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# ASSESSMENT OF INTEGRITY OF PRESSURE VESSELS FOR COMPRESSED AIR

# PROCENA INTEGRITETA POSUDA POD PRITISKOM ZA KOMPRIMOVANI VAZDUH

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- non-destructive testing
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**Ključne reči**
- posuda pod pritiskom
- NIOVAL 50
- zavareni spojevi
- ispitivanje bez razaranja
- dijagram analize otkaza (FAD)

*Abstract*

*Fracture mechanics approach for structural integrity assessment is described in the case of pressure vessels for compressed air. The results of non-destructive testing indicated unacceptable defects on the vessels and set a base for application of failure analysis diagrams (FAD) and risk-based analysis. Risk matrix are applied with the aim of assessment and analysis of the integrity of the vessels.*

*Izvod*

*Opisan je pristup mehanike loma u oceni integriteta i veka opreme pod pritiskom na primeru posuda pod pritiskom za komprimovani vazduh. Rezultati ispitivanja metodama bez razaranja posuda poslužile su kao osnova za izradu i primenu dijagrama analize otkaza (FAD) i analize rizika. Matrica rizika je takođe primenjena u cilju određivanja integriteta posuda i uticaja prslina na integritet posuda.*

## INTRODUCTION

Installation and maintenance of pressure equipment to meet basic customer requirements involves a range of activities, starting from the project phase to the exploitation of the equipment until reaching a designed or expected working life, while at the same time taking into account all aspects: the structure, materials selection, quality of performance, manufacturing and testing, operating conditions and the monitoring and maintenance of the equipment. User requests that the equipment is functioning reliably, and that it maintains integrity during the expected life. In the case of damage as a result of loading and working conditions, the performed inspections and quality maintenance need to be assessed for their impact on the integrity in the working life. Nowadays, these inspections are very accurate, thanks to modern non-destructive testing devices and the precise determination of the size and position of defects, the application of fracture mechanics parameters for evaluating the significance of failure, advanced computer software and high performance, /1-3/.

Today, the inspection and assessment of pressure equipment is performed according to the PED Directive 2014/14 /EU, /4/ and according to the standard EN 13445: 2015, /5/. As it is known and described above, assessing the integrity of pressure equipment is a very responsible job.

This paper will analyse the integrity of a pressure vessel made of NIOVAL 50, in the presence of defects that are found by non-destructive testing (NDT), mainly ultrasonic testing (UT). The presence of a defect and its behaviour is analysed via stress intensity factor, and structural integrity assessment using the Failure Assessment Diagram (FAD) and the risk matrix, /6, 7/.

## PRESSURE VESSELS AT RHE BB

In the further discussion, specific cases from practice are considered. Three pressure vessels are subjected to NDT inspections according to appropriate standards as described in the further text. Both pressure vessels used for compression air are shown in Figs. 1-3.

Figure 1. The pressure vessel 977 at RHEBB.

Figure 2. The pressure vessel 976 at RHEBB.

Figure 3. The pressure vessel 970 at RHEBB.

NON-DESTRUCTIVE TESTING

Visual testing is applied according to standard EN ISO 5817: 2015 /8/, along with magnetic particle testing, according to the standard EN ISO 23278 2020, /9/, to investigate the presence of surface and subsurface defects. For internal defects, the ultrasonic method is applied, according to EN ISO 11666 2018 /10/. Generally, it is known that ultrasonic testing is mostly used in the testing of pressure equipment, which in this case has proved to be the most reliable technique for detecting defects, /11/.

It should be noted that the base material of the inspected vessels is micro-alloyed steel NIOVAL 50, /12/ and the pressure in vessel 977 (Fig. 1) is $p$ = 78 bar. The geometry of this vessel is: thickness $t$ = 42 mm, with mean diameter $D$ = 1958 mm. Vessel 977 is inspected by 100 % ultrasonic testing on two vertical welded joints, and three circular welded joints, by USM 36XL Krautkramer device.

After the final UT testing of the vessel 977, Fig. 1, defect marked 2.5 is found with the following geometry and location: length 170 mm and width/depth 14 mm in a circular seam in the middle of the vessel, depth ranges from 28 to 42 mm. The position on the vessel where defect 2.5 is indicated is shown in Fig. 3. Another unacceptable edge surface defect in vessel 977 is marked as 1.6, of size 20 × 15 mm, also in a circular seam, between upper cover and mantle, which requires additional analysis, i.e. structural integrity assessment.

Internal pressure of vessel 976 (Fig. 2) is $p$ = 59 bar. Geometry of vessel 2 is: thickness $t$ = 30 mm, with mean diameter $D$ = 1958 mm. The following defects are found in this vessel, using UT testing:

- defect marked 1.1, 40 mm long and 15 mm wide, Fig. 4a,
- defect 1.2, 50 mm long and 14 mm wide, Fig. 4b.

Indications of UT testing of vessel 976, defect 1.1, are shown in Fig. 5. After indications are found, additional testing of the inner surface is performed, showing no defects. Therefore, it was decided not to remove these two defects, but just to monitor them further.

Figure 3. Position and size of defect 2.5 in vessel 977.

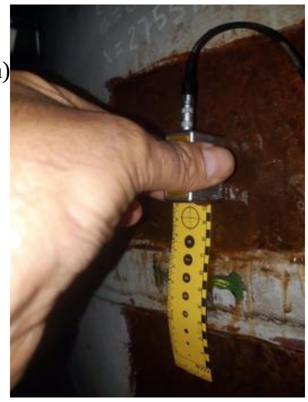
a)  b) 

Figure 4. Position of the UT sound for indications: a) 1.1, b) 1.2.

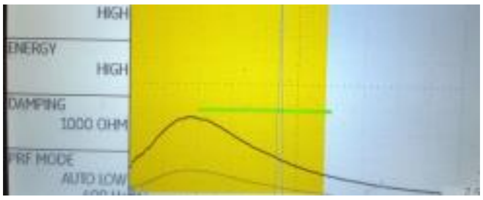



Figure 5. UT test indications for vessel 976, defect 1.1.

Finally, pressure vessel 970 is analysed: $p$ = 78 bar, thickness $t$ = 50 mm, diameter $D$ = 2150 mm. Vessel 970 was inspected by 100% ultrasonic testing on two vertical welded joints, and three circular welded joints, in the same way as the previous ones. Several defects are found, with unacceptable defect 5.6 (75 × 20 mm) as the worst case, positioned in the centre of welded joint, 18-38 mm, Fig. 6.

Figure 6. Defect 5.6, size 75 × 20 mm.

## FAILURE ANALYSIS DIAGRAM

Application of failure analysis diagram (FAD) at the same time takes into account plastic collapse ($x$ axis) and brittle fracture ($y$ axis), based on load, size of the defect and material properties /6, 7, 13/.

The obtained point can be in the safe part of the diagram, which is below the critical curve, or in the unsafe part of the diagram, which is outside the area of the critical curve, Fig. 6. The critical curve is obtained on the basis of Dugdale's model, and is defined by the following Eq.(1):

$$K_r = S_r\left[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi}{2}S_r\right)\right]^{-1/2}, \tag{1}$$

where: $S_r$ is the ratio of working and critical stress; $K_r$ is the ratio of the stress intensity factor and its critical value.

Based on previous experimental tests and works /14/, fracture toughness $K_{Ic}$ for the base material (NIOVAL 50) is taken as 1580 MPa√mm.

For the case of defect 2.5, stress intensity factor for edge surface defect of dimensions $2c$ = 170 mm, $a$ = 14 mm, under longitudinal stress, are calculated using Eq.(2):

$$K_I = Y(a/W)(pR/2t)\sqrt{\pi a}, \tag{2}$$

where: $Y(a/W)$ is calculated according to Eq.(3):

$$Y(a/W) = 1.12 - 0.26(a/W) + 10.52(a/W)^2 - 21.66(a/W)^3 + + 30.31(a/W)^4, \tag{3}$$

for $a$ = 14 mm; $W$ = 42 mm; $Y$ = 1.77; $K_I$ = 1074 MPa√mm .

One should notice that all the results presented here for vessel 977 are conservative since the surface cracks are considered as being all along the axial welded joint.

Bearing in mind that the resulting value $K_I$ is less than the minimum value $K_{Ic}$ = 1580 MPa√mm, $K_I/K_{Ic}$ = 0.68, it can be concluded that there is no danger of brittle fracture.

Ratio between critical cross-section stress and critical stress (half-sum of the yield stress, 500 MPa, and the tensile strength, 650 MPa) is calculated using Eq.(4):

$$S_R = \sigma_n/\sigma_F = 132/575 = 0.23\ . \tag{4}$$

The coordinates of the point in the Failure Assessment Diagram (FAD) (0.23; 0.65) are in the safe area, at the level of fracture probability approx. 0.66, Fig. 6.

Similar analysis can be performed for defect 1.6, with the only difference being $a$ = 15 mm instead of 14 mm, leading to the following values: $Y$ = 1.87; $K_I$ = 1138 MPa√mm; $K_I/K_{Ic}$ = 0.72; $n$ = 140 MPa; $S_R$ = 0.25, at the level of fracture probability approx. 0.73, Fig. 6.

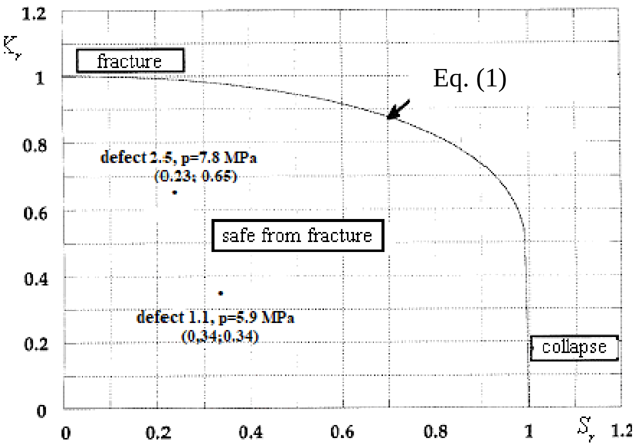



Figure 6. Failure Analysis Diagram for defects 1.1 in vessel 976; 1.6 and 2.5 in vessel 977; and 5.6 in vessel 970.

In the case of 'critical' defect 1.1 in the vessel 976, the stress intensity factor for an edge surface defect with dimensions $2c$ = 40 mm, $a$ = 15 mm, under longitudinal stress, is 538 MPa√mm ($K_I/K_{Ic}$ = 0.34). Ratio between critical cross-section stress and critical stress in this case is:

$$S_R = \sigma_n/\sigma_F = 195/575 = 0.34\ . \tag{5}$$

The coordinates of the point in the FAD are (0.34; 0.34), so the level of fracture probability is approx. 0.35, Fig. 6.

Finally, in the case of defect 5.6 in pressure vessel 970, the stress intensity factor for a central surface crack, $2c$ = 75 mm; $2a$ = 20 mm, under hoop stress, can be calculated as:

$$K_I = Y(a,c,W)(pR/t)\sqrt{\pi a} = 1.21(174)\sqrt{10\pi} = = 1182 \text{ MPa}\sqrt{\text{mm}} \tag{6}$$

where: $Y(a/W)$ = 1.21 for $a/W$ = 20/50 = 0.4; $a/c$ = 20/75 = 0.27. Since $K_I/K_{Ic}$ = 0.75, there is no danger of brittle fracture. The ratio between critical cross-section stress and critical stress in this case is:

$$S_R = \sigma_n/\sigma_F = 174 \times 1.67/575 = 0.49 \tag{7}$$

Coordinates of the point in the FAD are (0.49; 0.74), so the level of fracture probability is approx. 0.77, Fig. 6. One should notice that results presented here for vessel 970 are obtained taking into account the length of defect 5.6 ($2c$ = 75 mm).

## RISK MATRIX

Risk analysis represents a new approach to solving the problem of structural integrity assessment. Risk management within the business process is a challenge for every modern company, especially in industrial processes where certain risks can be at an extremely high level, and their consequences are significant. New risk-based decision-making procedures are an effective operational tool if used properly, /17/. The risk assessment of the integrity and life of the pressure vessel is performed by applying a new concept based on the application of a risk matrix to assess the level of risk according to the probability and consequences of failure. The primary focus here is the assessment of consequences, as shown in literature, /16, 17/.

The risk matrix can now be obtained in the usual way, as shown in /18, 19/, for the case of pressure vessels shown in Figs. 1 and 2. The risk matrix is given in Table 1, indicating medium level risk for PV 976 and high level risk for pressure vessel 977, which was the reason for repair of defect 2.5, and special solution for PV 970.

Table 1. Risk matrix for pressure vessels 977 and 976.

| | | Consequence category | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 very low | 2 low | 3 medium | 4 high | 5 very high | **Risk level** |
| Probability category | ≤0.2 very low | | | | | | **Very low** |
| | 0.2-0.4 low | | | | | **Defect 1.1** | **Low** |
| | 0.4-0.6 medium | | | | | | **Medium** |
| | 0.6-0.8 high | | | | | **Defects 1.6, 2.5, 5.6** | **High** |
| | 0.8-1.0 very high | | | | | | **Very high** |

## CONCLUSIONS

Based on reported defects and their effects on structural integrity and risk assessment, the following can be concluded about analysed defects:

Defects 1.6 and 2.5, vessel 977, with very high risk level, indicated a need to remove the defect by repair welding, especially knowing that residual stresses are not taken into account.

Defect 5.6, vessel 970, with very high risk level, indicated a need to provide a special solution for PV 970, since the repair welding was not an option for the central, internal crack.

Defects 1.1, vessel 976, with low risk level, indicating only the need for further monitoring by NDT.

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## REFERENCES

1. Jeremić, L., Đorđević, B., Šapić, I., et al. (2020), *Manufacturing and integrity of ammonia storage tanks*, Struct. Integ. and Life, 20(2): 123-129.
2. Jeremić, L., Sedmak, A., Petrovski, B., et al. (2019), *Structural integrity assessment of welded pipeline designed with reduced safety*, Tech. Gazette, 27(5): 1461-1466. doi: 10.17559/TV-20200413142538
3. Martić, I., Sedmak, A., Mitrović, N., et al. (2019), *Effect of over-pressure on pipeline structural integrity*, Tech. Gazette, 26(3): 852-855. doi: 10.17559/TV20180708213323
4. EN PED 14/68 - Pressure Equipment Directive
5. SRPS EN 13445: 2015 - Posude pod pritiskom
6. Kirin, S., Jeremić, L., Sedmak, A., et al. (2020), *Risk-based analysis of RHPP penstock structural integrity*, Frattura ed Integrita Strutt. 14(53): 345-352, doi: 10.3221/IGF-ESIS.53.27
7. Sedmak, A., Kirin, S., Martić, I., et al. (2020), *Structural integrity and life assessment of pressure vessels - risk based approach*, in: Proc. Int. Conf. of Experimental and Numerical Investigations and New Technologies, CNNTech 2020: 274-293. doi: 10.1007/978-3-030-58362-0_16
8. EN ISO 5817: Welding - Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) - Quality levels for imperfections (ISO 5817: 2014)
9. EN ISO 23278: 2015: Non-destructive testing of welds - Magnetic testing - Acceptance levels (ISO 23277: 2015)
10. EN ISO 11666: 2012: Non-destructive testing of welds - Ultrasonic testing - Acceptance levels
11. Kirić, M. (2006), *Ultrasonic testing with C-Scan - The application to pipelines and welded joints*, Struct. Integ. and Life, 6(1-2): 41-52.
12. Jovičić, R., Algool, M., Tatić, U., et al. (2014), *Storage tank integrity assessment after the removal of weld defects*, Struct. Integ. and Life, 14(1): 35-38.
13. Jeremić, L., *Assessment of the integrity of welded structures designed with reduced safety lever* (in Serbian), doctoral thesis, University of Belgrade, 2020.
14. Gerić, K., *Pojava i rast prslina u zavarenim spojevima čelika povišene čvrstoće (Crack appearance and growth in welded joints of high strength steel* - in Serbian*)*, doctoral thesis, University of Belgrade, Faculty of Technology and Metallurgy, Belgrade, 1997.
15. API 581 The standard for quantitative risk based inspection, American Petroleum Institute, 2010
16. Đorđević, P., Kirin, S., Sedmak, A., Džindo, E. (2011), *Risk analysis in structural integrity*, Struct. Integ. and Life, 11(2): 135-138.
17. Golubović, T., Sedmak, A., Spasojević Brkić, V., et al. (2018), *Novel risk based assessment of pressure vessels integrity*, Tech. Gazette, 25(3): 803-807. doi: 10.17559/TV-20170829144636
18. Vučetić, I., Kirin, S., Sedmak, A., et al. (2019), *Risk management of a hydro power plant - fracture mechanics approach*, Tech. Gazette, 26(2): 428-432. doi: 10.17559/TV-2018061810 2041
19. Vučetić, I., Kirin, S., Vučetić, T., et al. (2018), *Risk analysis in the case of air storage tank failure at RHPP Bajina Bašta*, (in Serbian), Struct. Integ. and Life, 18(1): 3-6.