P4.1 TEST FACILITY FOR ALTITUDE SIMULATION OF VINCI® ENGINE – BENCH DEVELOPMENT

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Abstract

The need to develop, qualify and accept propulsion systems under actual operating conditions in high altitude 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. 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 and condensation.

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.

The main task for the P4.1 altitude simulation was the definition of the operational behaviour with the development of a centre body diffuser.

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 the sea level and altitude simulation tests of the VIKING engine. 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

Test Requirements

The VINCI® engine (fig. 2) will be tested in 3 configurations (tab.1).

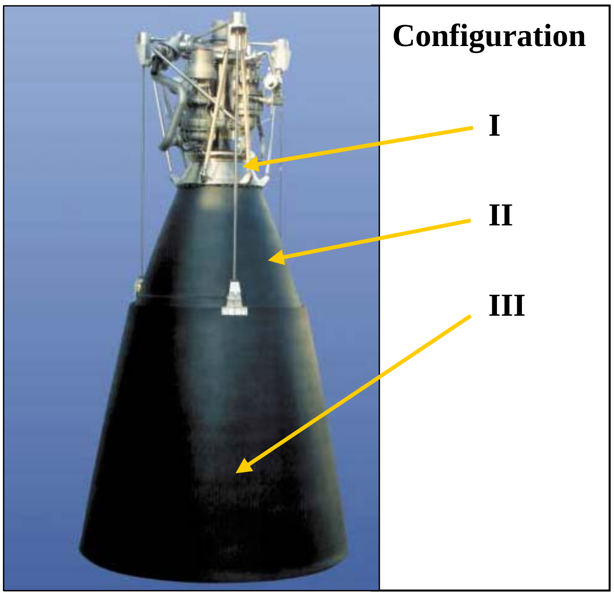

Fig. 2

Table 1

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

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.

P4.1 Test Bench Development

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

- **Phase 1:** Basic studies and general lay out.
- **Phase 2:** Diffuser subscale testing.
- **Phase 3:** Final lay out of the test bench.
- **Phase 4:** Commissioning.
- **Phase 5:** Reception with VINCI®.

The main developments for the P4.1 altitude simulation were the centre body diffuser, the ejectors, the rocket steam generators and the operational behaviour using modular systems for the adaptation to the different test configurations.

Studies and General Lay Out (Phase 1)

The basic studies are performed for the choice of the super sonic diffuser and the general dimensioning of the suction system.

Centre Body Diffuser: 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 test configuration I ($\varepsilon = 22, 3$) is designed as a short diffuser and for gimballing. The adapter for configuration II ($\varepsilon = 93$) replaces the extendable nozzle.

The basic design is mentioned in figure 3. Main drivers were:

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

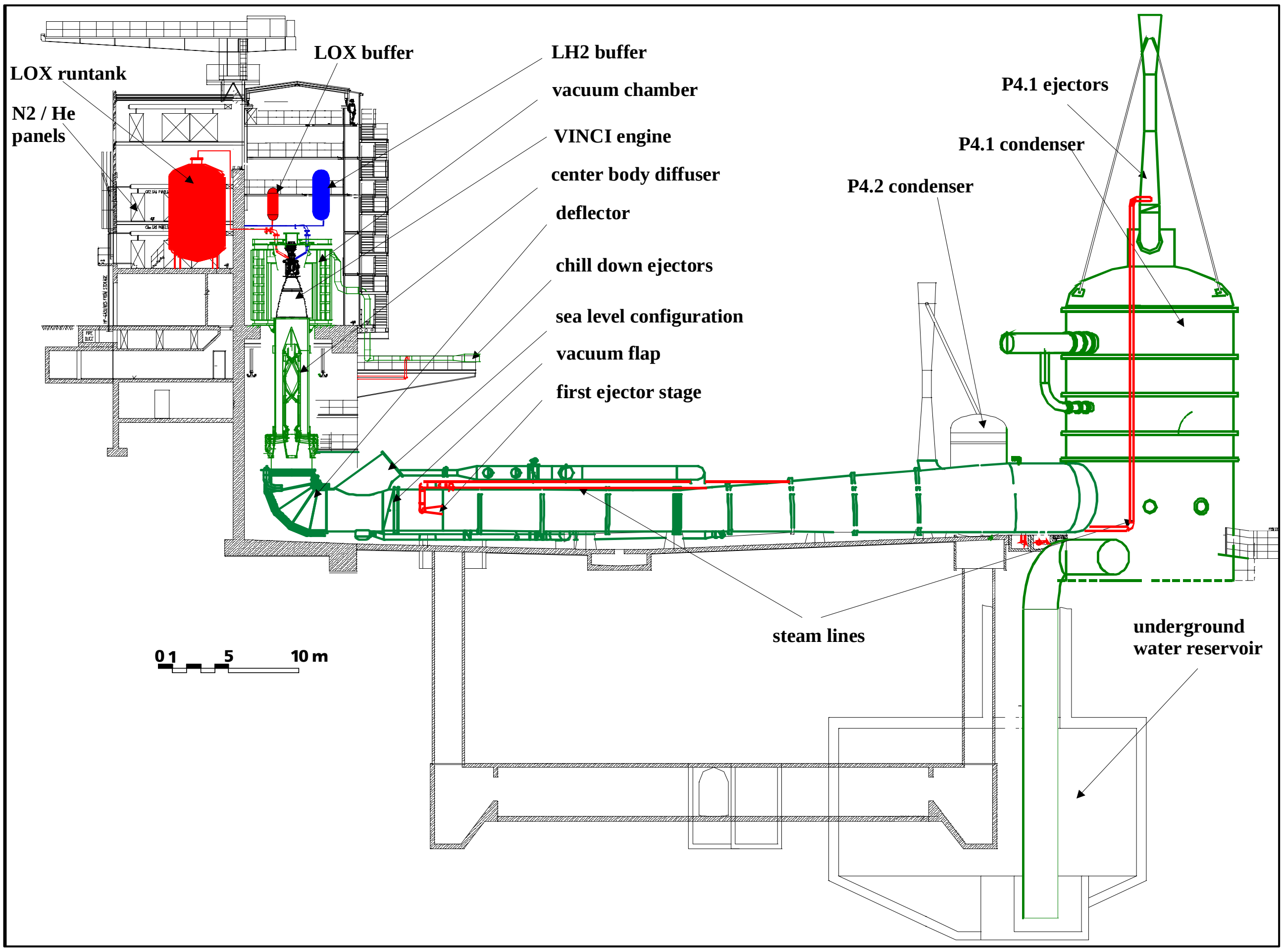

Fig. 3

The dimensioning of the diffuser and the ejector has been achieved by an experienced calculation process. The general way of calculation (fig. 4) consists of three steps. A forward calculation, to determine geometric parameters from input parameters, represents the first step. The second step is like a cross-check procedure by a backward calculation, receiving the characteristic curve from geometric parameters. Finally in a third step, the sensitivity to parameter-variations is evaluated to check the reliability of the prediction.

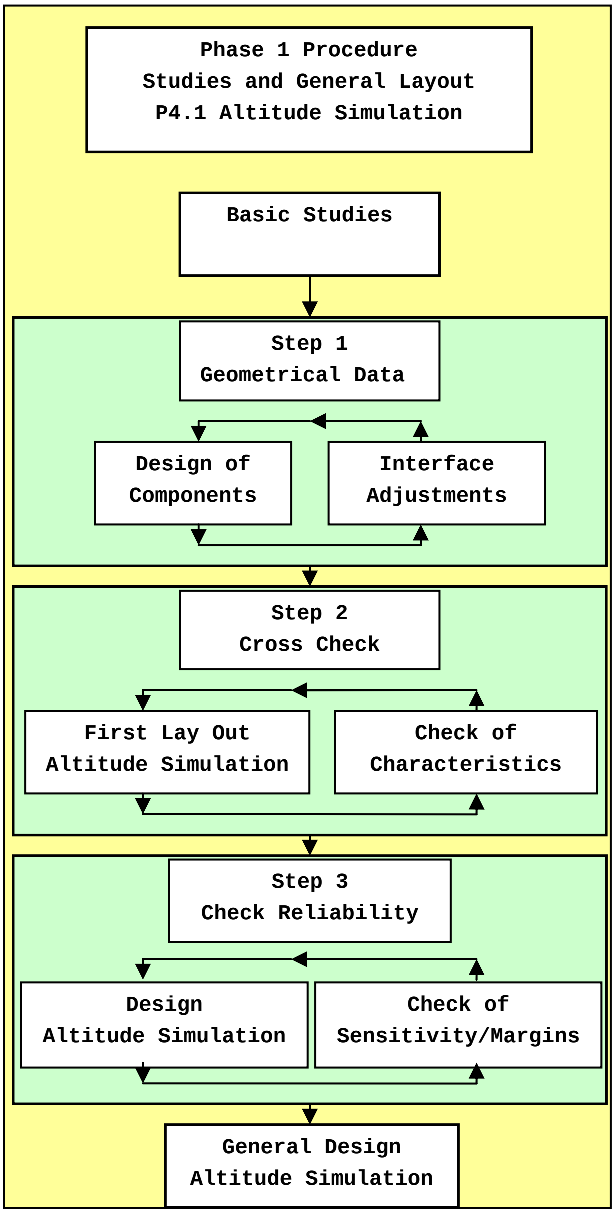

Fig. 4

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.

The general parameters for ε = 243 configuration are mentioned in table 2.

Table 2

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

Basic studies for the gas dynamic and thermodynamic conditions of the centre body diffuser were performed.

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 ejectors are designed for the transient conditions. Basic parameters are the “Blind stability” without mass flow and the operational conditions with running engine. Especially the first ejector stage has to prevent the backflow of hot gases during shut down of the engine and to limit the nozzle loads.

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.

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

The diffuser sub scale tests are done by N2 cold flow conditions. The simulation allows similar Mach numbers. The objectives were:

- Verification of the basic design
- Investigation of phenomena like engine gimballing (fig. 6)
- Transient studies for supersonic Start and Un-Start conditions.
- Parameter studies of diffuser arrangement (fig.7).

Fig. 6

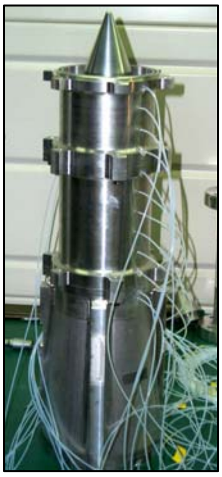

Fig. 7

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.

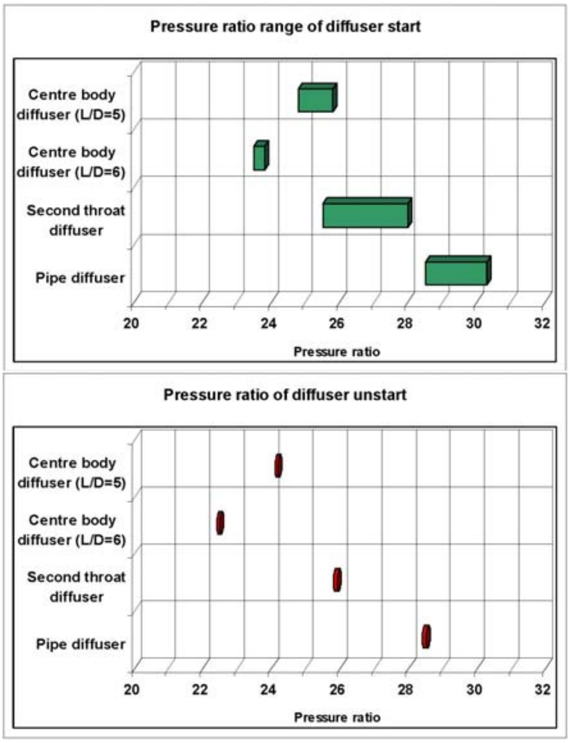

Fig. 8

The tests show for the Start of the diffuser an increasing supply pressure (fig. 9) from 10 - 18 bar with an gimballed angle from 0°- 7°.

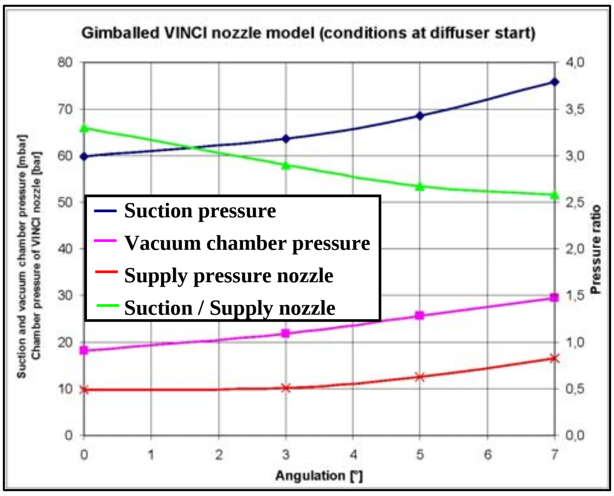

Fig. 9

Subscale Diffuser Hot Gas Tests

The hot gas model was tested at the test bench P8 with a H_2 / O_2 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

Table 3

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

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

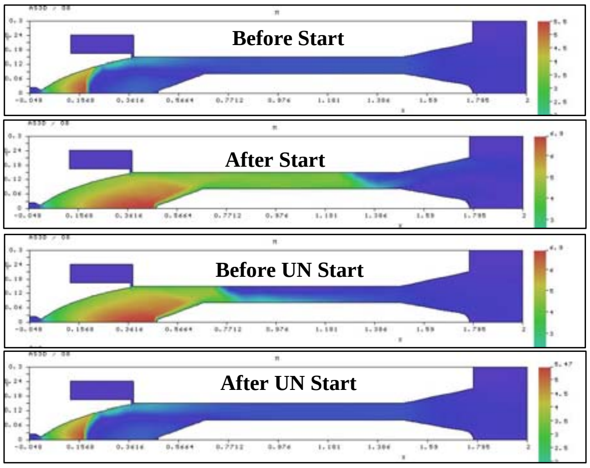

Fig.10

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.

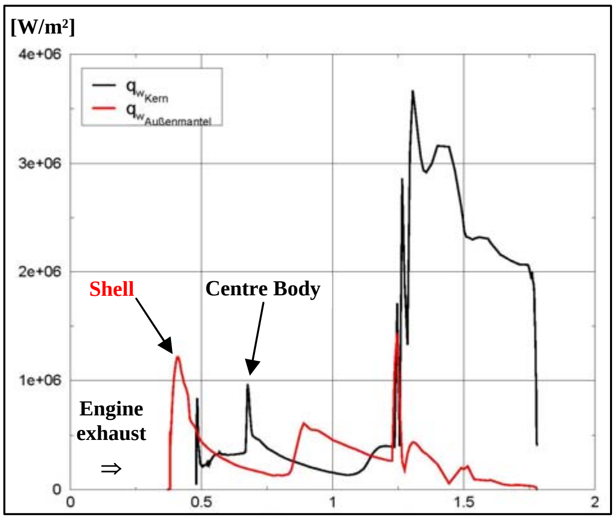

Fig. 11

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.

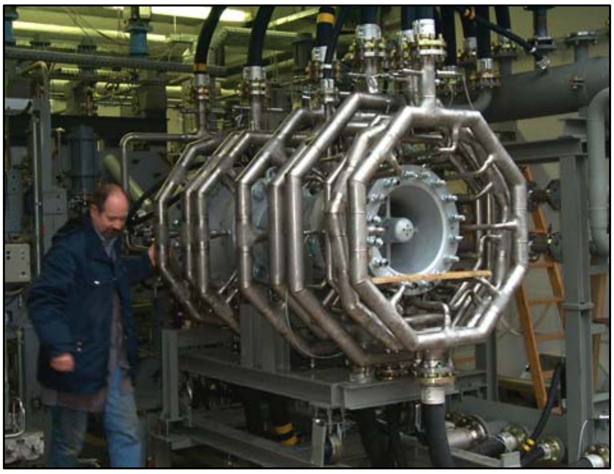

Fig. 12

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 but the prediction of the heat loads were under estimated. Especial hot spots with high heat loads were detected but not directly measured. The vacuum conditions were better than expected.

Generally the design fulfills all requirements.

Table 4

Hot Gas Model	Calculated	Measured
Heat Load Centre Body [kW/m²]	1200 aver. 3500 max	2180–2600 aver. Hot Spots
Heat Load Cylinder [kW/m²]	500 aver. 1500 max	660 – 1130 aver. Hot Spots
Chamber pressure for Start [bar]	55	50 - 56
Chamber pressure for UN Start [bar]	48	48 - 50
Vacuum [mbar]	80	40 - 50

Final Lay Out of the Test Bench (Phase 3)

The final lay out (fig 3 and fig. 13) is a powerful two stage ejector system with an intermediate condenser.

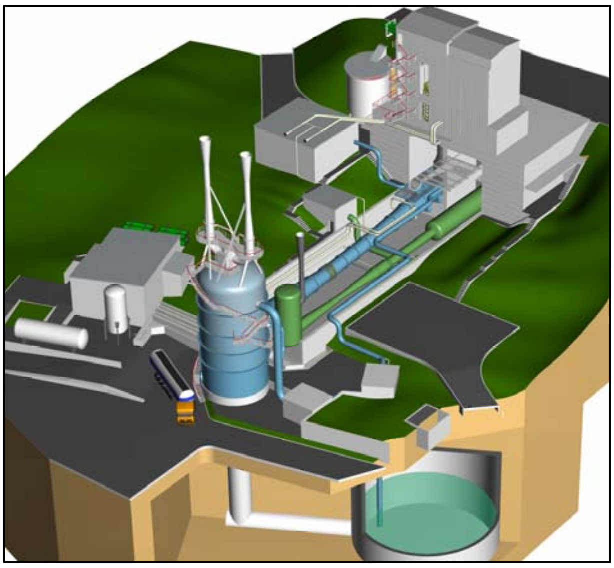

Fig. 13

Main parameters are:

- Vacuum chamber: ∅ = 5 m / h = 6,2 m
- Diffuser: ∅ = 2,38 m / l = 10 m Water: 2,0 m³/s / 10°C
- First Ejector Stage: Steam: 110 kg/s
- Condenser: Water: 3,6 m³/s / 10°C
- Second Ejector Stage: Steam: 2 x 59 kg/s
- Chill down Ejectors: Steam: 2 x 8 kg/s

Commissioning (Phase 4)

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

The suction capability of the end stage ejectors (fig 14) were tested by air. The calculations are with air (black), with actual test conditions (green) and for operational (red). The dots are measured values of different tests.

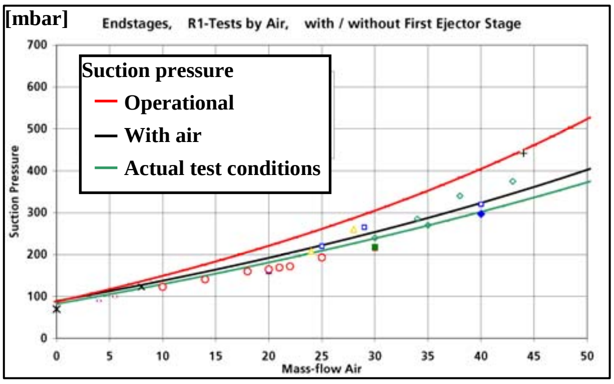

Fig. 14

The calculated profiles of the first ejector stage (fig. 15) were with air for the suction pressure (blue) and for the maximum counter pressure (red). The dots are measured values.

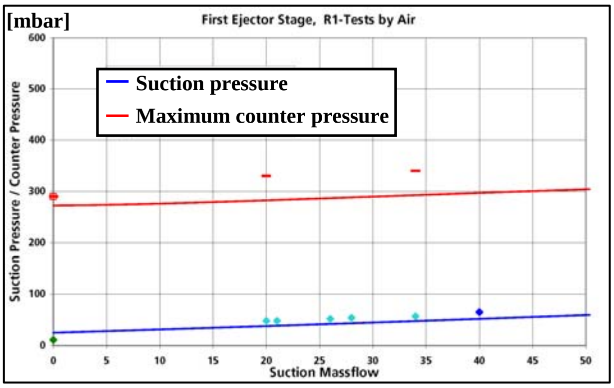

Fig 15

Reception with VINCI (Phase 5)

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

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