Operation of Test Facilities for Upper Stage Engines: High Altitude Test Facility P4

Dipl.-Ing. Christopher Gusinde (Christopher.Gusinde@dlr.de)

German Aerospace Center (DLR), Institute of Space Propulsion, Test Facilities,
74239 Lampoldshausen-Hardthausen, Germany

Contents

1. Introduction: High Altitude Test Facility P4

- Engines that are installed in rocket upper stages, satellites or space probes operate at high altitudes above ground (vacuum) which affects the ignition of the engines
- In vacuum there is no convection and engines develop more thrust and are thus exposed to greater stresses and strains.
- To simulate these conditions, vacuum test facilities like P4 are needed which are capable of creating vacuum during the hot firing test of an engine.
- During the test an analysis and measurement of ignition behavior, thermal stress of the structures, vacuum thrust etc. are performed continuously
- The German Aerospace Center at Lampoldshausen operates a variety of vacuum test facilities. The biggest one is P4:
    - P4.1: VINCI engine (cryogenic propellants, 180 kN)
    - P4.2: AESTUS engine (storable propellants, 27.5 kN) and currently 5 kN development engine

2. History of Test Facility P4

- P4 was erected in Lampoldshausen between 1964 and 1966 as state of the art high altitude test facility for the ELDO program
- For the operation of the high altitude test facilities special steam generators were developed by the engineers of the site in Lampoldshausen.
- Altogether 45 sea level and 76 high altitude tests under vacuum conditions took place with the main engine "Astris" and two vernier engines of the third stage of the planned Europe rocket ("Europa").

High Altitude Test with own development of steam generators and Astris engine at P4

2. History of Test Facility P4 (cont'd)

- In the 70’s the test facility P4 was converted several times to conduct numerous tests with Viking engines (Ariane 1 to 3), the PAL booster of Ariane 4 and the 2nd stage of Ariane 4.
- By the end of 1984 a total of six development and qualification tests had been conducted with two PAL boosters in the flight version of Ariane 4 on the P4.1 test stand.

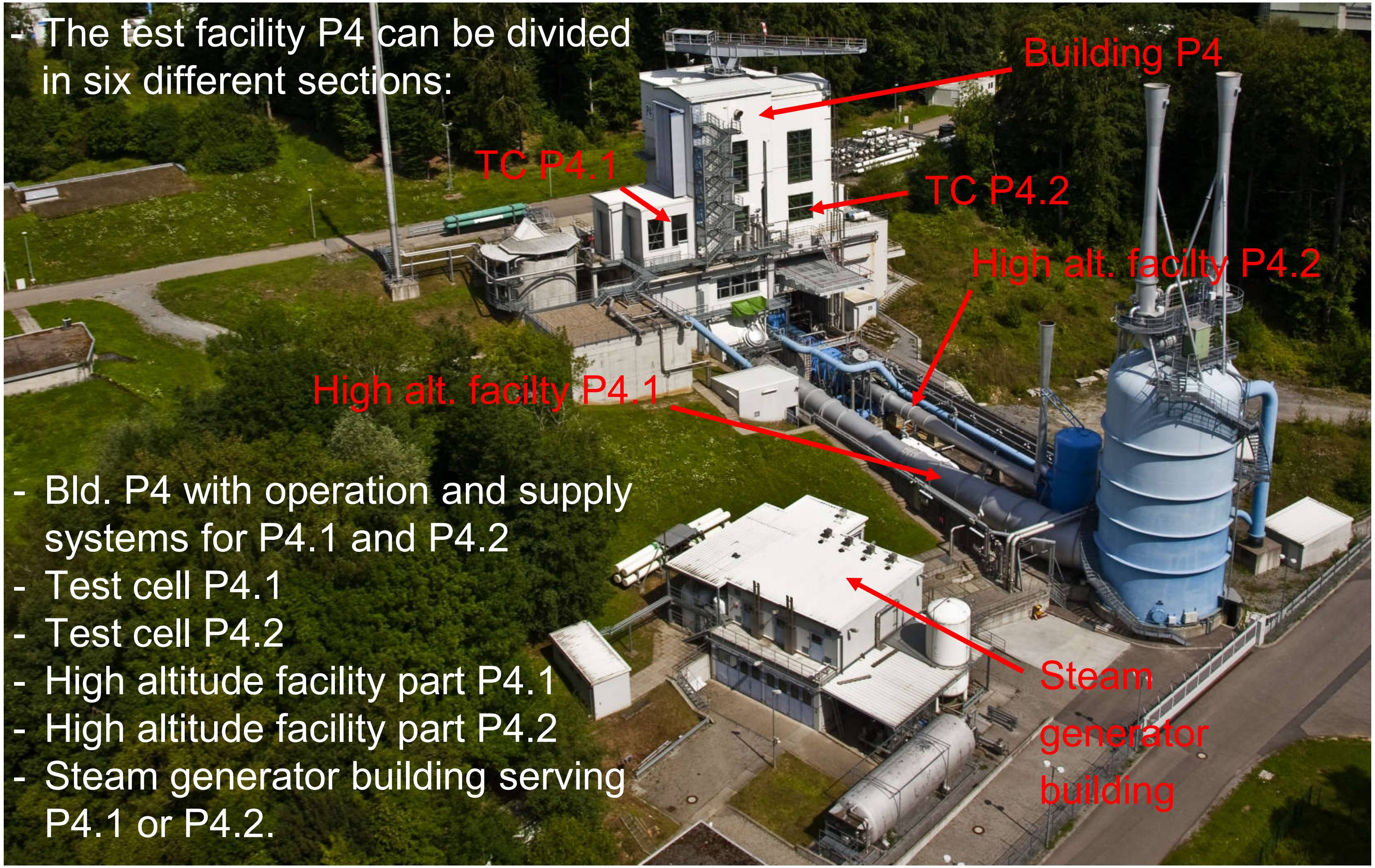
Left:

Test of the 2nd stage of Ariane 4 at P4.1

Right:
Integration of the PAL booster of Ariane 4 at P4.1

3. Current Status of High Altitude Test Facility P4
3.1 Introduction

- The test facility P4 can be divided in six different sections:



- Bld. P4 with operation and supply systems for P4.1 and P4.2
- Test cell P4.1
- Test cell P4.2
- High altitude facility part P4.1
- High altitude facility part P4.2
- Steam generator building serving P4.1 or P4.2.

3. Current Status of High Altitude Test Facility P4
3.2 Supply Building P4

The building accommodates the following main systems:

- 200 bar GN2 supply
- 200 bar GHe supply
- 200 bar air supply
- MMH storage tank, 25 m³, 5 bar
- N2O4/MON storage tank, 25 m³, 5 bar
- Mechanical vacuum pump station: two water-ring pumps down to 100 mbar, three vacuum pump units within the millibar range
- Water pump station for test facility cooling water and emergency shower supply
- Water supply tank of 300 m³ for steam generator
- Control and data acquisition system
- Test cell P4.1: vacuum chamber (6.9 m in height, 6,8 x 5,8 m² basic layout)
- Test cell P4.2: vacuum chamber (4.9 m in height, 2,8 x 2,8 m² basic layout), stage simulation setup (AESTUS), run tanks with engine supply

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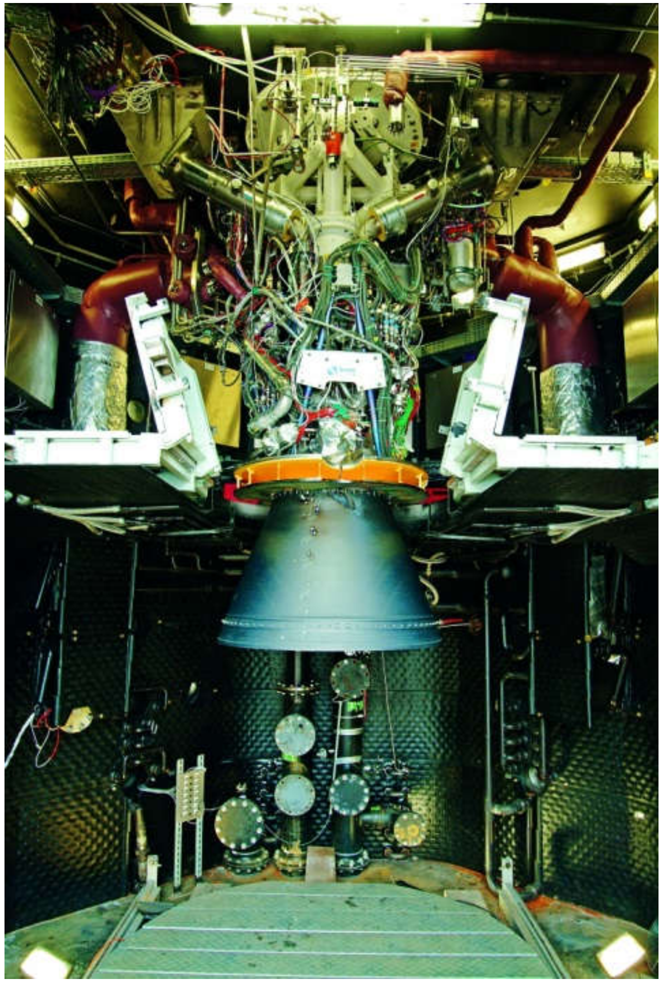
3. Current Status of High Altitude Test Facility P4
3.3 Test Position P4.1

- The test facility P4.1 is equipped for testing rocket engines using the cryogenic propellants liquid hydrogen (LH2) and liquid oxygen (LOX).
- Development of VINCI, the future upper-stage engine of Ariane.
  - Expander cycle engine
  - Re-ignitable up to 5 times
  - Thrust level of 180 kN under vacuum conditions
  - Extendable carbon composite nozzle



Vinci engine installed in P4.1 vacuum chamber

3. Current Status of High Altitude Test Facility P4
3.3 Test Position P4.1 (cont'd)

- P4.1 main characteristics

Sub-system	Component	Capacity
Cryogenic system	LH2 run tank	135 m³
	LH2 buffer tank	4,5 m³
	LOX run tank	50 m³
	LOX buffer tank	1,5 m³
Gaseous system	HP GH2	10000 Nm³
	HP GN2	6.400 Nm³
	HP GHe	3.450 Nm³
Cooling water system	Cooling water tanks	6000 m³ (2*1000 m³ + 1*4000 m³)

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3. Current Status of High Altitude Test Facility P4
3.3 Test Position P4.1 (cont'd)

- The P4.1 vacuum chamber allows VINCI engine tests in three different engine configurations
    - Engine w/o nozzle extension
    - Engine w/ nozzle ext. (fixed part)
    - Engine with full nozzle extension
- In order to bridge the gap between the engine and the inlet of the supersonic diffuser, water-cooled adaptors are utilized.
- Partially equipped with stage simulation hardware in order to simulate the conditions in the actual upper-stage.
- Last Vinci test was performed in July 2018

Vinci engine test at test facility P4.1

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3. Current Status of High Altitude Test Facility P4
3.4 Test Position P4.2

- The test facility P4.2 is equipped for testing rocket engines or stages using the storable propellants monomethylhydrazine (MMH as fuel) and dinitrogen tetroxide (N2O4/MON as oxidizer).
- Qualification and flight acceptance tests of the 27.5 kN AESTUS engine for the upper stage of Ariane 5 and especially on the upper-stage engine designed to transport the ATV were performed
- Last AESTUS test performed in July 2017
- Currently tests for a 5 kN development model are running

- P4.2 permits testing under ground conditions (ambient pressure 1.013 bar) as well as under vacuum conditions (ambient pressure < 5 mbar with the engine running)

Vacuum chamber with stage simulation tanks (SST) and integrated Aestus engine at P4.2

3. Current Status of High Altitude Test Facility P4
3.4 Test Position P4.2 (cont'd)

- The P4.2 vacuum chamber allows engine tests in different test facility configurations
  - Static vacuum tests
  - Dynamic vacuum tests

- During static vacuum tests only short ignition tests are performed using the static vacuum conditions generated by the vacuum pumps
- During dynamic vacuum tests hot firing durations up to 300 seconds for AESTUS were performed. The vacuum chamber is continuously evacuated during the test using the steam generator plant.

AESTUS engine test at test facility P4.1

3. Current Status of High Altitude Test Facility P4
3.4 Test Position P4.2 (cont'd)

- P4.2 main characteristics

Sub-system	Component	Capacity
Storable Propellant system	MMH run tank	1.5 m³
	MMH SST	0.21 m³
	N_2O_4 run tank	1.5 m³
	N_2O_4 SST	0.3 m³
	MMH/N_2O_4 storage tank	25 m³
Gaseous system	HP GN2	2000 Nm³
	HP GHe	1500 Nm³
Cooling water system	Cooling water tanks	2000 m³ (2*1000 m³)

3. Current Status of High Altitude Test Facility P4
3.4 Test Position P4.2 (cont'd)

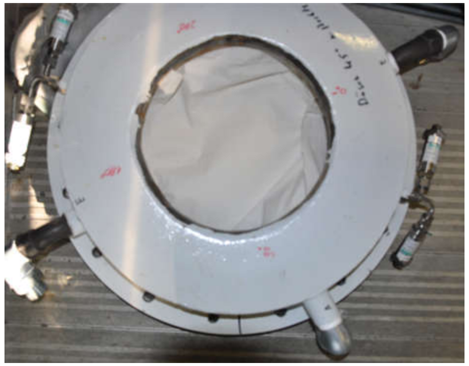
- Refitting of P4.2 for stage configuration tests for AESTUS was performed in 2001, i.e. construction and placement of the tanks and the lines supplying the engine so that the situation in the original upper stage is almost precisely reflected.
- Since 2001, P4.2 has been used exclusively for AESTUS vacuum tests with hot run times varying between 0.874 s and 300 s, depending on test requirements and test facility configuration.

Steam ejection of the main ejector stages (left) and at the vacuum gate valve location (right) during dynamic vacuum test at P4.2

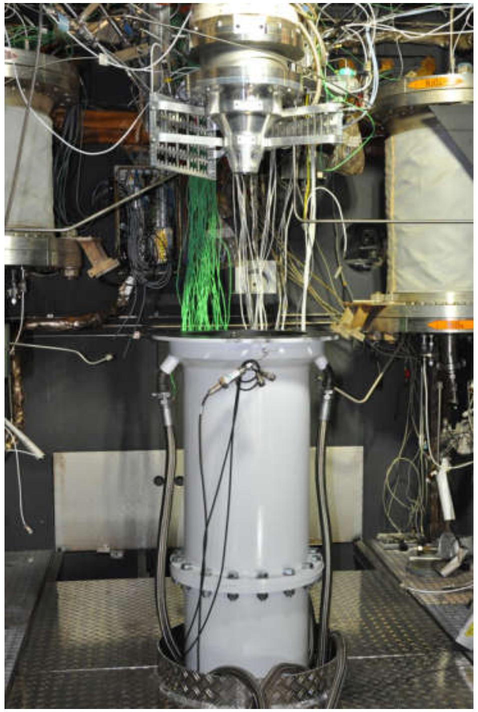
View of P4.2 from P3 test facility during dynamic vacuum hot run

3. Current Status of High Altitude Test Facility P4
3.4 Test Position P4.2 (cont'd)

- In 2020/2022 the P4.2 feed system and also a part of the exhaust system inside the vacuum chamber was again modified for tests with a 5 kN development model
- Therefore a similar but smaller feed system compared to the AESTUS feed system was erected
- Also a new diffusor inlet cone and extension for exhaust guiding the exhaust gases and for noise reduction during the sea level tests was installed inside the vacuum chamber



Diffusor Inlet



Diffusor Extension

3. Current Status of High Altitude Test Facility P4
3.5 TF measurement, command and ctrl. sys.

- Utilization of the MCC (Measurement, Command and Control) system for engine tests
- Real-time operating system which comprises a network of subsystems
- Each test position of the P4 has its own MCC (P4.1, P4.2, steam generators) which consists of a front and back end.
- The front end consists of
  - output modules controlling digital and analogue test facility components
  - systems required for acquisition of measurement data, test preparation, data evaluation/storage and monitoring of the test facility.
- The front-end computers handle the following operations:
  - LF data acquisition
  - HF data acquisition
  - System control
  - Backup system control

Test Facility	P4.1	P4.2	P4 SG
LF (max. 1 kHz per channel)	864	323	324
HF (max. 100 kHz per channel)	88	55	16

P4 MCC capabilities

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3. Current Status of High Altitude Test Facility P4
3.5 TF measurement, command and ctrl. sys.

- Front-end components are installed at the test facility itself
- Back-end computers are located in the test control center
- Front-end and back-end computers are interconnected by a high-speed fiber-optic network and a reflective memory.
- On P4.1 alone, the MCC acquires a data volume of more than 20 GB during an engine test duration of 700 s.
- In case of an MCC failure the control of the test facility is transferred to the ESS (Emergency Stop System), the engine test is stopped immediately and the reconditioning of the lines is performed.

3. Current Status of High Altitude Test Facility P4
3.6 Steam Generators

- The steam which is needed for the operation of the altitude simulation system is provided by rocket steam generators
- Steam generators run on Ethanol and LOX.
- The steam generators are an own development of DLR Lampoldshausen.
- The steam departs the generators at a pressure of 22 bar and a temperature of 583 K. Accelerated to supersonic speed by the vacuum system ejectors, the steam removes the gas from the vacuum chamber.

Four large steam generators

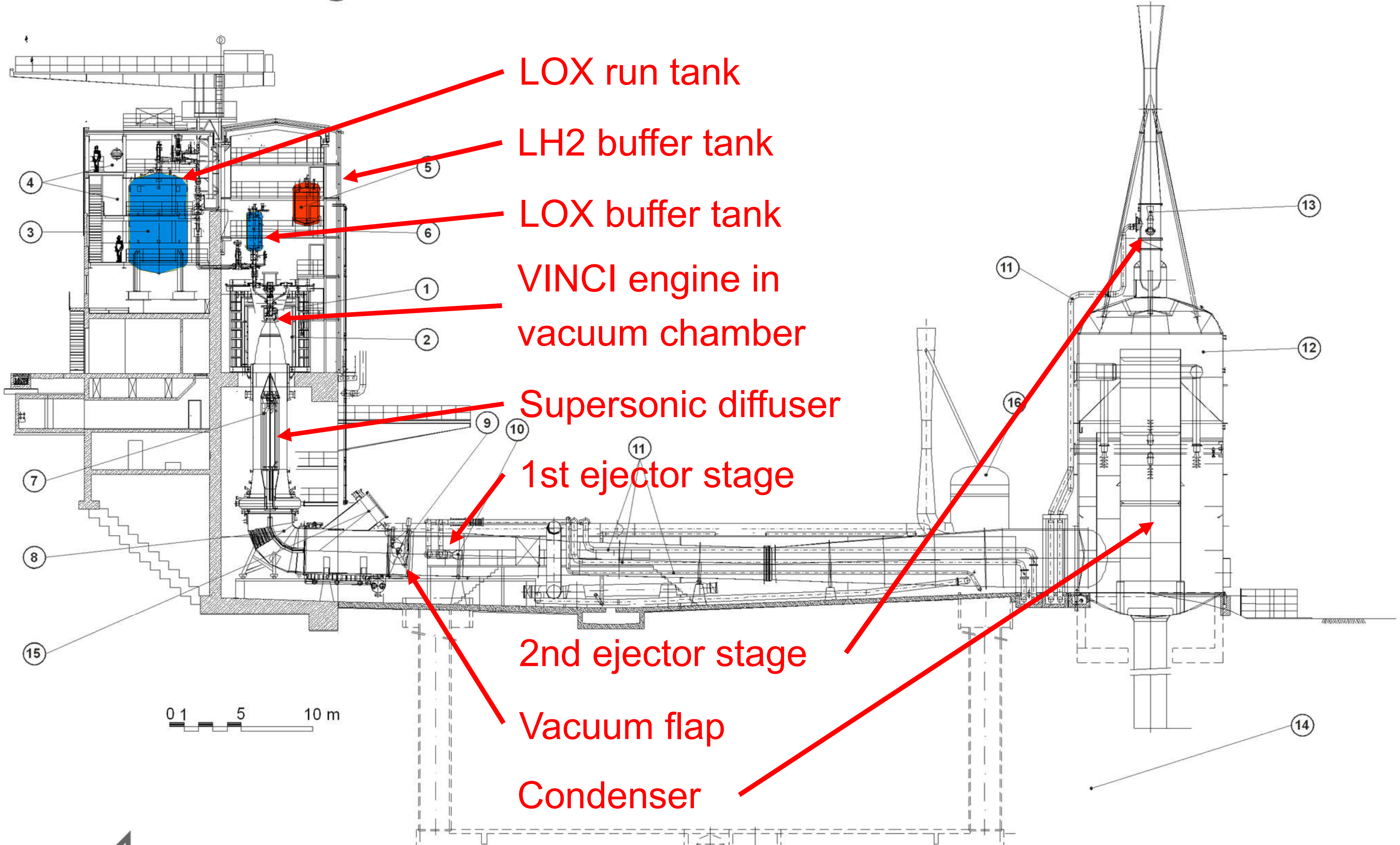
3. Current Status of High Altitude Test Facility P4
3.6 Steam Generators (cont'd)

- Two steam generators are used in the operation of P4.2 where bypass nozzles are installed to partially redirect the steam mass flow.
- The total thermal power of the five steam generators is approx. 650 MW.
- The fluid supply system (Ethanol and LOX) is designed for 1000 s of operation.

Max. test duration	1000 s
Number of steam generators	5
Total amount of steam	226 kg/s (2*50 kg/s + 2*55 kg/s + 1*16 kg/s)
Steam temperature and pressure	583 K at 21 bar
Total power (thermal)	650 MW
Total power (thermal)	650 MW
Ethanol tank	38 m^3
LOX tank	74 m^3
Cooling water tank	380 m^3
HP GN2	8 m^3 at 320 bar

Steam generator main characteristics

3. Current Status of High Altitude Test Facility P4
3.7 High Altitude Simulation Tests on P4.1



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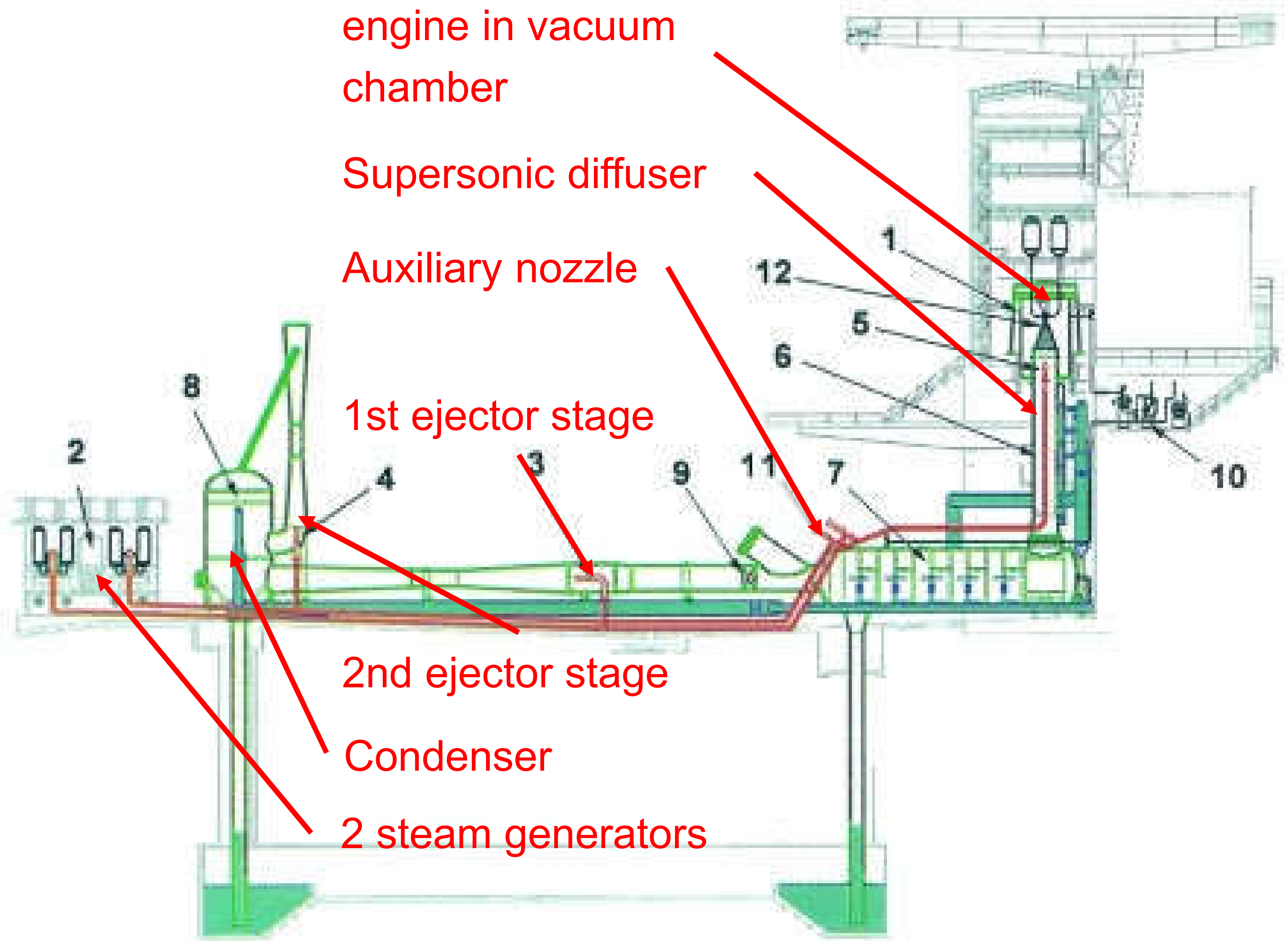
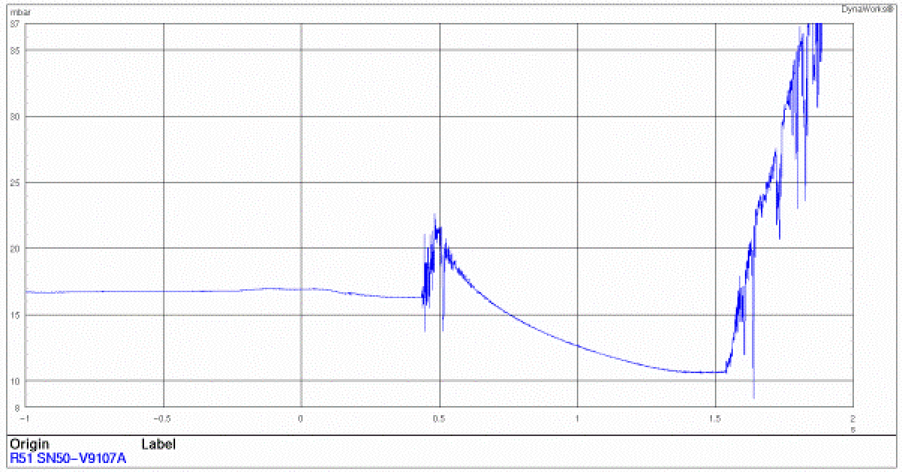
3. Current Status of High Altitude Test Facility P4
3.8 High Altitude Simulation Tests on P4.2

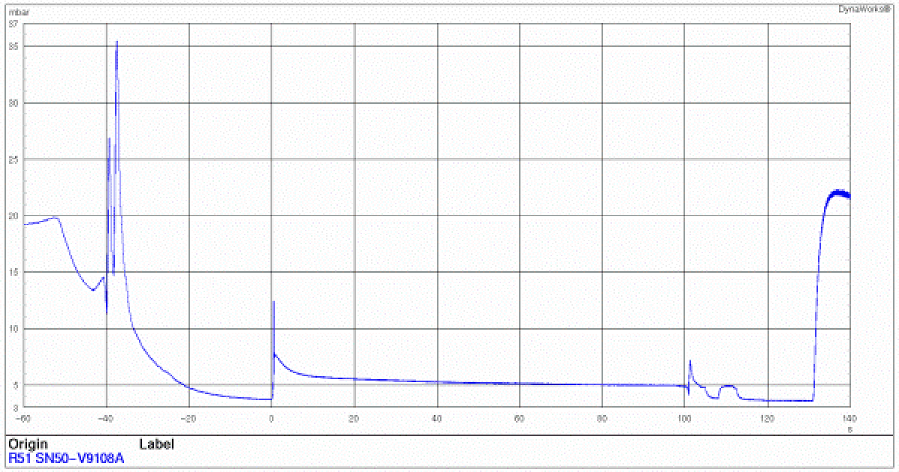


3. Current Status of High Altitude Test Facility P4
3.8 High Altitude Simulation Tests on P4.2 (cont'd)

- Two different test modes are possible:
  - Static vacuum conditions w/o steam generators for ignition tests only
  - Dynamic vacuum mode with steam generators for hot run times up to 300 s with different operation points



Vacuum chamber pressure profile during static ignition test for AESTUS at P4.2



Vacuum chamber pressure profile during dynamic vacuum test for AESTUS at P4.2

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4. P4 Future Activities

- Test facility P4.1:
  - Adaptation to sea level capability in progress

- Test facility P4.2:
  - Modifications and testing in frame of the 5 kN development engine

5. P4.2 Vacuum Test