AIAA 2001-2763

EXPERIMENTAL STUDY OF THE ARIANE 5 ATTITUDE CONTROL SYSTEM (SCA) PASSIVATION.

R. Foucaud *, FX d’Herbigny *, L. Marraffa †, D. Giordano †, P. Reynier †.

Abstract

On the request of CNES, ESA/ESTEC has led a study on the disposal of the hydrazine reservoirs of the Ariane 5 Attitude Control System (SCA). ESTEC has asked ONERA to propose an experimental assessment of risks of icing in piping and of generation of large debris in space during the process. After an examination of test conditions that would be representative of the reality, some campaigns have been realized at ONERA - Center of the Fauga-Mauzac. The objectives were the validation of the disposal system conceived for the SCA, also the general understanding of phenomena and consecutively a definition of the general trends to observe for ejection of liquids in space, and the constitution of a validation database for the modeling of hydrazine venting. Validation tests of the flight ejector performed with hydrazine have demonstrated that the passivation process could be done without obstructing the piping. Further tests proved that this kind of phenomenon could be simulated without hazards by using water as similarity fluid. An effervescent type injector could be appropriate in order to guarantee a fine pulverization of a liquid ejected in a vacuum.

1 Introduction. Objectives of the study

One can be led to inject a liquid in vacuum in various circumstances during a spatial mission. Quote for example the disposal of used waters from a shuttle or the re-ignition of a storable propellant engine in vacuum conditions. In what follows, our concern is the problem of the passivation of a launcher at end of life. This operation consists in bringing back the powered phase active elements, to a final state minimizing the risk of further production of wastes or remains of long life duration in orbit. A previous work [1] has showed that the device used in order to realize the passivation of the Storable Propellants Stage (EPS) of Ariane 5 did not generate such debris.

The present work is dedicated to the problems in relation with the passivation of the Attitude Control System (SCA) of Ariane 5, equipped with small hydrazine catalytic decomposition engines. The main aim of that study was to help to the definition of a disposal device for the hydrazine reservoirs of the Attitude Control System (SCA) of Ariane 5. This device has to achieve the ejection of liquid hydrazine in vacuum as a spray of fine particles or droplets.

2 General presentation of the problem

When a liquid under pressure at a ambient temperature in a tank is suddenly exposed to vacuum conditions, the difference in pressure between the reservoir and the exterior causes the liquid to evacuate the system through the piping and a nozzle. One could observe that directly after the point of nozzle exit, the liquid stream that is issued forth is smooth and coherent. It is instantaneously in thermodynamic imbalance, submitted in surface to vaporization leading to intense internal cooling. A rapid evaluation of the evolution of hydrazine isolated droplets in vacuum, ejected at room temperature, shows that the energy available in the liquid phase allows vaporization of a maximum of 30% of the liquid, the rest being then in solid phase.

Most observations come from earth experiments simulating the draining of liquid water from the Space Lab [2] or more recently of water ejection from the Discovery Space Shuttle in 1989 [3]. In environmental conditions, the injected liquid is overheated in depth, which induces the formation of bubbles of vapor inside the jet, which finally bursts after a delay (relaxation delay). Two regimes of droplets formation can be deduced from the observations, they can lead to two types of objects at the end of the process: firstly, of very small particles stemming from the vaporized gas, and secondly of larger objects stemming from the droplets formed during the bursting of the jet (sketch fig. 1).

It can be deduced from these considerations that when one achieves the disposal of hydrazine reservoirs in vacuum after the operation of SCA, some risks of icing in piping exist, as well as obstruction of the exit orifice, and generation of large particles in space. Our main objective is to define the conditions for the disposal of SCA reservoirs, minimizing these risks.

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The methods are based on a numerical simulation of the process: setting up of a thermodynamic model, building up of a physical properties database, determination of the equations governing the flow, development of a numerical model. Tests allowing the observation of the jet emitted by the flight device as well as tests devoted to the validation of models were planned. One expects the following results:

- knowledge of the functioning and validation of the flight device,
- obtaining of input data for the adjustment of models dedicated to the evaluation or to the simulation of the fluid flow in piping open to vacuum, by an experimental study of the vacuum relaxation, in similarity fluids and in propellant conditions,
- experimental approach of the role of injection parameters on pulverization characteristics with help of simple devices,
- proposal of devices adapted to shorten particle life duration in vacuum.

The present work is limited to the experimental part of that program. The other parts are presented elsewhere [4],[5],[6].

### 3 Experimental device

An experimental set-up dedicated to this objective was designed and manufactured (sketch fig. 2), it had to meet the following specifications:

- the flow rate should preserve an acceptable vacuum level inside the tests volume for a time long enough to allow the acquisition of valid data. It has been demonstrated during the different campaigns that this condition was filled (the possible tests duration could reach 10 s according to tests, what is largely enough for our acquisition system);
- the flow should allow spray exploration capacities for our measurement devices. According to our experience, this condition is filled when the injected flows are twenty times less than those generated by the flight device.
- the set-up should reproduce the nominal parameters of the SCA passivation device, that is to say ejection velocities in the 10 - 50 m / s range.

The measurement methods used during these tests were the following:

- Parameters dedicated to the control of the functioning of tests: reservoir and nozzle pressure measurements, temperature measurements in piping as close as possible to the ejection nozzle, flow-rate measurements.
- Different optical methods have been installed to study the pulverization of jets in vacuum: evaluation of the structure of jet expansion by strobe visualization, in global field or by tomography.

These methods have provided usable results:

- Evaluation of characteristic dimensions of the spray by drop-size measurements with a Malvern drop-sizer (equipment rented for the circumstance). There again some usable results have been obtained; A few difficulties appeared during the tests campaigns. Some were solved immediately and had not particular consequences. Some others, necessitating more important adaptations, can only be taken into account in future tests.

### 4 Experimental schedule, Problems encountered

Many experiments were performed, corresponding to the different objectives of the study:

- The experiments for validation of flight device were necessarily limited in hydrazine conditions. Some water tests with the same ejector allowed us to validate these tests and confirm that the use of water as similarity fluid can lead to representative observations and conclusions.
- The purpose of use of single (pure) ejectors was to make easier the observation of elementary phenomena in different ejection conditions (shape of the element, influence of input parameters pressure and temperature).
- The consideration of the known pulverization properties of the different kinds of ejectors used in aeronautic and space propulsion with respect to our objectives, led us to the choice of testing an effervescent ejector.

The tests were organized in 3 campaigns, corresponding globally to more than 60 experiments of vacuum injection. One must remember three characteristic consequences of the functioning of our experimental setting:

- 1° because the feeding valve is located slightly upstream of the pyrovalve, one cannot observe the effects of a long purge with beating phenomena such as those observed at DASA [7];
- 2° even in the case of purging the totality of the piping, the brief duration of our tests cannot allow the occurrence of such phenomena;
- 3° in that last case, the level of pressure established instantaneously in the vacuum enceinte cannot allow the continuation of the process of evaporation with consecutive cooling of the liquid phase emitted. This remark, that concerns only the propellant residue in piping after complete disposal of the reservoir, does not question the aptitude of the device to drain the reservoir during the passivation phase.
5 Study and validation of the flight device

5.1 Hydrazine acceptance of the flight device
One had to perform the minimal number of tests allowing the validation of the compatibility of operative conditions adopted with respect to the use of hydrazine with the aimed objectives, and to sweep the most largely possible the flight domain for pressure and temperature injection conditions.

5.1.1. Structure of the jet
- A constant pressure level established into the experimental volume during the injection duration, which corresponds to the vapor pressure of the emitted droplets. A first deduction is that there is no (or very little) dissolved gas effect in our experimental conditions;
- One deduces also that at this level, the cooling of the jet during the disposal and the relaxation at the exit of the ejector is not sufficient to provoke icing and obstruction of piping under stabilized draining conditions;
- These experimental conditions did not allow observing the ulceration formation of solid debris;
- The jets were straight during the stabilized phase of ejection, some bubbles were visible inside the jet, especially at high temperature (fig. 3);
- Cutting-off the device feeding valve resulted in a purge of the liquid contained in the piping section submitted to the vacuum, under the effect of its vapor pressure at piping temperature. A massive boiling at the orifice exit, without visible emission of large objects, is then observed (fig. 4).

5.1.2 Characteristic dimensions of the pulverized phases
Due to the high density of the jet or the emitted spray, the drop-size measurements were difficult and their results are not necessarily representative of the final state of the spray at equilibrium.

The drop-size measurements could only be done in the part of the jet that is atomized, and we have seen previously that in the observation zone the pulverization of the jet is not complete. Some acquisitions were not usable for analysis, and when some data were obtained, the transmission levels were generally weak, with simultaneously saturation of the signal of detectors corresponding to the smallest drops. We are therefore in presence of a multiple scattering phenomenon, whose known defect is an apparent displacement of the drop-size spectrum to small sizes. These characteristics of tests lead to get, consequently, dispersed results, especially for the small sizes. Results have therefore to be considered cautiously. General trends have however been highlighted:
- the vacuum level does not influence the ejected particles dimensions;
- droplets are smaller when the ejection velocity increases;
- their diameter is also smaller when the temperature increases.

5.2 Flight injector. Validation of hydrazine tests
The objective of the tests performed during this campaign was to validate the use of water as fluid of similitude for flow and atomization studies of hydrazine in vacuum. The compared properties of these two fluids are presented in the table figure 5 and graph figure 6. It stands out that the use of water as similarity fluid can allow a good validation of the functioning of devices using hydrazine. The main results of these tests are recapitulated as follows:

5.2.1. Aspect and angle of the jet
The images obtained during the different tests with water lead to the same conclusions as for the tests performed with hydrazine: the jets are straight in the observed field during injection. A snapshot (left image) and an average value (right image) taken during the stabilized phase of the water test 0.3 Mpa, 10°C, are reported fig. 7, and should be compared to the equivalent hydrazine test visualisations (fig. 3 and 4). The aspect is very similar, and our observation conditions show evidence of the same phenomena in the jet. One observes the jets opening near the output plan with an angle of 10 to 12 degrees.

The pressure does not seem to influence the jet fundamental structures (fig. 8). This is confirmed for tests undertaken at higher temperature and for a larger pressure domain. One will also note that the opening distance to the ejection orifice increases with the ejection pressure (or the speed) of the jet, though the effect is relatively small; the distance is in the range of centimeters. This opening of jets must not be confused with bursting phenomena put in evidence earlier [8] during tests of single elements, and that happen later according to the thermal conditions of flow.

The final phase (end of injection) presents a difference of aspect; an internal intense boiling of the jet is not observed with water but rather a bursting structure (fig. 9). It is not cautious to conclude on this point, the observation area being different due to the lighting by luminous plan rather than by stroboscope, and the exposure times being a lot shorter.

5.2.2. Physical state
The images obtained during the different tests do not show evidence of a phase transition near the ejector in permanent flow conditions. The form of the luminous objects appearing in the jet’s periphery on snapshots does not necessarily correspond to ice pieces. Fragments of non-disintegrated liquid cloths during a normal
pulverization process would have the same aspect (ex. fig. 7).
The most favorable conditions in producing a phase transition near the ejector are encountered during disposal tests of loaded piping in vacuum environment, without pressurization.
Such tests have been realized for temperatures of the fluid upstream of the ejector varying from 14 to 2°C.

<table>
<thead>
<tr>
<th>Test</th>
<th>Injection Temperature</th>
<th>Vapor pressure (measured)</th>
<th>Liquid temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>14°C (16 mbar)</td>
<td>10 mbar chamber</td>
<td>equiv. 6°C</td>
</tr>
<tr>
<td>46</td>
<td>8 to 5°C (11 to 8 mbar)</td>
<td>9 mbar</td>
<td>equiv. 6°C</td>
</tr>
<tr>
<td>48</td>
<td>6°C (10 mbar)</td>
<td>6 mbar</td>
<td>equiv. 0°C</td>
</tr>
<tr>
<td>49</td>
<td>2°C (7mbar)</td>
<td>6 mbar</td>
<td>equiv. 0°C</td>
</tr>
</tbody>
</table>

In these conditions the ejection pressure level that is established corresponds to the vapor pressure of liquid in piping near the fusion temperature. Considering the appearance of the jet emitted in these conditions during the test, a noticeable difference is also obvious at the beginning of injection between the test performed with Tinj. = 14°C and that one performed at 2°C.

At 2°C, the interpretation of images realized in stroboscope lighting is not easy. Some large objects are emitted that radiate sharply when they are in the luminous plan. The vision is limited out of this plan. The same test performed in regular lighting (fig. 10) allows observing thin liquid trickles that flow gently in exit of orifices and gather further in relatively large objects whose physical state is not evident. Pictures of flow realized at the same instant for water at 14°C present a different aspect. One notes in this case that the emitted liquid is dashed all around in a relatively opened dense plume.

It is supposed that at low temperature, there is ice formation inside the piping with its partial obstruction.

5.2.3. Drop-size measurements
The measurement zone is located on axis of the jet, at approximately 30 cm of the exit, some tests having been undertaken with measurements at 30 mm out of the axis. Several acquisitions are made during each injection. Due to the high density of the spray and to the deposits of liquid on the windows during the tests, although the drop-sizer was operating for all tests, all data are not usable, and the windows were polluted from the very beginning of injection for some tests.
When the analysis was possible, the values are presented further (graph). Abnormal widths of distribution (far from 1) displayed by the mean that the distribution is not centered, and therefore that the validity of the presented results is questionable. Due to the multiple diffusion phenomena that systematically happen in these test conditions, and despite of the use of correction software for this phenomenon, that is reputed efficient for transmissions above 10%, the results of the analysis have to be used cautiously.

Only few tests had usable results, and among them many incoherent values must then be eliminated. These results have to be compared with those obtained with the same ejector during hydrazine tests. The result of this comparison, in terms of conventional D32 diameter (mean diameter of a monodispersed spray for which the surface of spheres is equal to that computed for the actual spray) is displayed on the following graph.

One can regret that the tests realized using water at or below 10°C are not exploitable, and that the pollution of the windows has prevented to obtain results during water injection at higher pressures at the level of injection orifices, what limits the analysis possibilities. It appears however that the obtained values are quite well gathered. It can be noted that they are very close to each other in the common water and hydrazine result range, around 120 µm. The already noted tendency of a reduction in the diameter of the particles with increasing injection pressure is confirmed. One must however be aware that the values obtained at high injection pressure for hydrazine are suspect considering the difficult conditions of their determination. The differences of temperature in the studied area do not have a significant impact on the results obtained.

It can then be deduced that in the studied range, the passivation tests performed with water represent correctly the phenomena occurring with hydrazine. Due to the experimental difficulties, correlations cannot be deduced from the results at this level of analysis.

6 Experimental study of atomization in vacuum
The design of a device adapted to an efficient atomization of a liquid in a vacuum is based on the study of the existing devices. They can be classified as:

**Pressure atomizers:**
- Fluid assisted atomizers:
  - These injectors need enough pressurizing gas to evacuate all the liquid that remains in the tanks.
  - A specific feeding device is needed.
  - Example: effervescent injectors

All these devices are optimized to inject fluids in a more or less dense gaseous environment.

Different devices were tested (figure 11). The results of this study are summarized here:

- Pure injectors yield straight jets in stabilized regime. Some bubbles can be observed inside these jets, some explosions occurred in and around the flow. This linear structure exists up to the end of the observation chamber, its disintegration can lead to the formation of smaller pieces giving large drops.
- The drop-size measurements undertaken in these conditions are little significant, since they only take into account the pulverization around the non-open main jet. One notes a decrease in the characteristic diameters when the blast pressure (and therefore the injection speed) increases.

When the temperature of the injected jet increases, the frequency and intensity of internal explosions (bursts) increases. This disintegration is instantaneous at the exit of orifice for temperatures above 80°C (fig. 12).

The interest of feeding the ejection orifice by a convergent profile is put in obviousness by a surprising and unexplained value of the flow-rate coefficient. Preliminary tests of an effervescent injector designed and manufactured to operate in the flow range of the SCA draining gave very promising results:
- The liquid/gas mixture ratio obtained is compatible with SCA characteristics.
- The spray is located inside a cone of same opening angle than the one of the ejector.

As the effervescent ejector was the most promising emptying device tested during this campaign, complementary tests have been performed during the last experimental campaign, the results are presented in the following paragraph.

### 6.1. Study of effervescent injector

An effervescent injector is an injection device allowing an internal intimate mixing of the liquid to pulverize and of a gas, the atomization is obtained during the expansion of the mixture at the exit of the device. The known studies (A. H. Lefebvre works for example) correspond to aeronautic injectors applications, for which a large amount of air is available. A minimum quantity of gas is needed for the functioning of such an injector. The available quantity of pressurization gas on the stage for the passivation of the SCA seeming compatible with this mode of functioning, we have conceived and realized an injection element in order to test some operating and pulverization characteristics.

This element is represented fig. 11.

The drop-size measurements were practically only possible for one test corresponding to a weak ejection pressure, at higher pressure the measurement device was blinded by water projection on the windows since the beginning of the test. It should however be noted here that these projections were produced by a true spray, which was not obtained with other devices.

### 6.2. Appearance of the jet

The pictures fig. 13 and 14 display average and instantaneous jets produced by an effervescent injector at low and high ejection pressure, compared with those of the nominal injector.

These images are to be compared with those of the functioning of the nominal injector (fig. 7 and 8).

The formation of ice crystals during the stabilized test phase was never formally observed. The only test for which some ice has been observed at the nose of the effervescent ejector is the one for which the operating conditions were not properly adjusted due to the presence of gas in the liquid piping.

The compared flow-rates of the two kinds of injectors are shown on the next graph. They are displayed according to an equivalent exit section.

![Graph showing flow rates vs. pressure]
The evolution of the ejected liquid flow-rate versus injection pressure follows a tendency curve for the operating points of the nominal device according to the correlation:

$$\text{flow-rate} = 663.2 \times \text{pressure}^{0.525},$$

that corresponds to a flow-rate proportional to the square root of pressure drop,

$$\dot{m} = k \Delta p,$$

which is the classic law for this kind of injection device. The corresponding liquid flow-rate determined for valid experimental points of the effervescent seems to follow a linear regression law.

One remarks that at equivalent ejection section, the operation of such a device would lead to a draining time a bit longer than that obtained with the current device.

### 6.3. Drop-size measurements

Very few tests were exploitable due to the abundant watering of the windows. Drop size results are obtained only for one valid test corresponding to a relatively weak ejection pressure, the width of distribution of that test did not allow to guarantee its quality. In these conditions, the values indicated by the device are similar to the previous results, at the reserve that the whole spray is here effectively pulverized.

One has represented on the next graph the characteristic dimensions of the spray produced by the effervescent device, for the tests where measurements were possible, compared with values obtained with the nominal injector for the pulverization in periphery of the jet. The conventional D32 diameter is plotted versus the flow-rate of ejected liquid. Flow-rates without ejection pressure for nominal ejector were evaluated taking into account the law in $\sqrt{\Delta p}$, and a blasting due to the vapor pressure at 10°C (12 mbar). One has chosen a representation in flow-rate of liquid rather than in speed, because it was difficult to evaluate the speed of the spray (and drops) issued from the effervescent injector with our experimental device. Here again the flow-rate of the effervescent injector was considered at equivalent section.

The variation of diameter with the water flow-rate for nominal injector is relatively weak. When a liquid is injected in vacuum, the diameter is depending on the Ohnesorge number,

$$\text{Oh} = \sqrt{\frac{\nu}{\rho \sqrt{\frac{\sigma}{l}}}},$$

where $\nu$ is the cinematic viscosity. This number expresses the ratio of viscosity forces to surface tension forces, and is not (or little) variable versus the flow-rate in the considered area, its evolution is mainly function of the temperature.

Note that the results obtained with hydrazine at medium flow-rate are in the same domain than that obtained with water. The results at highest flow-rates, unreliable, have not been reported here.

In this representation, one observes that the average diameter in the spray generated by the effervescent injector is in the same domain that values measured around the jets of nominal ejector. This point deserves a more thorough analysis.

### 7 Conclusion

Validation tests of the flight ejector have demonstrated that the passivation process could be done without obstructing the piping by solidified hydrazine during the relaxation. This confirms the results of model and computation data [6]. In addition, it has been demonstrated that this type of phenomenon could be simulated without hazards by using water as similarity fluid. With this device and in our experimental conditions, it was not possible to quantify the characteristic dimensions of the objects emitted during the process. To answer to this need, it would be necessary to use a vacuum volume and an observation field much larger.

Studies of elementary injection devices have led us to suggest an effervescent type injector in order to guarantee a fine pulverization of the liquid ejected in vacuum. The operation of this type of injector needs the use of a gas, we demonstrated that the quantity of gas available on SCA is compatible with the need and that the operation is ensured for a very large domain of operating pressure. One has therefore there a technology adapted to cases where the passivation process would have to be enhanced (nature and quantity of fluids to passivate, quality of atomization).

A complementary study on these themes would need a large investment to end to quantification and to a model of injection and pulverization phenomena in vacuum. One would have to work in two directions:

- experimental work : it is necessary to observe phenomena in the zone where processes driving the final state of the fluid in vacuum happen. This needs an experimental installation of large size, and the development of measurement devices allowing the study
of the characteristics of a jet generated in vacuum: structure of the jet, formation and division of the spray, evolution of the characteristic parameters (diameter, temperature…) during the relaxation;
- modeling work: the work initiated during a trainee period [9] will have to be resumed and completed, this operation has to be led on the long term.
In these two cases, cooperation with laboratories and specialized research institutes would have to be developed for the best efficiency.

Acknowledgments

That work was funded by European Space Agency (ESA). The flight ejector was provided by MATRA The effervescent device was conceived thanks to P. Trichet.
The authors are grateful to all their colleagues of CNES, ESA, ONERA, DASA and MATRA for the interest that they have granted to this work and for their precious advises.

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[8] Foucaud R. Etude expérimentale de la passivation du système de contrôle d’attitude d’Ariane 5, rapport intermédiaire ONERA R13/5400.37 DMAE / Y
Figures

Fig. 1: Evolution of the flow in vacuum (sketch)

Fig. 2: tests set-up (sketch)

Fig. 3: Structure of an hydrazine jet near the flight device exit

Fig. 4: Structure of an hydrazine jet (end of injection)
<table>
<thead>
<tr>
<th>Property</th>
<th>Water</th>
<th>Hydrazine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula</td>
<td>H₂O</td>
<td>N₂H₄</td>
</tr>
<tr>
<td>Molar Mass (kg/mol)</td>
<td>0.018015</td>
<td>0.03204</td>
</tr>
<tr>
<td>Mean Density (kg/m³) at 15°C</td>
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<td>1011</td>
</tr>
<tr>
<td>Melting Point (K)</td>
<td>273.15</td>
<td>275.16</td>
</tr>
<tr>
<td>Boiling Point (K)</td>
<td>373.15</td>
<td>387.37</td>
</tr>
<tr>
<td>Vapour Pressure (kPa)</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Solid (at 0°C)</td>
<td>0.610</td>
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<td>Viscosity (Pa·s)</td>
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<td>0.00104</td>
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<td>0.0329</td>
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<td>Heat of Formation (kJ/mol)</td>
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<td>Liquid</td>
<td>-285.83±0.042</td>
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</tr>
<tr>
<td>Gas</td>
<td>-241.814±0.042</td>
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<tr>
<td>Heat of Vaporisation (J/mol)</td>
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<td>Specific Heat (J/gK, at 25°C)</td>
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<td>Liquid</td>
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<td>Liquid</td>
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<tr>
<td>Vapour</td>
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<td>Critical Point Temperature (K)</td>
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<td>Critical Point Pressure (MPa)</td>
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<td>Critical Point Volume (m³/kg)</td>
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<td>Triple Point Pressure (Pa)</td>
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<td>Triple Point Temperature (K)</td>
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<td>Van der Waals constants</td>
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<td>a (Pa·m⁶/mol²)</td>
<td>0.5523</td>
<td>0.846</td>
</tr>
<tr>
<td>b (m³/mol²)</td>
<td>0.0479x10⁻³</td>
<td>0.0462x10⁻³</td>
</tr>
</tbody>
</table>

Fig. 5: Compared properties of water and hydrazine

![Fig.6: Vapor pressures of the two fluids](image)

Fig. 6: Vapor pressures of the two fluids

![Fig.7: Appearance of water jets 0.3 Mpa, 10°C](image)

Fig. 7: Appearance of water jets 0.3 Mpa, 10°C

![Fig.8: Appearance of water jets 0.6 Mpa, 10°C](image)

Fig. 8: Appearance of water jets 0.6 Mpa, 10°C
Fig. 9: End of injection: comparison hydrazine / water

Fig. 10: End of injection, low temperature tests

Fig. 11: Devices tested

Fig. 12: Influence of temperature

Fig. 13: Snapshots, 1 lightning by image

Fig. 14: Average values