POLLUTION CONTROL ON A TEST FACILITY FOR A CRYOGENIC ROCKET ENGINE

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ABSTRACT

The environmental pollution due to the exhaust of the rocket is widely studied and strong efforts were made to reduce or avoid this kind of pollution. On the other hand the rocket engine itself can be sensitive to pollution. Therefore pollution control is an important aspect within the operation of a rocket engine. On the test facility P5 at DLR in Lampoldshausen, Germany the cryogenic rocket engine VULCAIN is tested since eighteen years. A permanent pollution control against particles, humidity and foreign gases is an important part of the test procedures. Pollution from extern and intern of the facility and engine has to be faced and the impact to the operational aspects of the rocket engine has to be considered. An attentive pollution control is necessary and possible to ensure a good performance of the test facility and the rocket engine.

1. INTRODUCTION

Pollution is one of the undesired effects when a propulsion system is operated. We mostly speak about the pollution of the environment due to the exhaust of the propulsion systems. This pollution strongly depends on the fuel/oxidiser combination of the propulsion system. On the other hand the propulsion system itself can be very sensitive to pollution. For rocket engines running on liquid fuel/oxidiser the operational aspects such as performance, function and reliability are depending on the purity of the engine fluids. A basic demand is that fuel, oxidiser and complementary fluids fulfil their specification. But also the handling and operation of the rocket engine might induce a risk of pollution. Pollution control on a test facility for a cryogenic rocket engine means

an accurate identification of sources of pollution,
reasonable definition for pollution limits,
application of adequate cleaning procedures,
and
systematic cleanliness checks.

The structure, scope and details of pollution control procedures are depending mainly on the test specimen and on the design of the test facility.

2. SHORT DESCRIPTION OF THE TEST FACILITY

In the field of *rocket testing*, the facility P5 covers all types of *static rocket system tests* [3] with complete propulsion system and simulated rocket operation [1], establishing full combustion under nominal and off-design conditions. 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. A large number of subsystems, devices and components are 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.

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, and inerting).

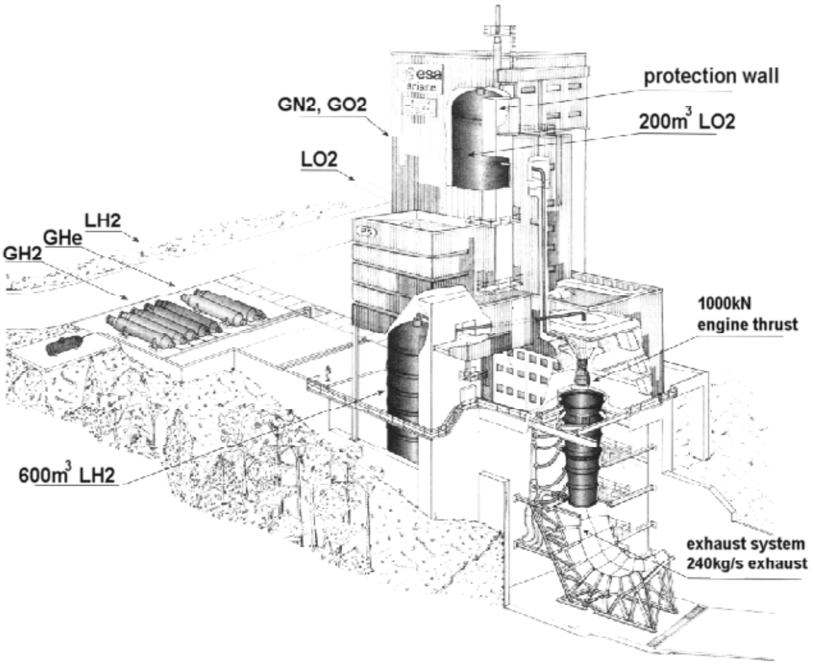

Figure 1: Test Facility P5

3. SOURCES OF POLLUTION

When a cryogenic rocket engine is operated mainly three kinds of pollution have to be considered : particles, foreign gas and humidity. The first potential source of particle pollution is the rocket engine itself. Several procedures within the production process can create deposits inside the components of the engine. There is the risk of metallic parts due to the milling process and the risk of weld beads and cinder due to the welding process. The same pollution is possible for many facility components. The requested cleanliness level has to be considered within the definition of a system, because the choice of material and the fabrication process limits the possible cleanliness level of many installations. A proper cleaning procedure before integration can reduce this kind of pollution. During operation of the rocket engine and the facility further particle pollution is possible. All supply lines induce the risk of particle pollution. A good filter configuration and filter management can reduce the introduction of foreign particles. The operation also induces a risk of internally created particles. Due to friction, the combustion process, the running of pyrotechnical elements and due to corrosion different kinds of pollutions have to be faced. Partially this kind of pollution has to be accepted or has to be cleared after every engine operation. The polishing of the inner surface of a combustion chamber is an example for this kind of pollution.

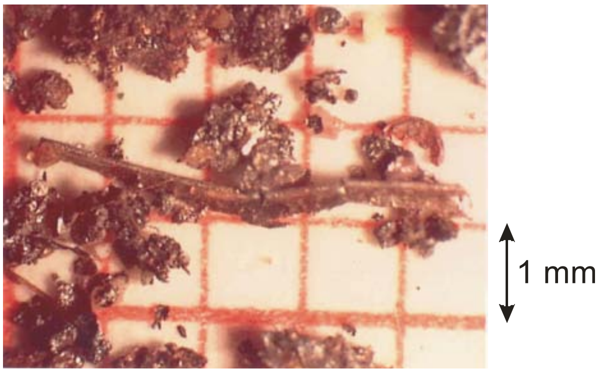

Figure 2: Initial Particle Sample before Cleaning and Integration of a Subsystem in a Storage Area

Filters normally avoid particle introduction but not the introduction of humidity and air. The presence of both is accepted during integration and the cleaning from humidity and foreign gas is performed when a fluid circuit is mechanically closed. Nevertheless there are several chances to reappear for a pollution of this kind during operation. The facility and the engine have venting openings and cannot be perfectly tight. Also the internal connection can cause a pollution of a fluid from one circuit to a circuit of another fluid.

3.1 Nitrogen Pollution of an Oxidiser

An example for an internal pollution with gas was studied on the oxygen supply of the facility P5. Most of the oxidiser vessels of a launcher or a test facility have a pressurisation system to push the fluid towards the rocket engine.

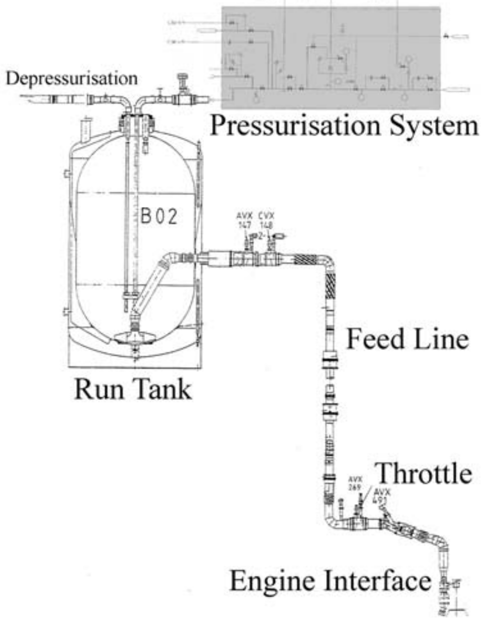

Figure 3: Liquid Oxygen Supply of the VULCAIN Engine

The pressurisation of liquid oxygen (O_2) with gaseous oxygen would be the best choice for the pollution aspect. But for safety reasons gaseous nitrogen (N_2) is often used instead of oxygen. In this case the condensation of N_2 at the surface of the liquid O_2 has to be considered. The equilibrium of both fluids close to their boiling point is shown in the phase diagram (Fig. 4).

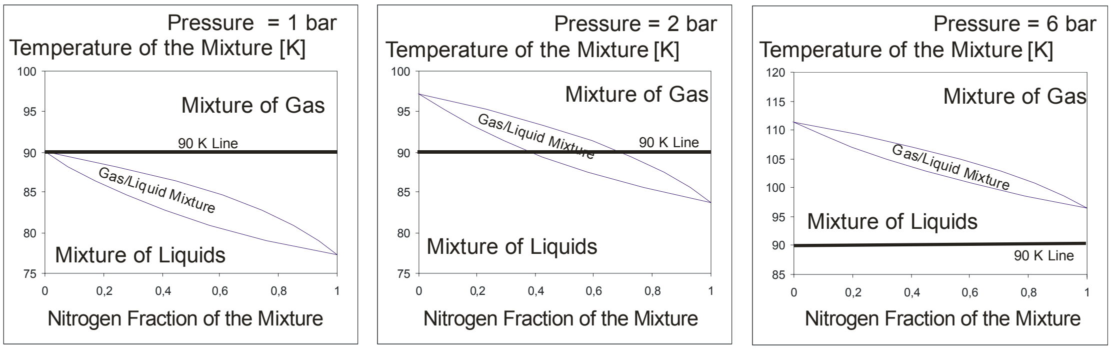

Figure 4: Phase Diagram of O_2 / N_2 mixtures at 1, 2 and 6 bar

For the calculation of the dew – and boiling curve (1) and (2) according [2] were used, the vapour pressure $P_i(T)$ was calculated according [4].

Boiling curve
$$X_1' = \frac{P - P_2\,(T)}{P_1\,(T) - P_2\,(T)} \tag{1}$$

Dew curve
$$X_1'' = \frac{-P_1\,(T)\,P_2\,(T)}{P_1\,(T) - P_2\,(T)}\,\frac{1}{P} + \frac{P_1\,(T)}{P_1\,(T) - P_2\,(T)} \tag{2}$$

The symbols are :

T *temperature of the mixture (here the temperature of the liquid oxygen O_2),*
P *pressure of the mixture (here the tank pressure),*
$P_1(T)$ *vapour pressure of the first component (here N_2),*
$P_2(T)$ *vapour pressure of the second component (here O_2),*
X_1' *liquid mole fraction of N_2,*
X_1'' *gaseous mole fraction of N_2.*

In fact the mixture is not homogeneous in time and space and not in its equilibrium. The pressure is defined by the pressurisation system, above the liquid it is constant, below the surface it increases with the depth. The temperature around the surface is dominated by the temperature of the liquid oxygen, normally it is close to 90 K. If the tank pressure was hold at 1 bar for a long time only a very small fractions of N_2 can be found in the liquid. When the pressurisation is started the condensation at the surface begins and the N_2 fraction increases.

We can assume that the condensed N_2 remains mainly in the upper layers of the liquid. After test, respectively when the pressure is reduced to 1 bar the N_2 as the more volatile component evaporates again. The typical evaporation rate of a vacuum insulated tank is 0.1% of the inner volume per day. For the oxygen tank (200 m^3) on the facility *P5* that means 200 litres per day. Hence it takes seven days to re-evaporate the N_2. But in the normal test cycle the tank is already refilled the day after the test. Due to this dilution the concentration of N_2 decreases to a tenth part which is a far more drastic decrease then due to the evaporation. Nevertheless for the engine test the N_2 fraction in the oxygen means pollution. A sample taken during a normal test period had a fraction of 0.36% of N_2 in O_2.

The importance of N_2 diffusion in the O_2 tank was studied within the constraints and conditions of normal test cycles. It became evident that the process of diffusion cannot really distribute the N_2 in the tank. Due to pressurisation, depressurisation and filling we have a much stronger mixing process of the two components.

The hydrogen tank of the facility P5 is pressurised with gaseous hydrogen and the pollution of this tank has to be checked in a time consuming procedure of purging, venting and conditioning combined with warming up the vessel. This procedure was applied two times within eighteen years of operation. The detected mass of foreign substances was 10 grams.

4. SENSITIVITY OF THE TEST FACILITY AND THE ROCKET ENGINE TO POLLUTION

Any pollution of the fuel or oxidiser can have an impact on the performance of the propulsion system. The specific impulse, the combustion pressure or the temperature can change when e.g. the liquid oxygen is polluted by a certain amount of nitrogen. This kind of pollution is normally very small and so is the impact on performance.

Pollution with humidity is much more important because it concerns not only the performance but rather the functional and reliability aspects of the rocket engine. A water fraction in liquid oxygen would instantly turn into ice particles and is therefore as severe as any other particle pollution. In the different components of the rocket engine and the test facility the fluids have to pass not only pipes of large diameter but also tiny ducts and slots. On the facility the filters can be blocked by particles and on the engine the particles can be captured in flow cooled bearings and sealings, in the injection elements of a combustion chamber or in cooling channels. Even a small pollution of this kind can have a drastic impact on the function and reliability of the rocket engine. On the hydrogen side the conditions are even more important because also any foreign gas (except helium) will turn into ice when it gets in contact with liquid hydrogen.

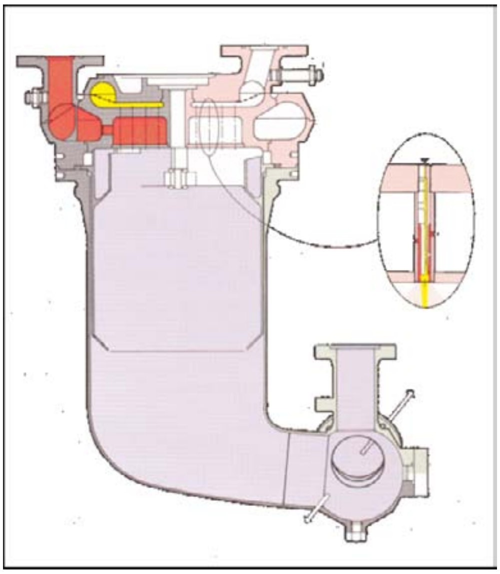

Figure 5: VULCAIN Gas Generator with Injection Element

The particle pollution of the VULCAIN chamber injectors was studied in a special campaign on the facility P5. Injector elements in selected circumferential and radial position were partially, artificially blocked and the impact on the injector plate was checked by an inspection of the surface after test.

The blocking of filters due to ice particles is hard to identify because an inspection at ambient temperature cannot reveal the pollution. An ice blocking of a small sensor tube in the vicinity of the hydrogen vessel of the facility P5 caused an important reduction of the reliability of the facility. The concerned sensor was one of three sensors used within the inlet pressure regulation for the rocket engine. The blocking of the tube was avoided by an adequate venting procedure.

Oxygen pollution in liquid hydrogen [5] does not only concern the functional aspects but even more and more important the safety aspects of the facility. Oxygen ice particles can react spontaneously in liquid hydrogen and even a small fraction can cause a pressure increase in a vessel. Pollution with chemical reacting substances is yet more dangerous on the oxygen side of the test facility. An ignition inside liquid oxygen can start a burning of the metal around, e.g. the pipe or the vessel itself.

Pollution of secondary fluids can concern the reliability of the facility. Pilot valves e.g. cannot work properly if the pneumatic gas has large particle pollution (see figure 2). Pilot valves are furthermore sensitive to pollution caused by insects, they intrude by the outlet into atmosphere.

5. CLEANING PROCEDURES AND CHECKS

All vessels, lines, valves and any other component of the flow circuit of a test facility have to be cleaned before integration. The total inner surface of the hydrogen tank (600m³) of the P5 and PF50 were washed with a dissolver to get it free of particles and grease. Lines are etched with acid, rinsed with demineralised water and sometimes taken into an ultrasonic bath. Directly before integration the preassembled segments of the fluid circuits are cleaned with inert gas. Normally pure nitrogen is used to blow through the system.

After integration the replacement of nitrogen by another gas is performed by a so called *conditioning procedure*. A dedicated number of cycles of pressurisation and depressurisation are performed on the segment in order to reach the requested purity of the final gas filling.

The best protection against pollution after installation is the fact that the circuits are closed, are equipped with filters and maintained at a slight overpressure.

For the interfaces between the test facility and the rocket engine the cleanliness concerning particles is obtained and proved during the integration of the engine into the test facility. For that purpose the connecting lines between engine and facility are blown through with nitrogen and the remaining particles are collected in a filter. This filter is made as an object holder and a microscopic examination reveals the size and number of particles of this sample. Table 1 gives the criteria of particle cleanliness for the VULCAIN engine.

Circuit	Pneum. actuators	Fuel / oxidiser lines	Hot gas lines
Particle Size	Max number		
15 - 25 µm	1000	2000	4000
25 - 50 µm	100	200	400
50 - 100 µm	10	20	40
100 - 500 µm	1	2	4
> 500 µm	0	0	0

Table 1: Particle cleanliness of the VULCAIN

The purity concerning foreign gas and humidity has to be established and proved before every engine test. Normally helium is used on the hydrogen side and nitrogen on the oxygen side of the test facility to purify the lines. During the cycles of the conditioning procedure the polluting fraction is diluted again and again until the requested cleanliness criteria (Tab.2) are reached. At the end of the procedure samples are taken in small bottles and the content is analysed with a gas chromatograph.

flushed area	**gas**	**max. allowed humidity**	**max. allowed fraction of polluting gas**
feed line liquid oxygen	nitrogen	< 15 ppm	no limitation
turbo pump liquid oxygen	nitrogen	< 15 ppm	no limitation
feed line liquid hydrogen	helium	< 15 ppm	no limitation
turbo pump liquid hydrogen	helium	< 15 ppm	< 1000 ppm nitrogen, < 100 ppm oxygen
hot gas circuit	helium	< 15 ppm	no limitation

Table 2:Cleanliness Criteria for the Hot Run of the VULCAIN Engine

Another check of pollution is performed online during the final test preparation and chill down of the cryogenic engine. It is at the same time a check of internal and external tightness. The close surrounding of the rocket engine is monitored with two gas analyser systems each working on another physical principle.

Inside the rocket engine further gas concentration measurements are taken. They reveal a possible internal leak during the chill down phase. The gas samples are taken with *teflon* hoses which burn off after ignition.

6. CONCLUSION

Though pollution is an undesired effect during rocket engine operation it cannot be avoided perfectly. Due to the fact that it has a significant impact to aspects such as performance, reliability, function and safety the pollution control is an important scope of work on the test facility as on the launch pad for a rocket. Attentive pollution control is necessary and possible to ensure a good performance of the test facility and the rocket engine.

7. ACKNOWLEDGEMENTS

Thanks goes first of all to the test team of the facility P5, their awareness of their responsibility for a good pollution control contributed to a safe operation of the facility because when it comes to pollution the devil is in the details and it can cause diabolic damage. The author would also like to thank his colleagues from the engine manufacturer SNECMA for the outstanding cooperation. As in all other fields of cooperation, the support from them gave the basis to reach the remarkable ability and professionalism of the whole test team.
The greatest honour is due to god, who did not deliver us to the devil in the tiny details of pollution.

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