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PERFORMANCE ASSESSMENT OF ADDITIVE MANUFACTURING COMPONENTS FOR AN EX-CORE NUCLEAR USER : VALVE COMPONENT – NUCOBAM PROJECT

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ABSTRACT

In recent years, the nuclear industry has been exploring the potential of additive manufacturing (AM) to create components for nuclear power plants (NPP's). Roadmaps have been developed within this sector, outlining the steps required to enable the use of AM components' production. In this context, several projects have been initiated, including the European project NUCOBAM [1]. The overarching objectives of the NUCOBAM project (Nuclear Components based on Additive Manufacturing) is to tackle the technical challenges associated with manufacturing NPP's components using AM [2].
One of the key elements within the NUCOBAM project involves the performance assessment of an ex-core component, specifically a valve. The AM process and alloy within the project's scope are Laser Powder Bed Fusion (L-PBF) and the austenitic stainless steel grade 316L. This assessment will be incorporated into a methodology for qualifying components produced trough AM that adhere to nuclear codes and standards. This paper will offer a detailed presentation of the study related to additive manufacturing valve body and the qualification methods for this component, along with the procedures developed within the NUCOBAM project.

Keywords: Additive Manufacturing, Nuclear codes, valves, qualification, procedures, functional test

NOMENCLATURE

AM	Additive Manufacturing
L-PBF	Laser Powder Bed Fusion
NPPs	Nuclear Power Plants
NUCOBAM	Nuclear Components based on Additive Manufacturing
NDT/NDE	Non-Destructive Test/Examination
WP	Work Package
VT, UT, PT	Visual Testing, Ultrasonic Testing, Penetrant Testing
TFM	Total Focusing Method (UT)
SPT	Small Punch Test
IBAMS	In-pile Behaviour of Additively Manufactured Samples
SPT	Small Punch Test

1. INTRODUCTION

The nuclear industry, like many other industries, is increasingly exploring new manufacturing technologies, including Additive manufacturing (AM). This technology offers innovative manufacturing solutions in terms of part geometry and functionality while optimizing economic factors such as part cost and lead time [3]. AM introduces new solutions that consider various aspects of a product's life cycle, from its initial requirements to its use and maintenance. Safety is of paramount importance in the nuclear industry, which imposes stringent constraints on equipment. Component qualification must meet strict standards. However, the adoption of such processes depends on demonstrating the equivalence in terms of the quality and safety of AM components compared to materials and processes conventionally used in the industry. This applies to components both within the reactor core (in-core) and situated outside of it (ex-core). To address this challenge, the European project NUCOBAM has been initiated. This paper deals with the development of an ex-core component : the valve body. In the following sections the challenges associated with selecting and justifying valve geometry; the printing and inspecting process of the valve bodies, the operational testing and the final post-test inspection program are presented. Each of these sections contributes to the understanding of the valve development and qualification in the context of this nuclear project.

2. NUCOBAM PROJECT DESCRITPION

The project consortium consists 13 partners and is organized into seven work packages (WPs) [5].

WP1 focuses on the methodology for AM qualification standardization, and was established to develop a qualification methodology for AM components, including a comprehensive review of the existing standards and qualification processes. WP2 handles the AM process qualification and the aim is to create a general methodology for qualifying L-PBF processes, in line with WP1. WP3 covers the Non Destructive Examinations (NDE) of two AM components (fuel debris and valve body) and evaluation of mechanical properties and microstructure of the material from WP2. Analyses of WP3 results ensure the capability to decide of the qualification as processed [7]. WP4 is dedicated to the assessment of the In-pile Behaviour of Additively Manufactured Samples (IBAMS) and deals with the description of the sample sets, irradiation conditions (fluence, temperature…), microstructure characterization, determination of mechanical properties and documentation. WP5 deals with the performance assessment of ex-core user case: valve component. It assesses the operational performance of ex-core valve component produced by L-PBF process. WP6 (dissemination and exploitation) and WP7 (Project Management) ensure support functions of the project. In this paper the status of WP5 activities is given.

3. VALVE BODY CHOICE JUSTIFICATION

As part of the evaluation of an ex-core component using the L-PBF process, the choice of component was narrowed down to a valve body. This valve body is used extensively in system of nuclear power plants (NPPs) and requires periodic replacement. Ramén Valves and Engie Laborelec presented several valve types, some of which closely match those currently used across European NPPs.

The first design suggested by the manufacturing Ramén Valves currently used in NPPs was not optimized for the L-PBF process.

This initial design required excessive post-print machining. The NUCOBAM consortium requested a design that minimized excess material.

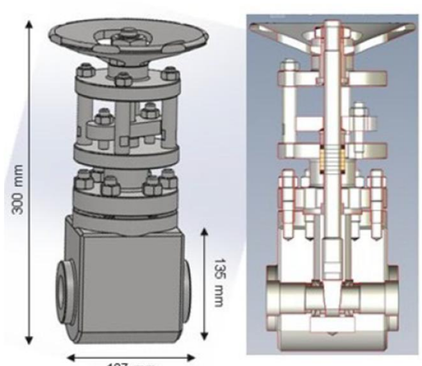

FIGURE 1: FIRST VALVE DESIGN (© Framatome)

The second design proposed by Ramén Valves was established in the past and the valve body, based on this geometry was successfully printed, with another alloy for traditional industry. This design was proven to be suitable for the studied L-PBF printing process and would facilitate the purpose of the demonstrators, that is, completion of all hydraulic test, performance test and non-destructive testing, explained in following sections.

FIGURE 1: SECOND VALVE DESIGN (©Tractebel Engie)

The selected valve is based on an existing valve model, with the following parameters:

- Valve type : ball sector valve (DN40, trunnion type);
- Seat : PEEK seat (leakage class V acc. to EN 60534 [8]);
- Design pressure : 27 bar (acc. to EN 12516-1 [9]);
- Rating : PN40 (~class 300, acc. ASME B16.34 [10]);
- Fluid : primary fluid;
- Actuation: manual;
- Pipe connection: non articular requirements, flanged.

It should be noted that the NUCOBAM valves are not intended for use in NPPs.

To print the valves, the additive manufacturing process was qualified through the WP2 specimens, following the NUCOBAM process qualification methodology [6].

4. VALVE BODY PRINTING AND INSPECTION

The valve bodies were printed by Engie Laborelec. In total, four valve bodies were produced using the same 3D printing machine. One was intended for exhibition purposes. Two others valves were printed for functional testing in WP5.

The last one was intentionally printed with process-induced flaws for NDT. This valve was studied in WP3 to determine the sensitivity of defect detection and to validate it with the intentionally induced flaws. The detection accuracy was assessed for both 2 mm volumetric and planar defects. These indications were detectable based on the intentionally induced flaws, in accordance with the standards outlined in the internal NUCOBAM documentation.

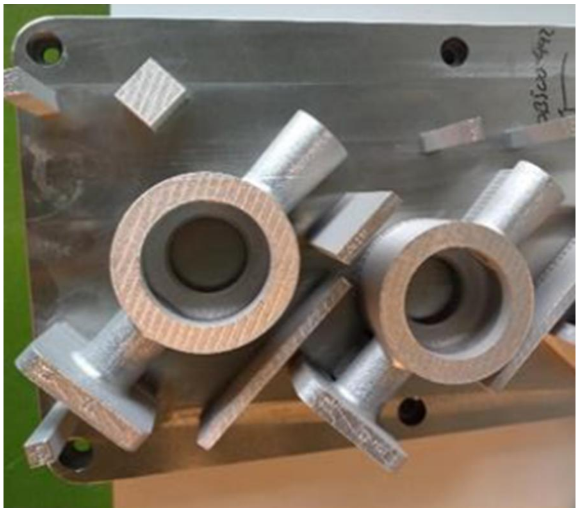

FIGURE 2: MANUFACTURED VALVE BODIES ON THE PRINTING PLATFORM

After the production using the L-PBF process, the valve bodies were submitted to a solution annealing treatment at 1066°C. Finally, machining was performed only on the surface that would receive internal components.

Several Non-Destructive Tests (NDT) were performed on the valve bodies in accordance with the internal NUCOBAM documentation. Initially, ultrasonic testing (UT – ISO 10228-4 [11], RCC-M M3301 [12], AMS-STD-2154C class B [13]) by the immersion Total Focusing Method (TFM) on both valve bodies were performed by Laborelec [17]. No flaws were detected on both valves. Subsequently, CIEMAT conducted visual inspection (VT – EN 1370 [14]) and liquid penetrant testing (PT – ISO 23277 [15]) on the machined surfaces of the valve bodies (figure 5).

The VT test revealed superficial indications (figure 4), such as milling marks on one side that left a mark at the end of the process and a slight concave indication below the final milling. These surface indications were investigated during PT test.

FIGURE 3: INDICATION DETECTED DURING VT TEST

The PT inspection revealed that no penetrant indication was present. The indication identified during the VT test was subsequently removed through machining to achieve an optimum surface finish for the subsequent step.

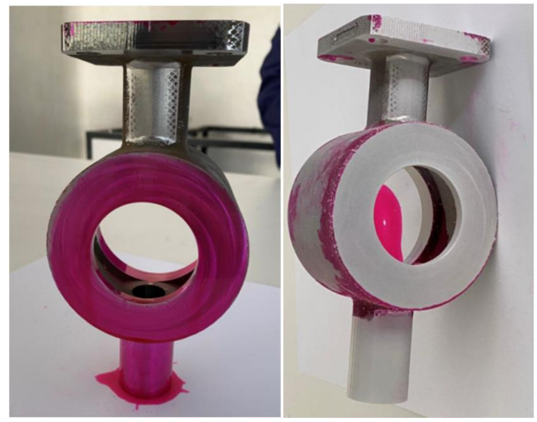

FIGURE 4: PT TEST ON MACHINED SURFACE OF THE VALVES

All of these NDT methods confirmed the integrity of the valve bodies. The two valve bodies are identical in terms of the detected indications, all of which are superficial and exhibit no apparent penetration.

5. OPERATIONAL VALVE TESTING AND EXPERTISE

5.1 STATIC TEST

Once the integrity of the valve bodies was confirmed by NDT tests, internal components were assembled on the valve bodies following the internal NUCOBAM documentation and manufacturer procedures from Ramén Valves.

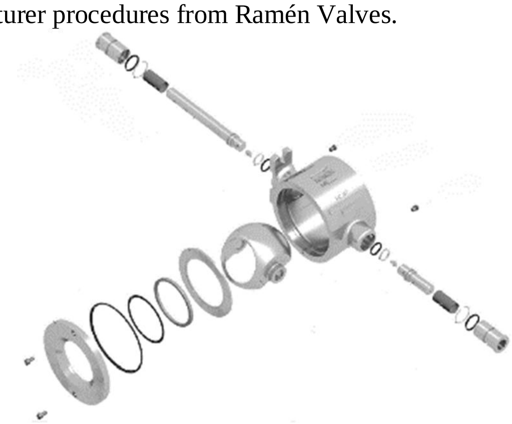

FIGURE 5: EXPLOSED VIEW OF THE VALVE INTERNALS [4]

The materials of each internal components were discussed with NUCOBAM partners to optimize the selection of test parameters without causing damage to the components. Based on the partners' feedback and collective knowledge, PEEK was chosen as the seal material because of its ability to withstand the pressure applied during the valve tests.

FIGURE 6: FINAL STATE OF THE ASSEMBLED VALVE

The functionality of the valves with internals was tested. The purpose of conducting a static test is to qualify the integrity of the additive manufactured valve body. After verifying the actuation torque, Ramén Valves carried out a seat leakage test at 44 bar for a duration of 10 minutes and a shell strength test at 60 bar for 10 minutes, following standards EN 12266-1 [16], specifically P12 and P11, respectively. No leakage was detected in either valve during the tests.

A second set of static tests was performed by EDF. For this second set, only one of the two valves was tested. The second valve is used as a back-up valve in case the first valve does not pass all the tests.

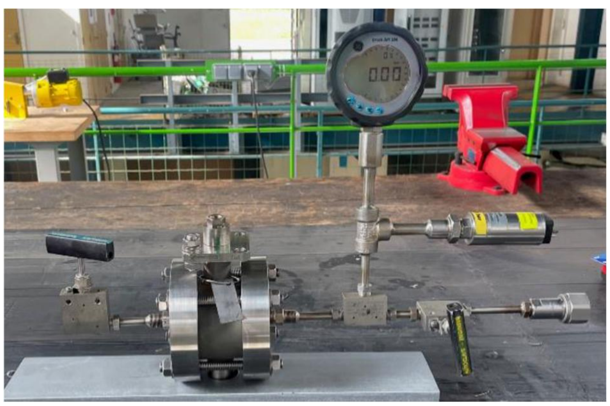

FIGURE 7 : STATIC BENCH TEST ON VALVE – EDF TESTS

Therefore, to perform static tests, the valve was mounted on a test bench (figure 8), and held in a mechanical installation, with 70Nm of actuating torque applied to the tie rods. The operating torques measured at the beginning of opening and at the end of closing were about 6 Nm without flanges fitted. With the fitting flanges, the torque reached 8 Nm. The external leakage test was performed following EN 1266-1 [16] standards, the test was carried out at 45 bar for 10 minutes, and no visible leakage to the outside was observed. A torque spanner was then used to turn the valve about ten times without any load to perform the static tests. This test confirmed the correct operation of the valve, with fluid and without pressure.

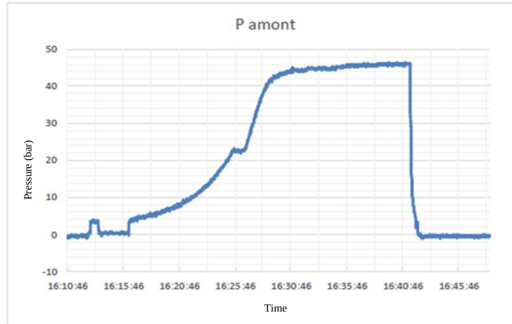

FIGURE 8 : EXTERNAL LEAK TEST (PRESSURE/ TIME)

A gasket leak test was performed to confirm that there was no leakage from the valve gasket. An upstream isolation valve was closed once the test pressure was reached. Results indicated that the valve met the acceptable leakage rate criteria (<0,5mm³/s), confirming the integrity of the valve sealing system. The last test performed in this second part of static tests was the seat leak test. This test evaluated the valve's performance by checking for leaks through the valves seats, which is essential to ensure the valve's sealing when it is closed.

5.2 ADDITIONAL TEST PROPOSAL

As an integral component of the comprehensive validation process for the valve at an industrial scale, partners involved in WP5 have submitted a proposal for a valve qualification test. It is important to note that these tests will not be performed within the scope of the NUCOBAM project.

Nevertheless, the presentation of the elements proposed by the different project partners is of interest as it provides a suggested methodology for the qualification of AM valves. The proposed qualification method is based on current standards for valve qualification, supplemented by the collective expertise of the project partners. This method seamlessly follows the static tests and serves as control tests at various stages throughout the qualification process presented below.

The static tests can be completed by a third party and will includes the last three tests. The first one is a functional static test where eight cycles of opening and closing at 30 bar are performed under monitoring. The second test will be a Cv test, designed to measure the flow rate of a fluid through a valve in order to determine its flow coefficient. The final test is a no-load-test, which provides valuable insights into the behavior of mechanical equipment when operating without an external load and help to evaluate its efficiency under ideal or minimum conditions. These final three static tests, together with those already performed, can contribute to the overall characterization of the valve's performance.

Upon successful validation of all static tests, the valve can be integrated in a cyclic loop, to verify that the valve body is properly manufactured using L-PBF technology. The objective of the test loop is to subject the valve to low pressure difference, high pressure difference, thermal shock and leak rate tests.

Most parameters, including power, voltage, operating torque, temperature, among others, must be closely monitored throughout the cyclic test phase, in accordance with established practices for industrial component qualification. The criteria for assessing the valve must be defined in accordance with standards specifications.

Additional tests could include 500 pressure test cycles at 30 bar and 180°C, with demineralized water flowing at a rate of to 22 m³/h. After the initial 500 cycles are completed, the previously described static tests (including six tests) can be performed again to evaluate the integrity of the valve. In the event that any defect or leaks are found during this assessment, an additional set of 500 cycles can be performed under the same condition. This second series is carried out on the condition that the intermediate static tests show that the leak rate meets the criteria standard. In this way, the valve undergoes 1000 cycles, 500 of which are followed by a final static test.

To conclude this qualification tests proposal, the valve can be subjected to 10 thermal shocks, following the NUCOBAM valve characteristics, at a pressure of 30 bar, a temperature of 150°C and a maintained demineralized water flow rate of 22m³/h.

5.3 EXPERTISE

After the valve is subjected to a series of static tests to assess its strength and integrity, a series of expertise steps are undertaken to ensure its ongoing quality and performance.

First, an overall visual inspection of the valve is conducted to determine if the valve has sustained any damage.

Next, the disassembly of the internal components of the valve is carried out to observe only the AM body. This allows the integrity of the 3D printed structure to be verified and ensure that it has not been deformed or degraded.

This is followed by an assessment of wear areas to determine if specific areas of the valve were more affected than others during testing. The next stage of the expertise includes a visual examination of the guiding and friction areas. This thorough inspection is aimed to identifying any signs of wear or damage in these critical zones of the valve. In addition, a visual examination of the components of the valve is conducted to identify any potential anomaly or deformation that may have escaped the previous inspection. Finally, a final dye penetrant test is conducted on the spans of the valve to ensure that there are no hidden cracks or defects are present.

The purpose of this expertise is to guarantee that the valve maintains its integrity and performance and can be used even after being subjected to rigorous industrial testing conditions. This ensures that the AM valve can be relied upon to be safe for use in safety-critical applications such as the nuclear industry.

5.4 BURST TEST

A burst test, also known as a pressure resistance test, was executed on valve. This test consists of subjecting the valve body to a specified high pressure without the internal components. This is a critical step for the valve body and aims at evaluating the performance of the valve.

The primary objective is to ascertain the maximum pressure threshold that the valve can withstand before showing signs of cracking or warpage or, in extreme circumstances, complete rupture. The test procedure does not specify a specific pressure increase rate up to 60 bar. Between 60 and 100 bar/min, the pressure increase is linear or by steps of 10 bars increments. Above 100 bar, the pressure increase rate is lower and performed by steps of 5 bars. It is important to note that this test is performed only on the valve body, clamped between flanges.

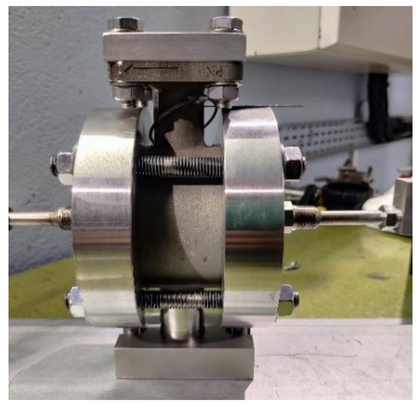

FIGURE 9: VALVE BODY CLAMPED BETWEEN FLANGES – BURST TEST

The valve body was positioned within the burst test fixture, enclosed by a protective cage. The test was monitored by cameras strategically placed around the test rig for safety considerations. Progression ramps were executed in accordance with the prescribed procedure. No anomaly was identified up to 230 bar, pressure at which leakage was detected.

FIGURE 10: BURST TEST BENCH WITH SAFETY CAGE

The pressure increase was stopped at 230 bar, and the operators investigated to determine the cause of the leak. The integrity of the flange-to-valve connections was inspected, revealing that the leak was coming from the junction between the screw and the flange. Since the leak was apparently not attributed to any deformation or crack in the valve body, it was decided to tighten the screw (100Nm) and repeat the test. For this second test, the pressure was promptly increased to 200 bar and then gradually elevated until the recurrence of the leak at 270 bar.

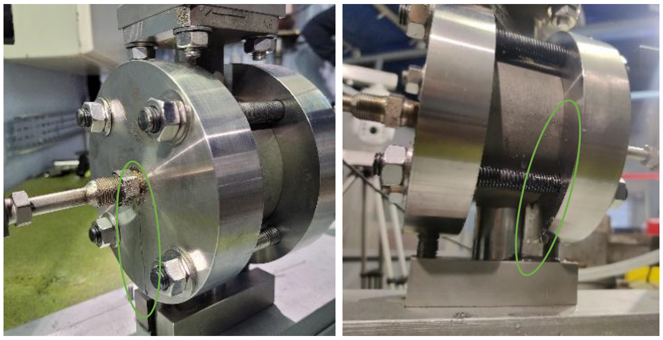

FIGURE 11: LEAKAGE AT VALVE RETAINING FLANGES

To conclude, the assembly, including the valve body, withstood a pressure of up to 270 bars, considering that the pressure is approximately 5 times the operating pressure of approximately 200 bars. No visible damage was observed on the valve body. However, there is evidence that the gasket seals started to degrade, resulting in multiple leaks and the stop of the burst test.

This test sheds light on the component's response to high pressures providing critical information to ensure the safety and integrity of the valve in environments with common pressure fluctuations. The valve's ability to withstand elevated pressure levels is a key feature of its reliability and operational efficiency, making it an essential criterion in the qualification process.

The results of the burst test indicate that the AM valve reaches pressure values comparable to those of a conventionally milled valve.

6. INSPECTION AFTER COMPONENT TESTING AND FINAL DESTRUCTIVE TEST

This final phase of the AM valve qualification is intended to conduct post-pressure test characterization activities to assess the integrity of the additively manufactured valve component under stress. This includes a combination of non-destructive and destructive examinations of test coupons extracted from the valve body.

In terms of NDT, the initial step will entail a 3D laser scanning measurement to compare it with the 3D scanning performed on the valve body not submitted to the burst test. The second NDT test will consist of a UT Phased Array and advanced technology using the Total Focusing Method, complemented by PT test. The combination of Phased Array Ultrasonic Testing and the TFM aims at maximizing the accuracy of defect detection in a material or component. UT Phased Array provides detailed information about the geometry, size, and depth of defects, while TFM offers improved spatial resolution and enhanced ability to detect small defects. By merging these two techniques, a more comprehensive approach to material inspection is achieved.

A destructive examination will be conducted on coupons from the valve body after final inspection. Three areas (yellow square, blue square and red square, figure 13) of the valve body were defined for sampling.

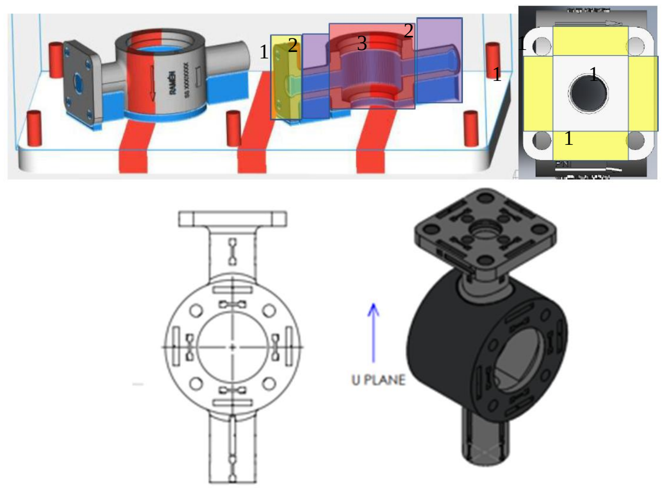

FIGURE 12: EXTRACTION AREA AFTER BURST TEST ON VALVE BODY

The testing campaign will include metallographic examination, density measurement, tensile testing, Charpy impact testing, Small Punch Test (SPT), and hardness. The results obtained from these tests will provide valuable information on the potential degradation of the material microstructure and thus its mechanical properties after the valve tests.

In particular, miniature specimens form these three different areas will be mechanized for tensile and impact tests. The selected specimen geometry is the same as for the tests on irradiated material (WP4) and was also used for the WP3 tests [7]. Small punch tests will be used as screening method to assess the potential degradation but also the anisotropy of the valve body. Since the yellow area (flange) was not affected in the valve tests, specimens mechanized from this area will be used as reference values to assess the potential degradation. In addition data found in the literature about the tensile an impact properties of 316L fabricated by AM, in particular by L-PBF process, will be also taking into account as reference values.

This datasets will be of great significance as it will enable a comprehensive assessment of the 3D-printed valve's performance and reliability. Furthermore, the test results will be compared with the findings from other work packages of the project, ensuring a comprehensive and consistent evaluation of the valve's quality and suitability for its intended applications.

This cross-referencing of data from other work packages of the project will enhance the overall assessment's robustness and support the development of high-performance AM valves for the nuclear industry.

7. CONCLUSION

In conclusion, the additive manufacturing of the valve was accomplished successfully, using a geometry adapted to the L-PBF printing process. The assembly of internal components proceeded seamlessly, ensuring optimal functionality. Non-destructive testing was executed successfully, confirming the integrity of the valve. Static and burst tests allowed to prove the valve resistance, and sustained pressures up to 270 bar.

While the initial inspection and NDT phases have been successfully completed, the final inspection and additional NDT processes are currently underway. These concluding steps aim at providing a comprehensive evaluation of the valve's overall reliability.

A detailed final report containing all test results, spanning from 3D printing to static and burst tests, will be compiled. This report will also incorporate the outcomes of the other Work Packages and consolidate all the project’s findings [5].

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