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DEVELOPMENT STATUS OF THE VULCAIN THRUST CHAMBER†

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Abstract—The Vulcain engine planned to power the cryogenic main stage of the future Ariane 5 launcher is presently under development. MBB is responsible for the thrust chamber of this engine. After 4 years predevelopment and 2 years development, numerous successful tests have been performed on thrust chamber level and the engine development tests have just started with the first ignition tests. The thrust chamber is scheduled to be qualification tested in 1993 and the first technological flight is planned for 1995. The main development results for the thrust chamber are given in this paper as well as an outlook of the further development activities.

1. INTRODUCTION

The Ariane 5 represents the next member of the successful Ariane launch vehicles family. The flight performances will be

- with an upper stage (Fig. 1)
  in GTO max 6800 kg payload
  in LEO 18,000 kg payload
- with the Hermes space plane 23,000 kg.

In both cases the lower stage is powered by two solid boosters (P230) and one single cryogenic stage (H155). Its Vulcain engine provides most of the energy to place payloads into the orbit.

More than 20 European companies contributed to the development of the Vulcain engine (Fig. 2).

The European Space Agency (ESA) has assigned the programme management to the Centre National d'Etudes Spatiales (CNES). As the main contractor for the development of the Vulcain engine the French company SEP has been selected.

MBB, a member of the Deutsche Aerospace, has taken over the responsibility for the development of the thrust chamber (TC). Within this task MBB has entrusted the Swedish company Volvo Flygmotor (VFA), Trollhättan, with the Nozzle Extension, and the German company MAN, Munich, with the Cardan.

Furthermore, the facility for development and qualification tests of the TC had been realized also under the responsibility of MBB in Lampoldshausen, Germany.

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2. THRUST CHAMBER MAIN CHARACTERISTICS

The main data of the Vulcain TC are summarized below:

Total TC thrust (vacuum)	1007.7 (kN)
Chamber pressure	100 (bar)
Mixture ratio	5.6 (—)
Specific impulse (vacuum)	>439 (s)
Mass	<620 (kg)
Life	20 cycles and 6000 s cumulated lifetime
Reliability	>0.99957
Overall dimensions	
—Total length	3002 (mm)
—Nozzle outer diameter	1855 (mm)

Figure 3 shows a sketch of the Vulcain TC and its main components.

The following features characterize the thrust chamber concept

—LOX/LH_2 combustion
—coaxial propellant injection
—regenerative cooling of the combustion chamber
—dump cooling of the nozzle extension
—pyrotechnical ignition
—gimbal joint to the structure.

The TC is composed of the following components

—cardan (CA)
—injector (IN)
—combustion chamber (CC) and
—nozzle extension (NE).

2.1. Cardan

The cardan design has been selected as a ball type cardan after a thorough study of comparison between

Fig. 1. Ariane 5 launcher.

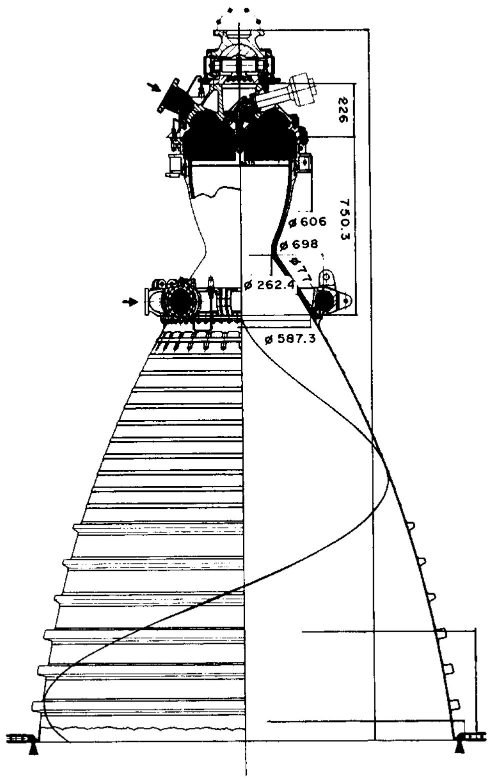

Fig. 3. Vulcain TC.

the cross type and the ball type version. The main advantage of the ball type had been found in the relation stiffness to mass and in the compact design. However, it requires a higher gimbal force because of a greater friction moment.

In Fig. 4 the ball type cardan is presented with its major components. These are the

—ball unit, attached to the injector LOX dome
—shaft unit, connecting the ball and socket unit
—socket unit attached to the thrust cone
—bolts and bellow.

Main features are

Ball diameter	135 mm
Mass	33 kg
Friction moment	<5 kNm
Angular movement	±5° each axis.

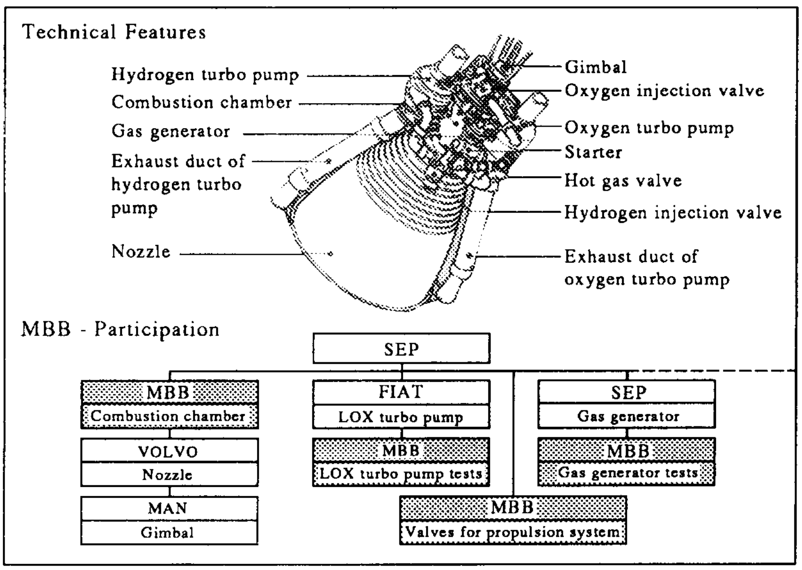

Fig. 2. Vulcain engine.

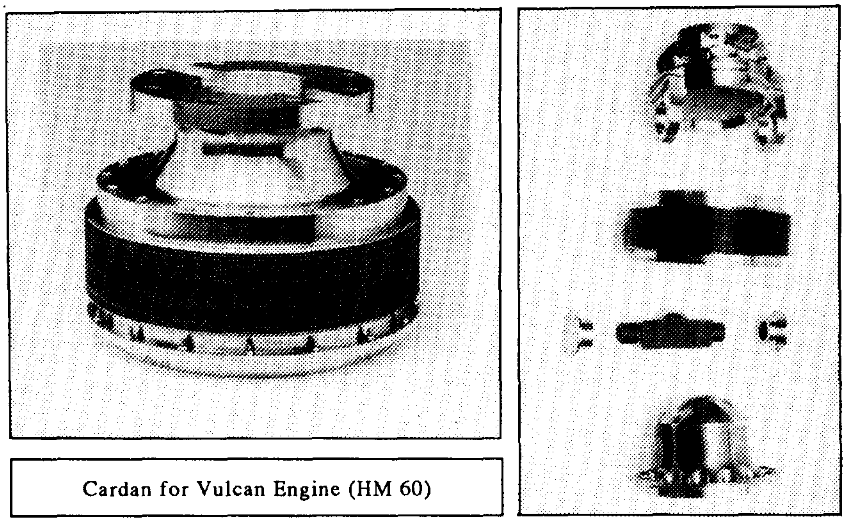

Fig. 4. Ball type cardan.

2.2. Injector

The most efficiency influencing component of the thrust chamber is the injector. Using the coaxial injection principle for the two propellants, the centre bore serves as the feeder for the liquid oxygen and the surrounding angular gap injects the warmed-up hydrogen. The injector consists of the following major components

LOX dome
Base body with LOX posts
Face plate
H_2 sleeves and H_2 screws
Screws and seals.

The LOX dome is a cast, HIP-treated and machined piece made from Inconel 718. The base body is machined from a forged Inconel 718 plate. In 516 drilled holes the LOX posts are diffusion bonded. In the centre hole the igniter tube is arranged. The gaseous hydrogen is introduced into the combustion chamber by means of the H_2-sleeves screwed on the LOX posts. The face plate made out of pure copper is fixed by CuCr screws on the LOX posts. Figure 5 shows the base body with 516 LOX posts ready for assembly.

2.3. Combustion chamber

The life determinative component of the thrust chamber is the regeneratively cooled combustion chamber with its liner. The latter is designed to work within the plastic range up to 3% strain. The liner is fabricated out of a vacuum cast blank from

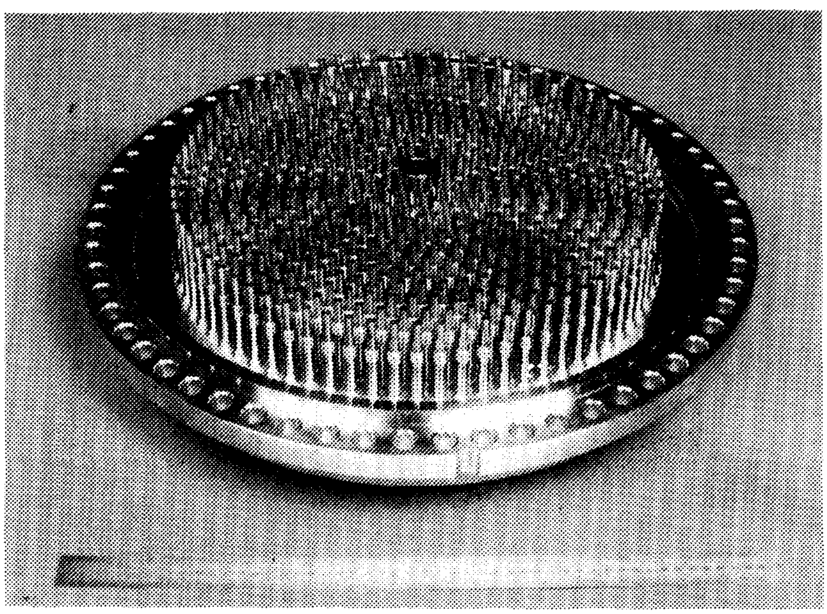

Fig. 5. Injector base body.

a CuAgZr alloy. It contains 360 cooling channels closed out by an electrodeposited nickel shell. The manifolds for the inlet and outlet of the coolant are made from Inconel 718, both attached to the chamber body by EB welding. Figure 6 shows the CC liner with the slots filled with wax and prepared for the electrodeposition process.

2.4. Nozzle extension

The dump cooled NE subcontracted from MBB to VFA (Sweden), is one of the most filigree components of the HM60-thrust chamber. It consists mainly of the

- structure
- inlet manifold
- outlet manifold with the brackets for the TP exhaust pipes and with 228 nozzlets for exhausting the dump and
- various stiffener rings.

The structure is composed of 456 square tubes of 0.4 mm wall thickness, 4 mm outer dimension and constant cross section. The tubes are made out of Inconel 600, as well as all other NE components. The tubes are bent in a special arrangement, thus covering the increasing surface area of the nozzle extension. Fixed on a cone with wire the tubes are TIG welded together by means of a robot welding machine developed within the frame of the contract. All the manifolds and the stiffeners are attached by welding. The total weld seam length is around 2000 m per each NE.

The NE surface is 7.6 m^2. The mass of the engineering model is around 220 kg. Its flight version is expected to have 170 kg, yielding a surface mass of 2.2 g/cm^2. Figure 7 shows the finished NE with instrumentation ready for TC integration.

3. THRUST CHAMBER DEVELOPMENT

The development of the TC is performed in two parts:

a preparatory phase and
a development phase.

3.1. Preparatory phase

After several studies in the period 1980–1984 the preparatory phase for the TC and TC-components had been performed from October 1984 to 1987.

The main objectives can be summarized as follows

—to develop the adequate software for modelization and calculation
—to create the required technologies respectively to adapt existing technologies from previous programmes
—to realize the necessary facilities for manufacturing and testing
—to design and manufacture subscale hardware for the demonstration and optimization of critical development items in hot tests.

3.1.1. Software for modelization and calculation. Numerous finite element models for the total TC and its components have been established to determine stresses, masses, centres of gravity and moments of inertia, to ensure an optimized component design. Computer programmes for calculations of the following main design works have been established, adopted to the present task and permanently improved on the basis of hot test results gained from previous in-house and external development programmes and from the below described HM60 subscale programme.

These are, in detail, programmes for the calculation of

—the thermodynamic and transport properties of the relevant fluids

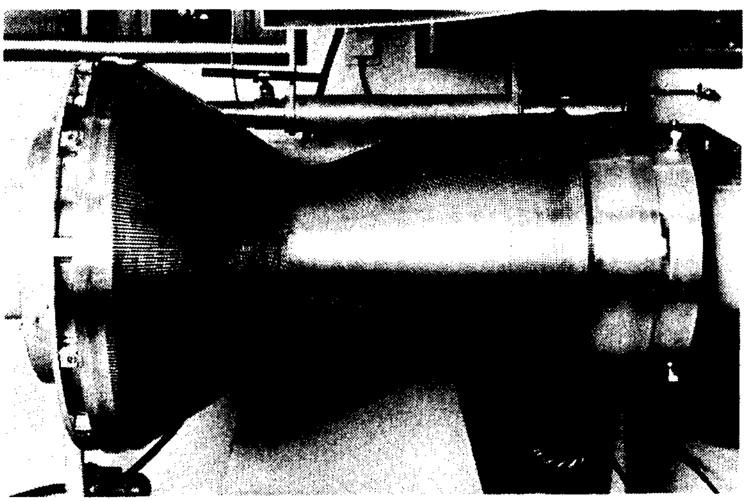

Fig. 6. Combustion chamber liner.

—the geometrical definition of the contour of combustion chamber and nozzle extension
—the plastic stress and strain of the CC hot gas wall resulting in life prediction
—the cooling performances and pressure drops for CC and NE
—the transient and steady state behaviour of cryogenic rocket engines.

Furthermore, programmes for prediction of ignition and start up behaviour, of stability at low and high frequencies and for the calculation of supersonic flow expansion in nozzles have been developed and permanently checked and adapted on the basis of available test results.

3.1.2. Technologies. Within the preparatory phase critical manufacturing steps of all TC components had been investigated as well as all tools and devices for fabrication and cold testing were realized in their basic version.

After an intensive comparison study of different cardan concepts the cardan design was selected as a ball type with respect to the excellent mass to stiffness ratio. The important item for this component was to select suitable gliding foils ensuring the required low friction moment, acceptable wear out behaviour and high resistance against peeling off. A PTFE based foil was chosen which fulfilled the requirements in the best way.

For the injector two major problem areas had occurred during the development. The first one concerned the casting process of the complicated LOX-dome, which yielded some scraps in the beginning. However, after some modifications of the casting tools and optimization of the design with respect to the requirements from the casting process, the production of this Inconel 718 part is now running without problems. The second problematic item had been found in the LOX posts to injector base body connection. Excessive technological work had been

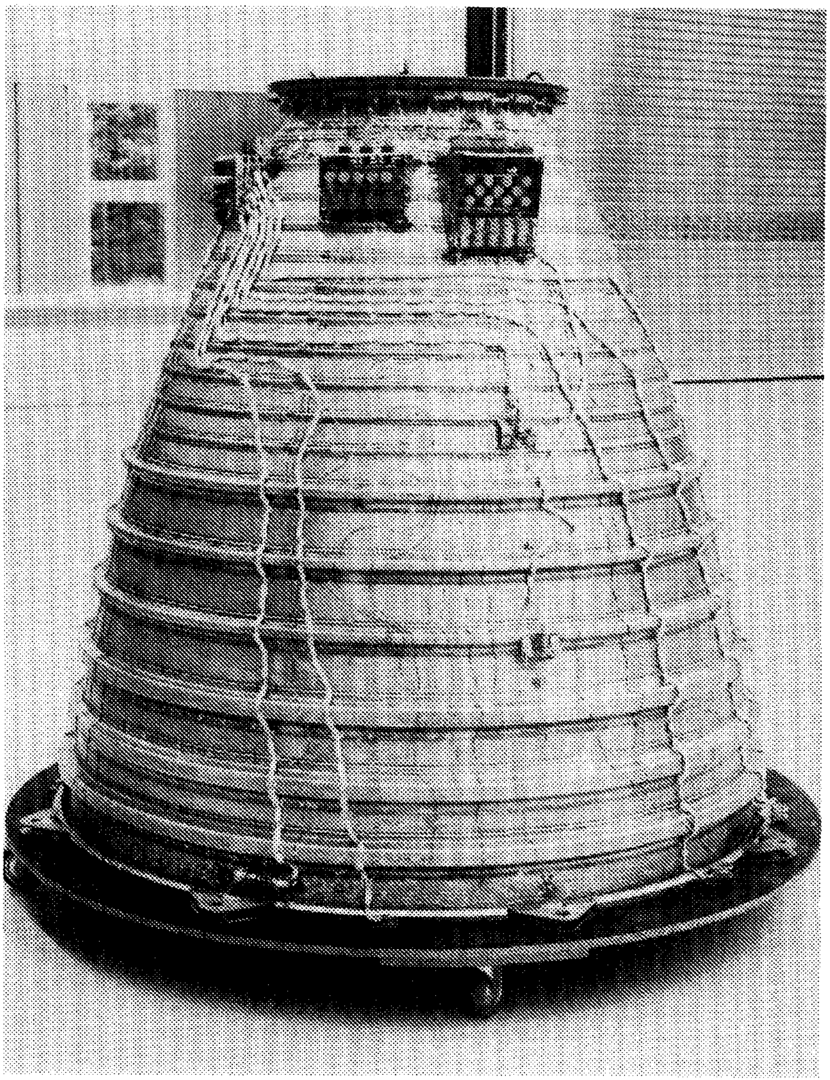

Fig. 7. Nozzle extension ready for integration.

performed in order to select the most reliable and cost effective connection technique between the three most promising methods, i.e.

- —to spark erode the 516 posts out of a forged Inconel 718 plate
- —to connect separately fabricated LOX posts with base body by friction welding or
- —to connect posts and base body by means of diffusion bonding.

Regarding all aspects, like safety, reliability and cost, the last method had finally been selected.

The main technological efforts for the predevelopment of the combustion chamber had been concentrated on the investigation of the properties of the improved liner material CuAg3Zr0.5 in the total application range, i.e. between 20 and 700 K. Also the bond strength to electroplated nickel had been thoroughly investigated.

Furthermore, the H_2 embrittlement risk for the relevant component materials had been studied in detail (i.e. Cu, Ni and their alloys). Especially the optimization of the casting and forging process for the liner blank consumed a lot of time and effort until the required quality could be reached.

The fabrication technology for the NE had already been developed by MBB within the Ariane 1 programme. This technology had been transferred to VFA and adapted to the significant enlargement of the nozzle extension for the Vulcain engine in the Ariane 5 programme. All devices for bending, bundling, welding and handling had been realized. The main efforts here had been put on the development of a robot welding system, because hand welding was no longer reasonable with respect to the weld seam length of about 2000 m for each nozzle extension.

3.1.3. Facilities. Two major facilities for the TC development had to be realized and adapted. The Galvanic plant used for Ariane 1 was too small for the larger preparation—and electrodeposition—bathes required for Ariane 5. The existing building had been extended and larger bathes had been procured, installed and activated.

As a test area for TC hot tests, the existing facilities in Lampoldshausen on the premises of DLR (Deutsche Luft- und Raumfahrtagentur) had to be modified and a new hot test facility, called P3.2, had been designed and constructed during the predevelopment phase under a separate contract from CNES (see Fig. 8). This high pressure fed facility allows chamber pressures up to about 150 bar corresponding to a thrust of about 1500 kN. For reference point conditions a run duration of about 17 s is possible, the limitation is resulting from the tank capacities for the LH_2—resp. LOX—run tanks. The test facility had been established with a suitable control and measurement centre during the predevelopment phase.

3.1.4. Subscale programme. A subscale thrust chamber programme had been initiated, in order to investigate some critical design features. The existing HM7-TC-test facility in OTN was adapted to the Vulcain subscale conditions. Watercooled and regeneratively cooled TCs subscaled by 1:27 (thrust) with a 19 element injector had been designed, manufactured and tested (Fig. 9). The following objectives had been investigated and successfully demonstrated:

- —combustion efficiency of more than 99% with optimized injection element geometry having a propellant velocity ratio of 21 and a recess of the LOX posts of 3 mm. Swirlers in the LOX posts did not improve significantly the efficiency
- —no hints on combustion instabilities
- —the thermal and mechanical integrity of the stability improving devices like the 60 mm long baffles and the acoustic cavities
- —thermo-mechanical integrity of the new liner material
- —jet separation in a water cooled subscaled Cu-nozzle to demonstrate the transiental behaviour of the nozzle flow and define the correct contour with respect to side loads and nozzle efficiency
- —cooling performance of the tubular subscaled dumpcooled nozzle having the inlet at a nozzle area ratio of 5.

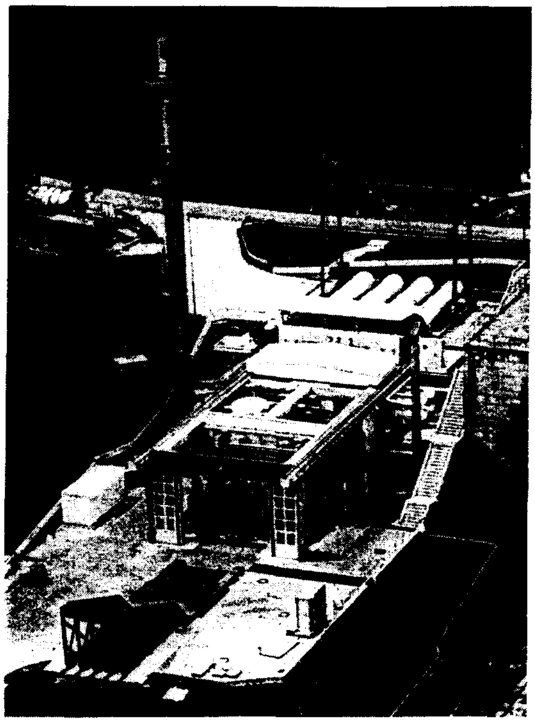

Fig. 8. TC test facility P3.2 in Lampoldshausen.

3.2. Development phase

The TC development was initiated in 1988 and is scheduled to be concluded in 1994. Within this period the TC will be

- designed (including 3 redesign cycles)
- fabricated (30 operational TCs)
- tested at TC level (~220 tests)
- tested at motor level (~400 tests)
- qualified (at TC level).

The general development logic is to improve the TC stepwise from a first engineering (E)-type version up to the final flight version taking into account both theoretical and experimental results gained during the development phase (Fig. 10).

Four different hardware design status will be realized which allows for three redesign-cycles:

- E-type hardware is a battleship-like design version
- PI (Prototype 1) is based on FEM-calculations and partially on test results gained with the E-type TC
- PII (Prototype 2) takes into account test results from E- and PI-TC and first engine test results
- PIII (Prototype 3) is the final version to be qualification tested, which considers all available information including motor test results.

3.2.1. Design status. The design of the E- and PI-type TCs is concluded. The PII-type TC design is presently in progress. Several modifications relative to the previous TC types will be implemented into this design, which results from TC hot tests and from fabrication experience. Major modifications are:

- The cardan is presently in optimization relative to mass, stiffness and friction moment

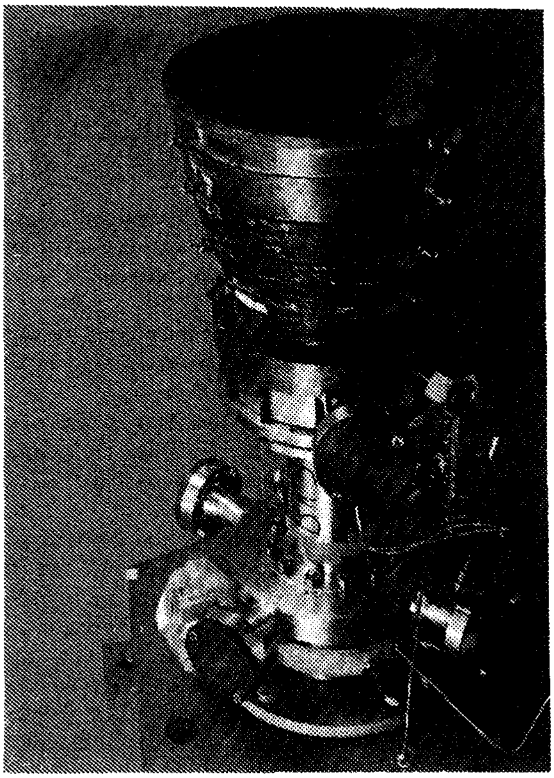

Fig. 9. Subscale experimental TC.

- Injector pressure drop
  The oxygen-pressure drop in the injector is increased to provide higher margin against low frequency chamber pressure oscillations
- LOX-dome casting
  Several design modifications have been applied to reduce fabrication cost and scrap rate

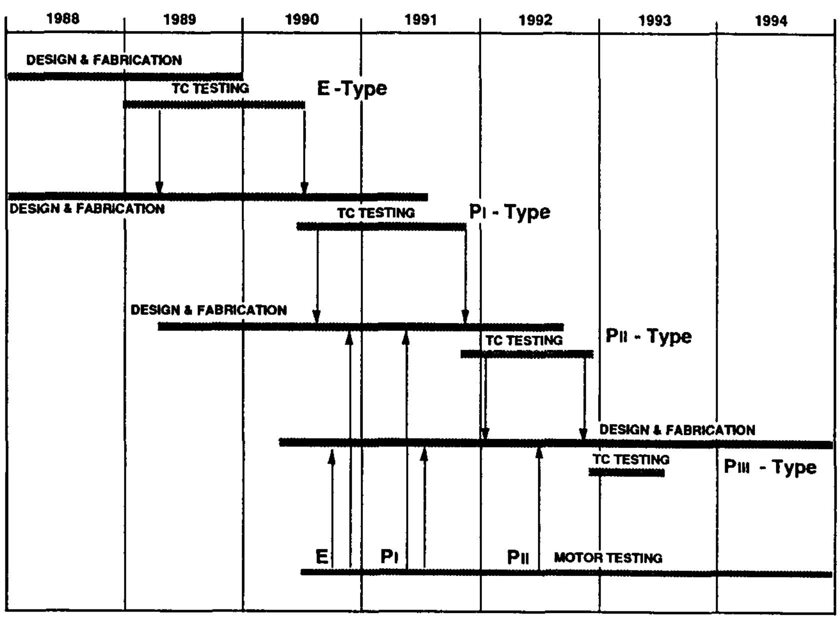

Fig. 10. Vulcain TC development plan.

- Combustion chamber cooling jacket
  In order to increase the CC life beyond the specified value the height of the cooling channels will be reduced
  By this measure the low cycle fatigue life of the chamber will be increased by a factor of 2.
- Nozzle extension stiffening
  The nozzle is stiffened by additional hatbands in order to avoid buckling under extreme conditions during start- and shut-down transients.

Minor modifications might be introduced resulting from experience gained on further TC and engine tests.

3.2.2. Fabrication status. A total of 30 operational TCs and 2 fullscale mock-ups are planned to be fabricated. The repartition of these TCs is as follows: 8 for TC-development, 15 for motor development, 5 spares and 2 for the technological flights. Presently 6 TCs are available for testing, 3 of them are delivered to SEP for motor integration. In addition 10 TCs are in fabrication at various finalization status.

Recently a problem in the electrodeposition process occurred; due to an impurity in the galvanic bath the requested Ni-layer strength could not be achieved. The Ni-outer shell of four chambers had to be partially removed and reworked after regeneration of the bathes.

3.2.3. Status of testing at the TC level. Testing comprises cold testing on subcomponent level (e.g. injector, combustion chamber), on integrated TC level and hot testing of the TC on the pressure fed test facility P3.2 in Lampoldshausen, Germany.

All subcomponents were exposed to numerous non destructive cold tests (e.g. pressure-, leak- and thermocheck tests) before release for TC integration.

A total of 220 tests with the integrated TC are planned, of which about 200 are hot test runs. The main objectives of hot testing are

- proof of hardware thermal and mechanical integrity
- demonstration of the theoretically predicted design data and adaption of modelizations (performance, cooling, etc).
- proof of cycle life
- proof of combustion stability
- demonstration of margins
- investigation of TC behaviour under specific failures
- proof of RAMS aspects (Reliability, Availability, Maintainability, Safety)
- analysis of ignition, start and shut-down
- achievement of the qualification on TC level.

A total of 70 successful TC tests were performed until August 1990. The TC has been tested in the entire operational and extreme envelope (Fig. 11), wherein, depending on the type of test, the exploration of up to five envelope points was achieved within one particular run. The most essential results are presented in the following.

3.2.4. Ignition and start up. Reliable ignition in normal TC hot tests (i.e. high pressure start up) is achieved by using a pyrotechnical igniter having a mass flow of 300 g/s and a flame temperature of about 2200 K.

In specific tests ignition of the TC was investigated even under extreme propellant inlet conditions (i.e. temperature, pressure, igniter mass flow, purging). The results gained in this particular test series are the basis for tailoring the engine ignition and start sequence under low pressure tank head conditions. Figure 12 shows a typical ignition and start sequence.

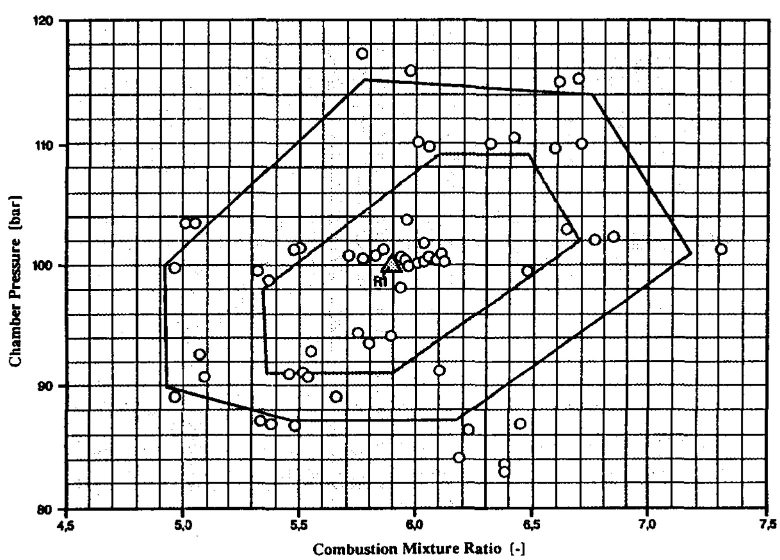

Fig. 11. Achieved test points.

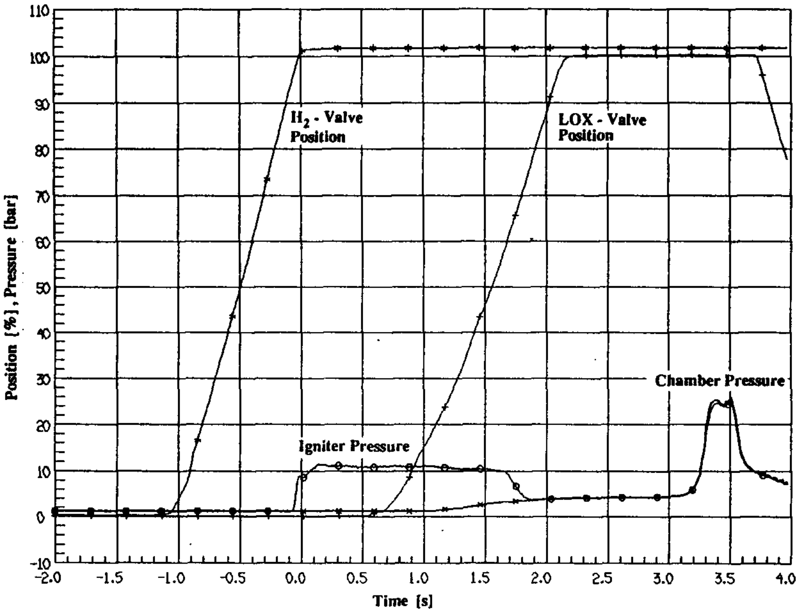

Fig. 12. Ignition and start up sequence (tank head start).

3.2.5. Combustion stability. In each TC test specific care is taken on the occurrence of possible low frequency (LF) and high frequency (HF) instabilities; up to now, even under adverse test conditions, no instabilities could be observed.

A typical record of the feed line frequencies in the LOX-dome is shown in Fig. 13 for the transient phases and for a main stage condition as indicated. The diagrams show frequencies below 500 Hz (chugging), mainly determined by the hydraulic data of the feed lines and the LOX-dome and varying with the conditions of the LOX during the transient phases in start and shut down. The second remarkable frequency is that about 1500 Hz, independent

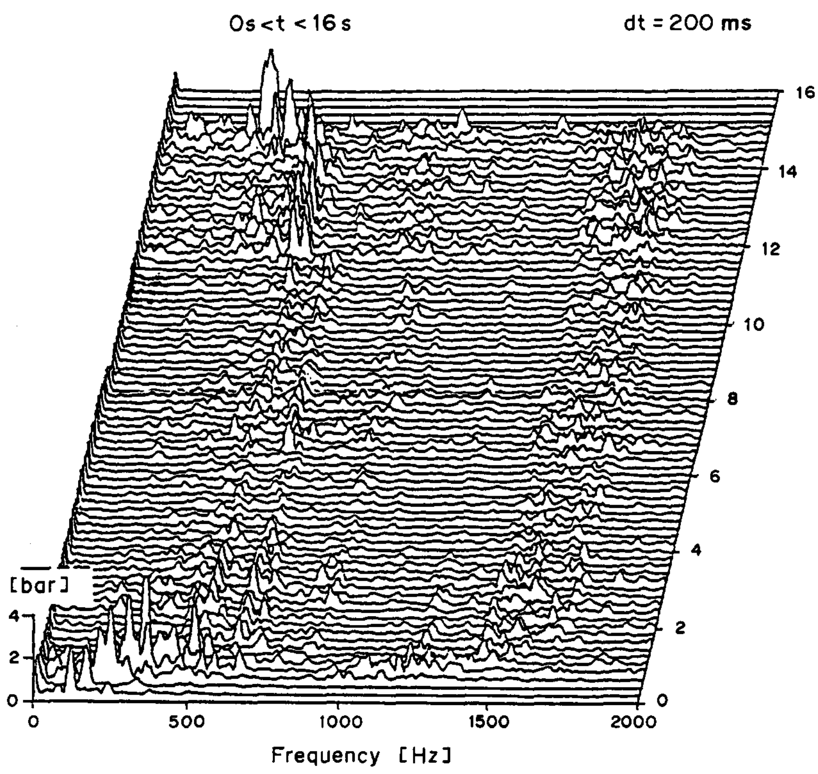

Fig. 13. Start phase and mainstage ($P_c = 109$ bar, O/F = 6.6) frequency analysis.

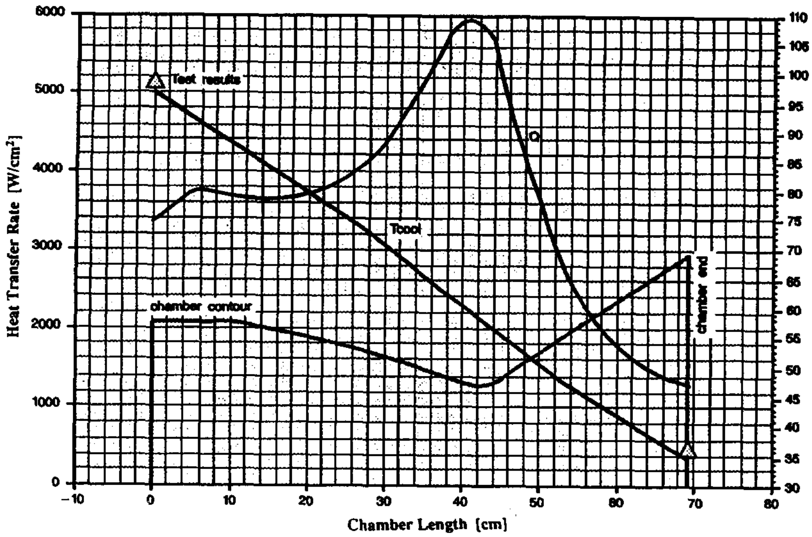

Fig. 14. Predicted heat transfer rate and coolant temperature as a function of chamber axial position.

from the transient conditions and apparently a mechanical resonant frequency of the LOX dome. The low frequencies have been reduced significantly by the already mentioned modification of the LOX restrictor orifices.

In the HF-range above 2000 Hz no significant frequencies are detectable.

3.2.6. Cooling performance. In Figs 14 and 15 the cooling performance of both actively cooled components, i.e. CC and NE are presented. For both components good agreement of theoretical and experimental values is found.

3.2.7. Combustion efficiency. The experimental combustion performance values are presented as a function of the propellant mixture ratio in Fig. 16. Some uncertainties may have led to the scattering of the measurement values, e.g. LOX flowmeters were not calibrated in the original medium and some problems with freezing of the chamber pressure transducer capillaries occurred. However, the c^* efficiency requirement of 99% can be achieved.

3.2.8. Sideloads. During start up and shut down transients the TC is exposed to severe lateral vibrations caused by non attachment and separation of the hot gases at the nozzle wall. In several hot tests the design load assumptions for these sideloads of 50 kN acting at the nozzle end have been verified by measurement of the reaction forces in actuator struds supporting the horizontally arranged TC in the test bench (Fig. 17).

Figure 18 shows the reaction forces measured during a typical test run, indicating high peak loads in the start up, the relatively low reaction on the

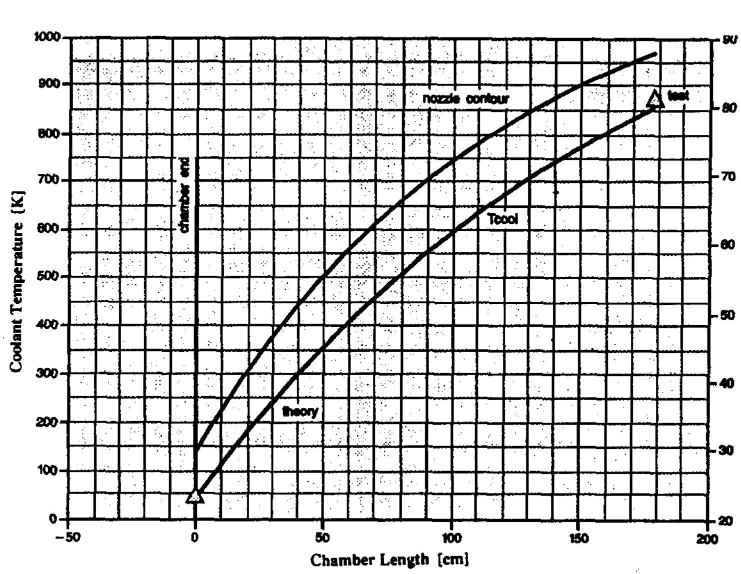

Fig. 15. Predicted and experimental coolant temperature as a function of the NE axial position.

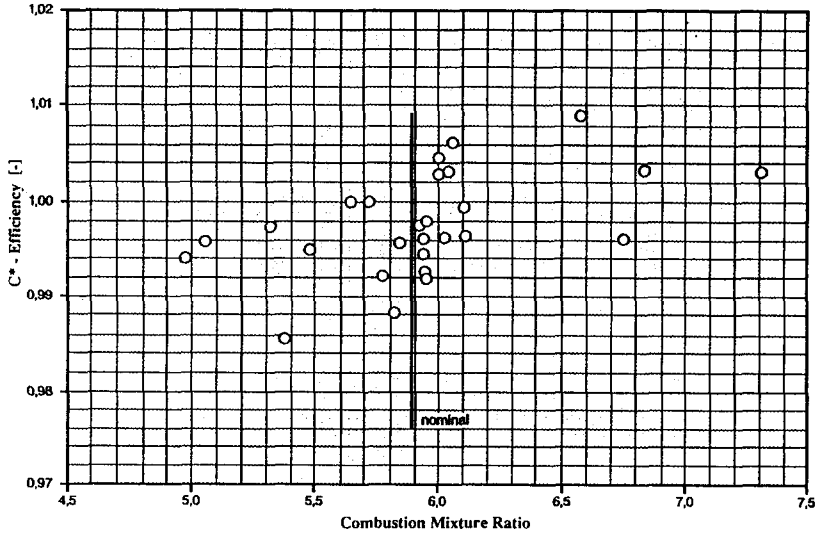

Fig. 16. Combustion efficiency at nominal chamber pressure.

combustion noise during main stage and again higher loads during stop transients.

3.2.9. Status of testing on engine level. The first engine was integrated into SEP's test facility PF50 in Vernon, France in April 1990. After cool down investigations the first ignition test took place in July 1990. Until the end of 1990 the engine is scheduled to be hot fired at nominal conditions up to 50 s run duration.

In parallel to this test facility, a second one in Lampoldshausen, Germany will be operational in October 1990 for engine tests.

3.3. TC development outlook

As stated before, experimental results for TC development will be available in the near future both from motor and TC testing. The results gained might influence the design of the final TC version PIII.

On motor level confirmation of TC behaviour under extreme loads, e.g. gimbal loads, turbopump and other components acting on the TC, and the final proof of the calculated low cycle fatigue life will be gained.

On TC level the following major development objectives are planned to be demonstrated.

- Cycle life

Demonstration of 20 short duration runs (~15 s) nominal and off-nominal conditions.

- Ignition and start

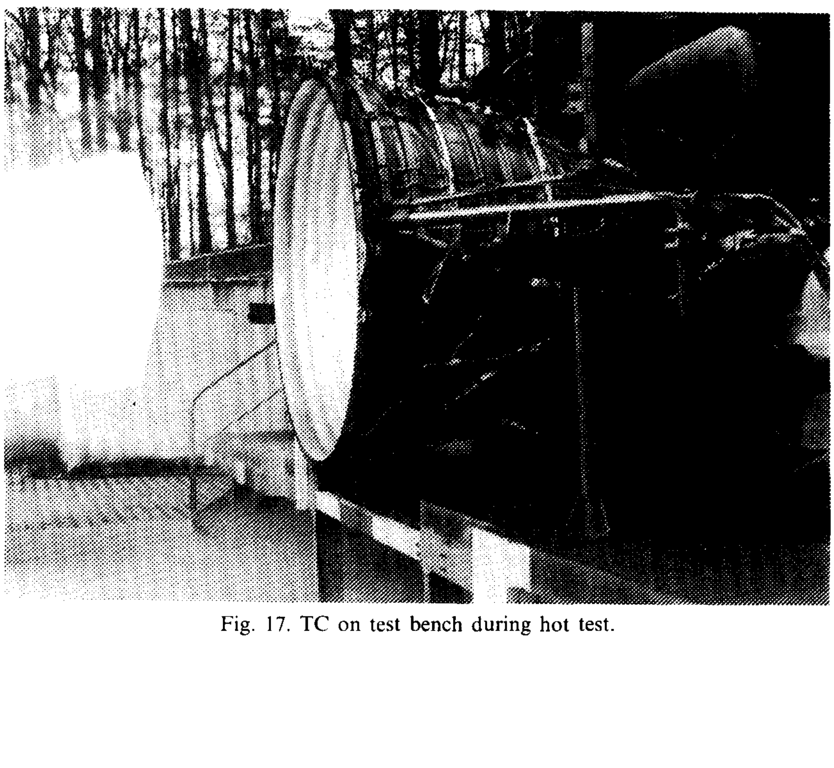

Fig. 17. TC on test bench during hot test.

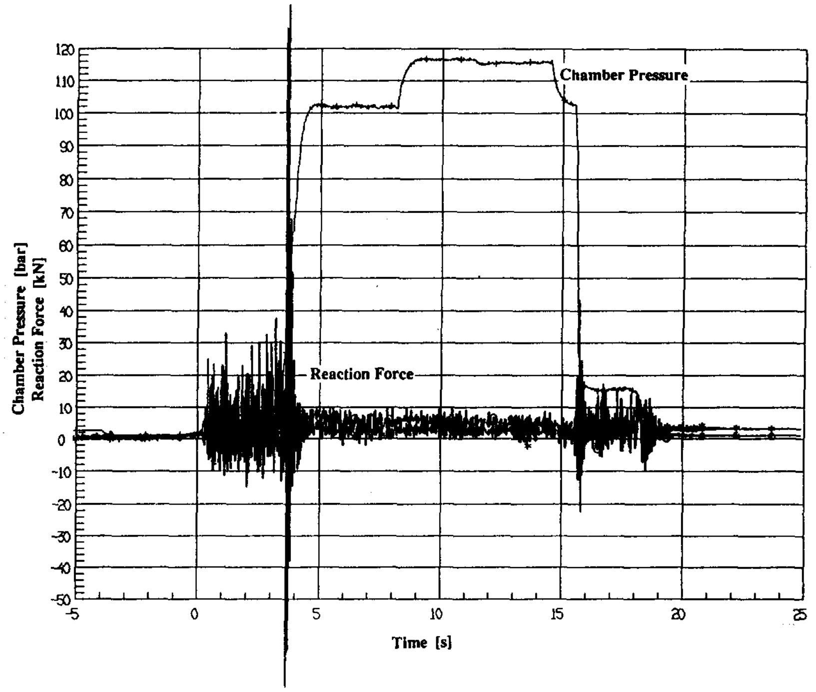

Fig. 18. Reaction force on side loads.

Further investigation of ignition by varying the governing parameters and demonstration of reliable ignition in the entire operational range.

- Combustion stability

Proof of HF-combustion stability by disturbance of the combustion process via pyrotechnical shock generators and by operation of the TC under instability provoking conditions.

- Performance demonstration

In numerous tests the specific impulse (I_{sp}) under sea-level conditions will be investigated based on thrust and mass flow measurement. The standard deviation of I_{sp} from test to test and from hardware to hardware will be determined.

- Limits

Demonstration of design margins by testing the TC beyond the extreme envelope, both relative to chamber pressure and propellant mixture ratio.

- Failure testing

Analysis of TC behaviour under specific failures, e.g. sealing failures between injector and combustion chamber which results in internal leaks and might influence the proper function and performance of the TC.

- Design modifications

Several design modifications, basically to allow for fabrication cost reduction to meet requirements gained by test results, will be investigated and implemented in the hardware design if applicable.

Following the development phase the TC will be submitted to a qualification. All specified parameters will be demonstrated and proven by studies, cold tests or hot runs. Specific effort will be given to RAMS aspects in order to fulfill the strong requirements of the Vulcain motor which has to be operational for manned flights in 1998.

4. CONCLUSIONS

The thrust chamber development status is in conformance with the planning schedule. All basic requirements, which were subject to the passed development tests, were met. Except the improvement of nozzle extension stiffening no major problems were encountered.

Future thrust chamber testing will be performed on two different levels: on component level at MBB and integrated in the motor at SEP and DLR.

Main testing efforts on component level are: proof of cycle life, proof of combustion stability, thrust chamber limits testing, testing of modifications for fabrication cost reduction and finally qualification testing.

On motor level, basic results on creep life, start- and shut-off behaviour under actual engine loads are expected.

The tests on thrust chamber level are scheduled to be concluded in mid 1993; the motor tests will take place in the period mid 1990 until the end of 1995.