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# High pressure burst tests at cryogenic temperatures

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**Abstract.** Based on the experience of different burst tests on neutron moderators, the best procedure of performing these tests, starting with cooling and filling the vessels, recording of the burst occurrence with high-speed cameras, the methods for evaluating the images and the comparison with the results of structural mechanical simulations are described.

## 1. Introduction

The so called moderators are key components of a neutron source and are used to slow down high energy neutrons, released by a nuclear reaction, to a required energy. Cold neutrons (ca. 10 milli electron volt energy) are used for a variety of experiments, which is why cold moderators at cryogenic temperatures are an important part of a neutron source.

A pressure vessel filled with liquid (para) hydrogen is for example a suitable cold moderator [3]. The vessel must be made of aluminium with thin walls so that the absorption of neutrons is minimised. The challenge is to manufacture an aluminium pressure vessel with minimal material content which should meet the high safety requirements of a nuclear facility. Moderators for various facilities have been designed, manufactured and tested at the Institute of Technology and Engineering (ITE) of Forschungszentrum Juelich. A test method was developed to validate the results of the structural-mechanical simulations. In this method, the pressure inside the moderator tanks is increased until they burst at a temperature slightly above the boiling point of liquid nitrogen.

## 2. Burst Test Procedure

Performing burst tests safely and reliably at cryogenic temperatures is a challenge. The purpose of the tests is to determine the pressure at which the vessel structure fails and to provide additional information about the fracture behaviour of the vessel. The basic procedure for the tests is to cool down a vessel to liquid nitrogen temperature at atmospheric pressure and fill its interior volume with liquid nitrogen. Then, to increase the pressure, the temperature of the liquid nitrogen inside the vessel is increased until it bursts. The temperature at which the vessel ruptures depends largely on the burst pressure. Typically, the temperature is below 90 K, corresponding to a pressure of over 225 bar.

### *2.1 Filling process*

The original idea was to cool down the vessel material from the outside first by immersing it in a bath of liquid nitrogen. Liquid nitrogen was then allowed to flow through the vessel until its volume was filled. The inlet and outlet of the vessel were then sealed, the vessel was moved out from the nitrogen bath and allowed to heat up until it burst.

However, this concept was not successful because small gas bubbles formed during filling, mainly due to the static heat load of the transfer line and accumulated in the moderator vessel. This created a gas buffer inside the vessel which, in contrast to liquid nitrogen, was highly compressible. Combined with tiny cold leaks in the screwed fitting to the pressure sensor, which only occurred at pressures above 100 bar, the pressure in the vessel could not be increased above 150 bar. With the butterfly 2 moderator (BF2) used during this first test, this pressure was not sufficient to cause the vessel to burst (see also chapter 2.2 Safety) [4].

A modified filling concept finally led to success. The vessel was connected via a pressure regulator to a pressurized gas cylinder filled with nitrogen gas and immersed in a bath of liquid nitrogen to be cooled. The vessel was then pressurized with gaseous nitrogen at a pressure of 5 up to 10 bar. Due to the higher pressure inside the vessel, the condensation temperature of nitrogen is higher than the condensation temperature of the nitrogen bath. As a result, the gaseous nitrogen begins to condense inside the vessel and heat released during condensation process is transferred to the nitrogen bath.

A disadvantage of filling the vessel with pressurized nitrogen gas is that the entire filling process must be carried out remotely, since there is a risk that the pressurized vessel could burst prematurely, for example, if there is a manufacturing defect.

Three indicators show whether the entire vessel is filled with condensed nitrogen. First, the amount of gaseous nitrogen that has condensed in the vessel can be calculated from the pressure difference measured at the gas cylinder upstream of the pressure regulator. Second, if the flow of gaseous nitrogen into the tank is interrupted and the pressure in the vessel drops slowly or not at all, no more nitrogen will condense. One reason for this is that the vessel is filled completely. As nitrogen condenses, heat is released and transferred to the nitrogen bath. Gas bubbles form on the outer walls of the vessel and the nitrogen bath boils. The third indicator that the pressure vessel is completely filled with liquid nitrogen is when the surface of the nitrogen bath settles.

### *2.2 Safety*

Safety in general plays an important role in burst testing. The tests are carried out in a small bunker at the ITE, Forschungszentrum Juelich, which has large labyrinth-like openings to the surroundings. This allows the shock wave and vaporizing nitrogen to be safely dissipated. . The entire process, from filling to bursting, must therefore be performed remotely with nobody allowed to enter the burst room.

Besides the electrical connections, the pipe between the nitrogen gas cylinder and the vessel to be tested is the only connection between the bursting chamber and the control room. It is a source of danger therefore the connection needs to be mechanically disconnected after filling outside of the bursting chamber. Otherwise, if the solenoid valve breaks under pressure, the pressure wave will bounce back into the cylinder. Liquid nitrogen could enter the pressurized gas cylinder, vaporize abruptly and cause it to explode. As an additional safety feature, the connecting

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hoses have a small inner diameter of 4 mm, are not resistant to cryogenic temperatures, and have a low burst pressure of approx. 25 bar (design pressure 8 bar).

**Figure 1.** Moderator vessel (BF1, Generation 2 moderator for the ESS) prepared for burst test mounted on a linear actuator with installed pressure sensor and cryogenic high pressure magnetic valves and a liquid nitrogen bath below

A worst case scenario is that the pressure inside the vessel to be tested is high, but not high enough to cause the vessel to burst, whithout having the chance to release the pressure This can happen especially if the vessel is not completely filled with liquid nitrogen and/or if a cold leak occurs at high pressures, which closes again when the pressure drops. To overcome this problem, the internal volume of the vessel to be tested is connected to two cryogenic high pressure valves that allow the pressure to be released. For additional redundancy, both valves can be operated by separate circuits that can also be powered by emergency power supply. If both valves cannot be opened, for example because they are jammed under pressure, the container can be submerged back into the liquid nitrogen bath. The cooling causes the pressure inside the container to decrease. If this is also not possible, for example in the event of a complete power failure and loss of the emergency power supply, the container can be cooled by pouring liquid nitrogen over it with a lance. This emergency cooling system does not require electrical power, as the necessary supply pressure is provided by a pressurized gas cylinder.

When the vessel ruptures, very high forces are generated, which can cause the mechanical connection between the vessel and the support structure to break. Due to the sudden drop in pressure, the boiling point of the liquid nitrogen in the vessel drops, so that a permanent force acts on the container caused by the escaping gas stream. To prevent the container from becoming loose, the mechanical connection and the pipe connections are designed to be flexible and not rigid. The deformation of the components absorbs some of the energy, reducing the risk of breakage. If the bracket breaks anyway , there are safety chains that limit the "flight radius" of the vesselt.

*2.3 Experimental setup*

Figure 1 shows the moderator vessel (BF1, Generation 2 for the European Spallation Source ESS) to be tested [2]. It is connected to an 8 mm Swagelok tube that ends in a cross piece. The connection is made with a screw-on adapter that is double-sealed with a metal cooper gasket and Teflon. A calibrated pressure sensor (0...600 bar) is mounted opposite the vessel and wired to a permanently recording electronic measuring unit via a 4...20 mA signal line. The pressure sensor is located approximately 500 mm above the vessel to be tested, outside the cold zone, even when the vessel is completely immersed in the nitrogen bath.

The two cryogenic high-pressure valves branch off to the left and right of the cross piece and are mounted together on a common aluminium profile. The connecting tubes from the valves to the cross piece hold the vessel to be tested and the pressure sensor in position. The tube for filling the vessel with nitrogen gas is connected to one of the two solenoid valves. After filling, the tube connection is disconnected so that the valve can be opened to release the pressure and allow the nitrogen to escape from the vessel if necessary. The second solenoid valve acts as a redundant pressure relief device and can be switched and powered on a separate circuit in an emergency.

The two valves are connected by an aluminium profile which is connected by an extension arm to a linear motion drive. The linear actuator allows the vessel to be remotely lowered into a 100 l bath of liquid nitrogen. In this position the vessel is first cooled and then filled with gaseous nitrogen which is liquified by condensation (see chapter 2.1). Once filled, the vessel is pulled out of the bath to an upper position where the lighting and cameras are aligned. The vessel filled with the liquid nitrogen inside the vessel is warmed up until the vessel bursts. During the warmup phase under isochoric conditions, nitrogen always remains liquid and would only become supercritical at pressures above 793.5 bar and a temperature above 127 K [1].

The bursting of the vessel is recorded with two Photron, Fastcam Mini AX200 high speed cameras. Typically, frame rates of 15,000 frames per second provide a good compromise between the available illumination and the desired temporal resolution. The spatial resolution of the cameras at 15,000 fps is 768 times 512 pixels and the maximum available recording time is 1.9 seconds. The images are stored in a volatile ring buffer inside the cameras. As soon as the end trigger is activated, the cyclic recording is stopped so that the images of the last 1.9 seconds before the trigger pulse can be read out from the volatile memory. Due to the large amount of data, it takes between 20 and 30 minutes to read out one camera. Any interruption of the power supply to the camera during recording or reading will result in the loss of data in the volatile memory, which is why the two cameras are operated on separate power circuits.

There are two different concepts for protecting the cameras and lighting sources from flying parts or fragments after the burst. The equipment can be installed in thick-walled steel enclosures sealed with 15 mm thick Plexiglas windows. While this provides good protection against damage, there is a risk of overheating due to reduced system cooling. In addition, handling is more difficult, especially when adjusting the focus and aperture of the camera lenses, and the image quality is reduced by reflections on the Plexiglas windows. Increasing the distance between the camera/lighting and the vessel to be tested offers also some protection against damage. This option is used in combination with zoom objectives with a high light transmission and special focusable lighting when lower burst pressures are expected.

## 3. Results

Several different moderator vessels have been tested and bursted. The results for the first generation BF2 moderator for ESS, the first target station moderator and the feasibility study moderator for the second target station of the Spallation Neutron Source (SNS) at Oak Ride National Lab, USA and the second generation BF1 moderator for ESS are shown in Table 1. The maximum pressures achieved were obtained from the pressure curves recorded during the tests.

**Table 1.** Different types of cold moderators and their operation, design and burst pressures [3, 4, 5]

| Moderator type | Operation pressure [bar] | Design pressure [bar] | Burst pressure [bar] |
|---|---|---|---|
| BF2, ESS first generation moderator | 10 | 17 | 182 |
| SNS Second target station prototype | 14 | 19 | 257 |
| SNS First target station moderator | 14 | 22 | 105 |
| BF1, ESS second generation moderator | 10 | 17 | 100 |

*3.1 Digital image analysis*

Several approaches were tried to evaluate the image data recorded by the two high-speed cameras. In the beginning, the images were evaluated visually. While the first burst test was only concerned with visualizing the bursting of the vessel, in the next burst test the lighting and camera technology was improved to such an extent that the structural failure could be localized and the crack propagation made visible. To gain more information, Digital Image Correlation (DIC) was used in the following burst test. A speckled pattern was applied to the surface of the vessel to be tested and evaluated. To ensure that the pattern remained visible, ice formation due to water vapor in the ambient air had to be prevented. This was achieved by placing a Plexiglas frame over the nitrogen bath. The nitrogen evaporating from the bath created an atmosphere of pure nitrogen around the vessel, effectively preventing ice formation. However, reflections on the Plexiglas panels degraded the image quality. Once the frame was filled with nitrogen gas, the cold nitrogen gas flowed over the top of the Plexiglas and sank to the bottom due to its higher density. The different densities of the gases in the optical path between the cameras and the vessel caused noise in the pattern of the images. This effect made it even more difficult to evaluate the speckle pattern.

Therefore, a different approach was taken for the fourth burst test. As the metal surface of the containers to be tested is reflective for visible light, the distance between the cameras and the container was increased. A focusing spotlight was positioned at an angle of 5 to 10 degrees behind each of the two cameras. Even the slightest change in the surface, such as a bulge, will cause the light to be reflected at a different angle. In this case, the surface of the vessel acts like a curved mirror. The different light reflections in turn cause brightness variations in the recorded images, which can be evaluated.

*3.2 Image analysis of BF1, generation 2 moderator for ESS*

As an example, the results of the image evaluation recorded during the burst test for BF1, Generation 2 moderator for ESS are presented here. Figure 2 shows the live image and its analysis, focused on the region of interest (ROI) in the upper part of the vessel at time t = - 733 µs before

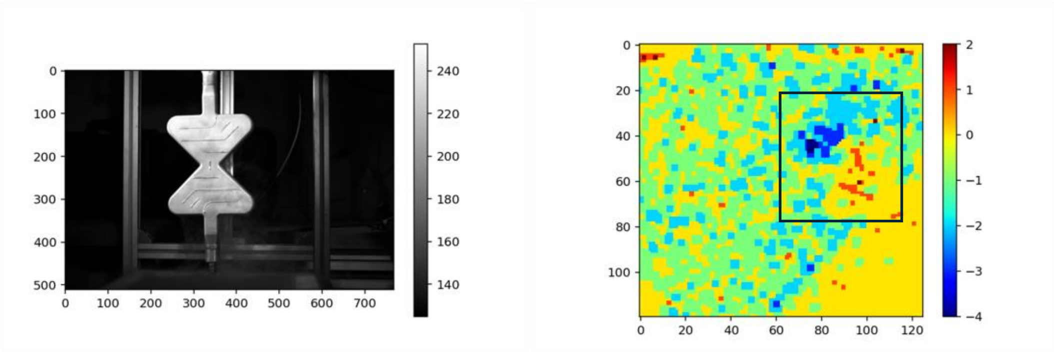


**Figure 2.** Image of the moderator vessel (BF1, generation 2 for the ESS) (left) with a height of 512 pixel (x-axis) and a width of 768 pixel (y-axis) and its analysed region of interest (ROI) (right) -733 µs before bursting. Initial changes in the surface structure, given in arbitrary numbers, are visible within the rectangularly marked area.

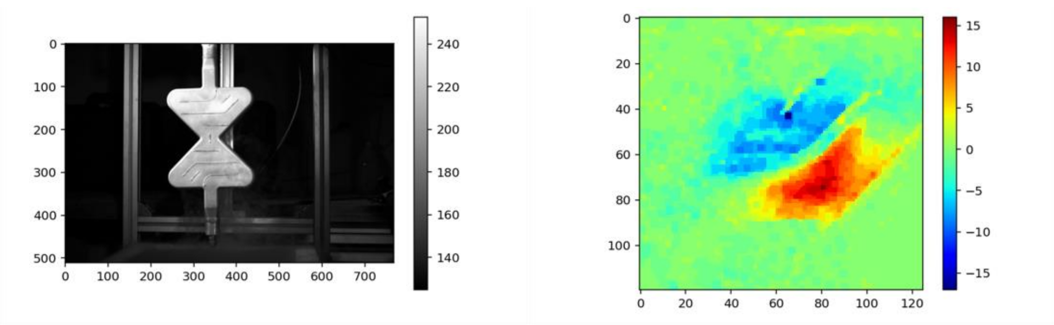


**Figure 3.** Image of the moderator vessel (BF1, generation 2 for the ESS) (left) and its analysed region of interest (ROI) (right) 66 µs before bursting

bursting. The analysis shows the beginning of significant structural changes, which can be recognized by the changes inside the rectangularly marked area.

Figure 3 shows the image analysis just before the failure of the outer structure. The regions that have tilted relative to their initial position are clearly visible. The bridge separating the two areas does not appear to have moved. The brightness change is calculated in two dimensions, so spatial movements directly towards or away from the camera cannot be analyzed. However, it is reasonable to assume that the surface in the right area and the left area have bent, and that the bridge in the middle of the two areas has moved toward the camera.

Figure 4 shows the analysis of the image where the outer structure begins to fail. The arrow indicates the point where the surface cracks. It is the region of the weld of the small fluid guide plate in the upper right corner [3]. Figure 5 shows the situation 400 µs after the first failure

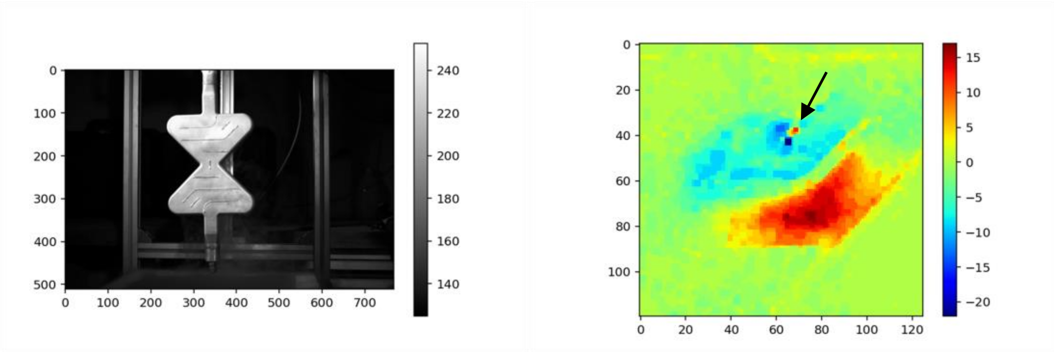

**Figure 4.** Image of the Moderator vessel (BF1, Generation 2 for the ESS) (left) and its analysed region of interest (ROI) (right) at the moment of bursting

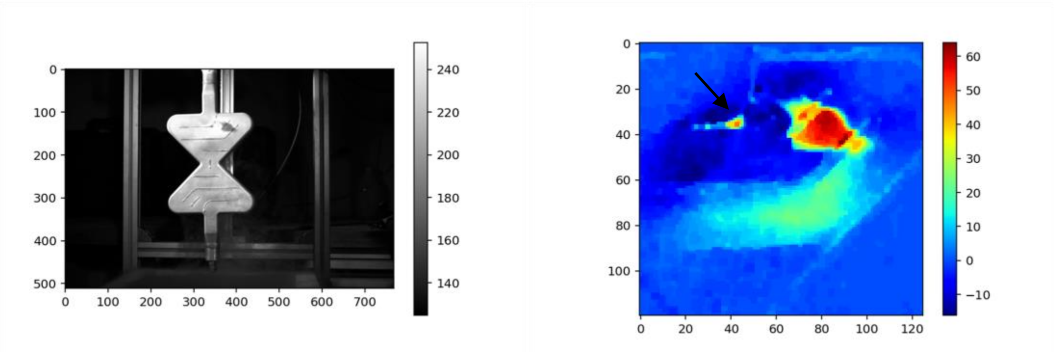

**Figure 5.** Image of the Moderator vessel (BF1, Generation 2 for the ESS) (left) and its analysed region of interest (ROI) (right) 400 µs after bursting

and tearing of the outer vessel wall. The arrow indicates the cracking of the surface along the larger fluid guide plate in the upper part of the vessel.

From the analysis the following scenario can be concluded. Inside the vessel, 866 µs before the failure of the outer structure, the largest of the fluid guiding plates began to lose contact to the wall, starting in the upper right corner. The outer vessel walls remained intact. Inside, the plate

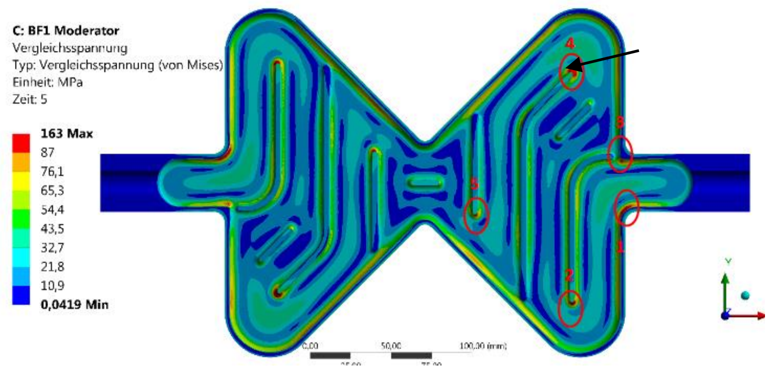


**Figure 6.** Result of the mechanical stress simulation (von Mises) of the BF1, Generation 2 moderator for the ESS. The region with the highest stress is marked with an arrow [3]

IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012118 doi:10.1088/1757-899X/1344/1/012118

continued to separate toward the center of the vessel. Since the plates connect the upper and lower vessel walls, the surface began to bulge in the area of the detached plate. The bulging caused an additional bending moment in the area of the two upper fluid guide plates. This caused the vessel surface to crack in the area of the weld seam of the small upper plate and also in the area of the larger upper plate 333 µs later.

*3.3 Comparison with the simulated result*

The results of the structural mechanical simulation of the moderator vessel are consistent with the experimental results. The location of the greatest stress, marked as number 4 in Figure 6, corresponds to the area where the first changes were detected in the image analysis. It is reasonable to assume that an internal crack will spread from this point. However, the static simulation does not take into account the bulging of the surface where the upper part of the moderator loses mechanical contact with the lower part during dynamic crack propagation. Therefore, it is understandable that the outer surface tears open in the area of the strongest bending rather than in the area of the highest stress. Detailed information about the mechanical simulations of the BF1 moderator vessel can be found in [3].

## 4. Summary and Conclusions

More than eight years of experience have been accumulated in performing burst tests at cryogenic temperatures between the BF2 test, first generation ESS moderator, and the BF1 second generation ESS moderator. Combining burst testing with high-speed imaging adds value to testing cryogenic pressure vessels, whether the goal is to analyze weak points or validate the results of mechanical simulations. Combined with digital image analysis, the test enables visualization and analysis of dynamic processes on a microsecond timescale. The results of the test series demonstrate the importance of cryogenic burst tests, also because the results differ from water-based burst tests at room temperature. This is why cryogenic burst test became a standard procedure at our institute, developing and manufacturing cryogenic neutron moderator vesselsHowever, visualizing deformations in the µm range remains challenging. An interesting approach could be to combine high-speed imaging with structured light projected onto the surface of the container under investigation.

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