Baffles)
- Chamber Cooling
- Igniter Position

7.1 HF STABILITY – QUARTERWAVE TUBES

An adjustable absorber ring was designed and tested at P1.1. Precondition for hot run measurement was the integration of HF pressure transducers inside the absorber in order to determine the tuning point of the absorber. Due to tuning problems the cavity ring is no more used.

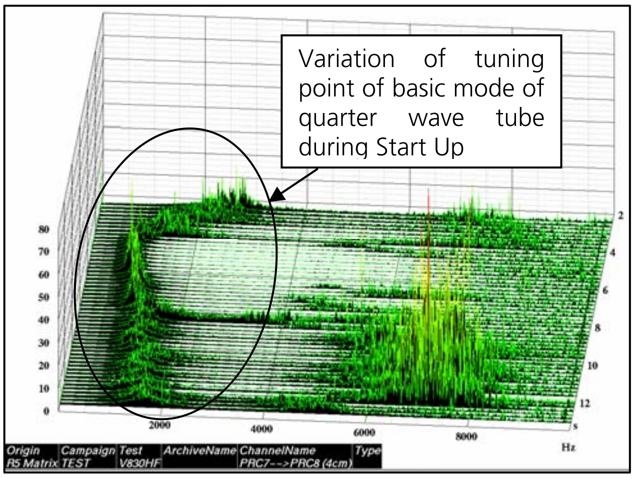


FIG. 14: TEST OF QUARTER WAVE TUBE

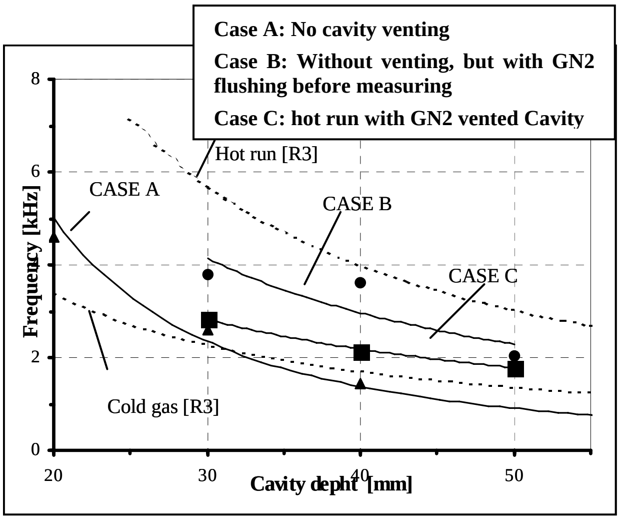


FIG. 15: TUNING FREQUENCIES FOR DIFFERENT CASES

7.2 HF STABILITY - BAFFLES

A prototype baffle (FIG. 16) was designed and installed inside the combustion chamber.

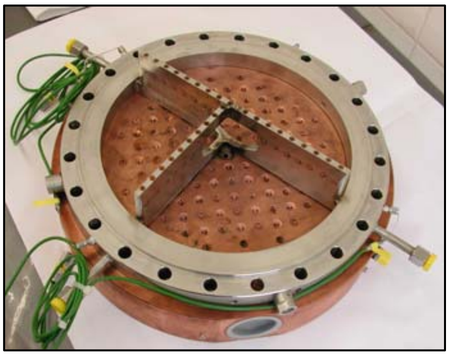


FIG. 16: BAFFLES

For triggering a little pyrotechnic charge has been installed inside the chamber and ignited during hot run (FIG. 17). A HF pressure transducer integrated into the chamber wall registered the pressure evolution in order to look for damping conditions inside the combustion chamber.

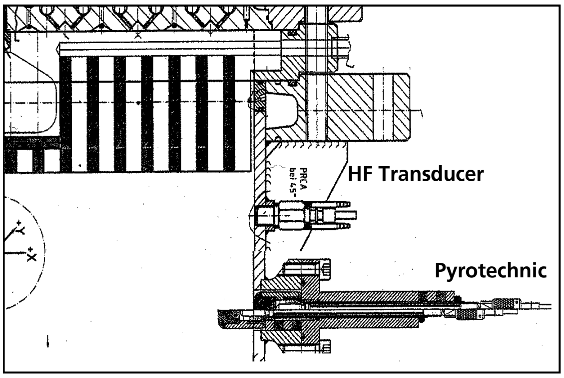


FIG. 16: BOMB TEST CONFIGURATION

The "bomb"-test shows decreasing oscillation after ignition of the pyrotechnic (FIG. 18). In contrast to the cavity ring tests the baffle proofed damping conditions in hot run test. The concept of a three blade baffle was introduced.

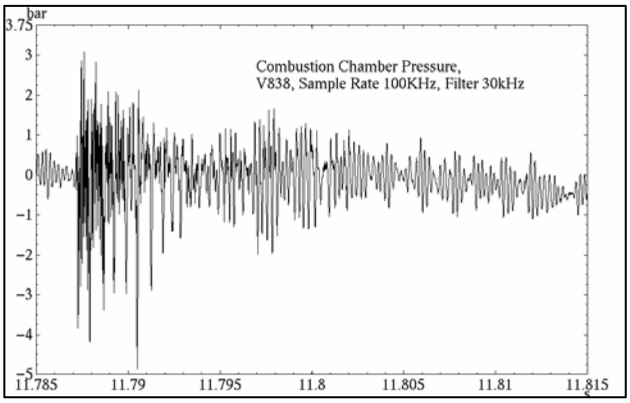


FIG. 18: BOMB TEST RESULTS

7.3 CHAMBER COOLING

Thermal foot prints (FIG. 19) of injection elements are observed when combustion gases rich of oxygen are contacting the wall. Modification of flow rate of ethanol and LOX during hot run gives indications for further adjustments. The tests resulted into installation of LOX injector orifices at the entrance of each like on like doublet element in order to control oxygen cross section distribution.

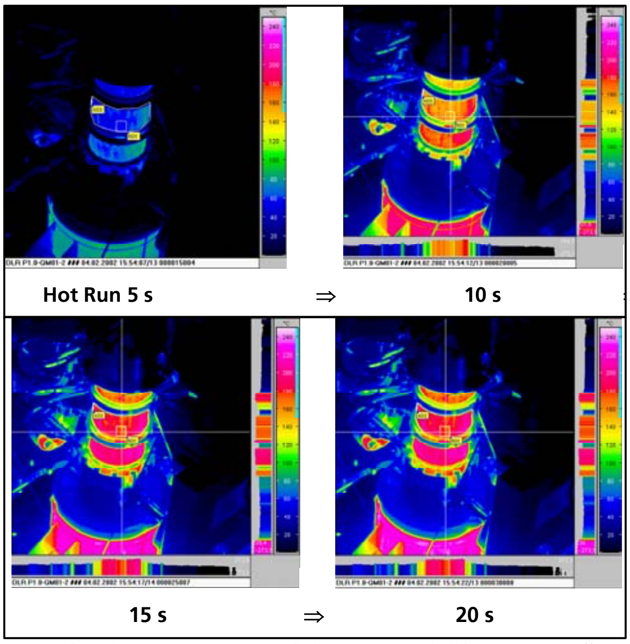


FIG. 19: THERMAL FOOT PRINTS “START UP”

7.4 IGNITER POSITION

The first model of the steam generator was equipped with a central positioned H2/O2 Igniter. This configuration has to be changed to a sideward Igniter position due to:

- Complex design of the Igniter inside the ejection head.
- Distribution of the LOX feeding for the injection head.
- With the integration of the baffles the ignition shock increases.

Water spray test were performed to optimize the position of the Igniter.

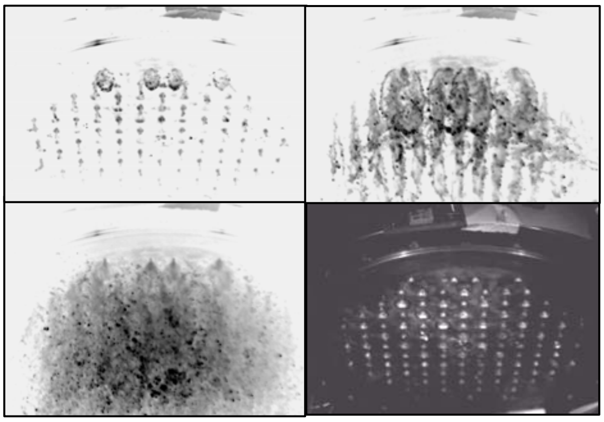


FIG. 20: WATER SPRAY TEST

8 FINAL LAY OUT OF THE TEST BENCH

The final lay out (FIG. 21) is a powerful two stage ejector system with an intermediate condenser.

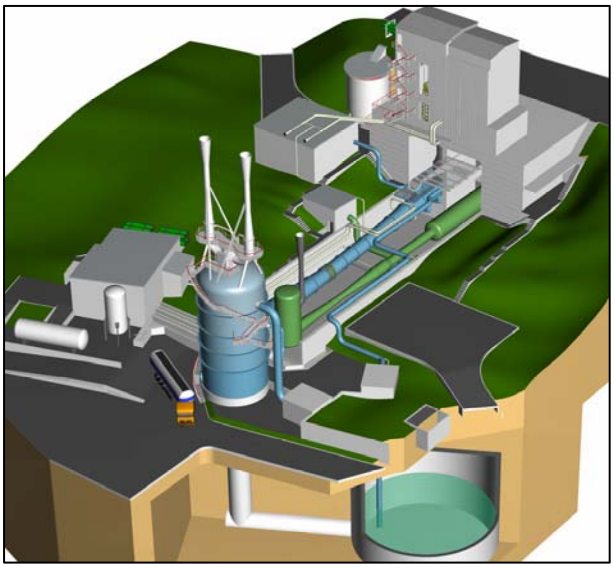


FIG. 21: P4.1 FINAL LAY OUT

Main parameters are:

Vacuum chamber: ∅ = 5 m / h = 6,2 m
Diffuser: ∅ = 2,38 m / l = 10 m
Water: 2,0 m^3/s / 10 °C
First Ejector Stage: Steam: 2 x 55 = 110 kg/s
Condenser: Water: 3,6 m^3/s / 10 °C
Second Ejector Stage: Steam: 2 x 59 = 118 kg/s
Chill down Ejectors: Steam: 2 x 8 = 16 kg/s
Steam Generator Plant: Steam: 244 kg/s ~ 450MW

9 COMMISSIONING

First test results of the commissioning phase shows the expected behaviour.

The first ejector stage was measured by different test conditions (FIG. 22):

- Different mass flows of sucked air for the verification of the suction pressure
- Increasing counter pressure and with the different mass flows for the verification of the stability

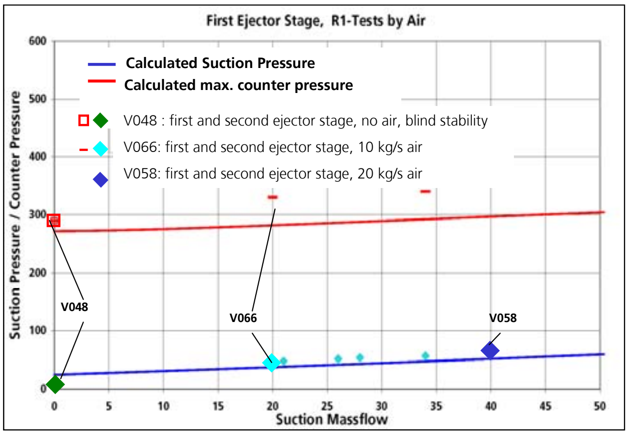


FIG. 22: FIRST EJECTOR STAGE

The second ejector stage was measured with different test conditions for the verification of the suction pressure (FIG. 23).

- Different mass flows of sucked air.
- With first ejector stage (additional mass flows of CO2 and steam) or without first ejector stage.

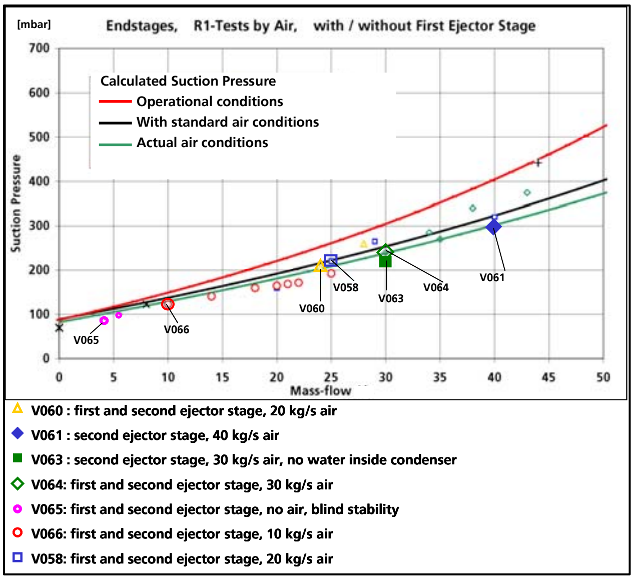


FIG. 23: SECOND EJECTOR STAGE

10 RECEPTION WITH VINCI (PHASE 5)

The reception of the test bench especially the verification of the diffuser with the first VINCI tests is still in progress.

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