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# CREEP-FATIGUE INTERACTION ASSESSMENT OF 16Mo5 STEEL

# PROCENA INTERAKCIJE PUZANJE-ZAMOR ČELIKA 16Mo5

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- bimetal shell lining
- reliability
- remnant life assessment expert system

**Ključne reči**
- komora za koksovanje
- bimetalna ljuska oplate
- pouzdanost
- ekspertni sistem za procenu preostalog veka

*Abstract*

*The paper presents an analysis of reliability and remaining life assessment of the reactor (coxing box) from a petrochemical plant, after the failure of the welded joint of the plated shell made out of W1.5423 (16Mo5) steel, 25 mm thickness, plated with W1.4002 stainless steel. The reactor failure has been associated with initial flaws from the welding process, which have accelerated remaining life exhaustion. The assessment was made in two steps. The VII section of ASME code specifications and iRiS-Thermo expert system for preliminary remaining life assessment was used. Concomitantly, experimental creep and thermal fatigue testing was performed. The programme results have defined creep and thermal fatigue exhaustion and the remaining life due to creep-fatigue interaction, under the condition of safety exploitation. The possibility to use an extra 40,000 hours of rehabilitated reactor under the safety condition of normal parameters was emphasized.*

*Izvod*

*Rad prikazuje procenu pouzdanosti i preostalog radnog veka reaktora (komore za koksovanje) petrohemijske instalacije, nakon otkaza na zavarenom spoju na pločastom zidu konstrukcije od čelika W1.5423 (16Mo5), debljine 25 mm, sa oplatom od nerđajućeg čelika W1.4002. Otkaz reaktora u vezi je sa inicijalnim greškama iz procesa zavarivanja, koje su skratile preostali radni vek. Procena je urađena u dva koraka. Primenjen je dokument VII glava ASME specifikacije propisa kao i iRiS-Thermo ekspertni sistem za preliminarnu procenu preostalog veka. Istovremeno, urađena su eksperimentalna ispitivanja puzanja i termičkog zamora. Rezultati programa su definisali nivo istrošenosti usled puzanja i termičkog zamora kao i preostali vek pri istovremenom dejstvu puzanja i zamora, u uslovima sigurne eksploatacije. Iskazana je i mogućnost dodatnih 40.000 časova rada revitalizovanog reaktora pod sigurnosnim uslovima normalnih parametara.*

## INTRODUCTION

The evaluation of the reliability and remaining life of the reactor (coxing box) in a petrochemical plant are very important and always actual problem because occasional failures seem to be inevitable. In this paper the failure of pressure vessel (the reactor) in a petrochemical plant is analysed. The failure affected the welded joint of the lining (shell plated with alloyed steel). The resistance and functional characteristics evaluations were made in two steps. The basic dimensional and technical characteristics of the coxing box are presented in Table 1, whereas its shape and geometrical dimensions are presented in Fig. 1.

Table 1. The dimensional and technical characteristics of reactor.
Tabela 1. Dimenzije i tehničke karakteristike reaktora.

| Nr.crt | Characteristics | Symbol | UM | Value |
|---|---|---|---|---|
| 1 | Interior diameter | D | mm | 6200 |
| 2 | The calculus length of the cylindrical element | L | mm | 18500 |
| 3 | Nominal volume | V | $m^3$ | 697 |
| 4 | Thickness projected (W 1.5423 steel) | Sp | mm | 25 |
| 5 | Addition for exploitation conditions (made out of X6CrAl13, W1.4002 steel) | C1 | mm | 3 |
| 6 | Maximum admissible pressure | PS | MPa | 0.5 |
| 7 | Work pressure | PL | MPa | 0.4 |
| 8 | Hydraulic test pressure | $P_{test}$ | MPa | 1.45 |
| 9 | Admissible temperature/ maxim admissible | $T_{Smin}/T_{Smax}$ | K | +288/ +758 |
| 10 | Minimum temperature / maximum for work | $T_{min}$ / $T_{max}$ | K | +303/ +748 |
| 11 | The numbers of functional cycle | | h | 66,000 |
| 12 | Thermal isolation, min | | mm | 250/200 |

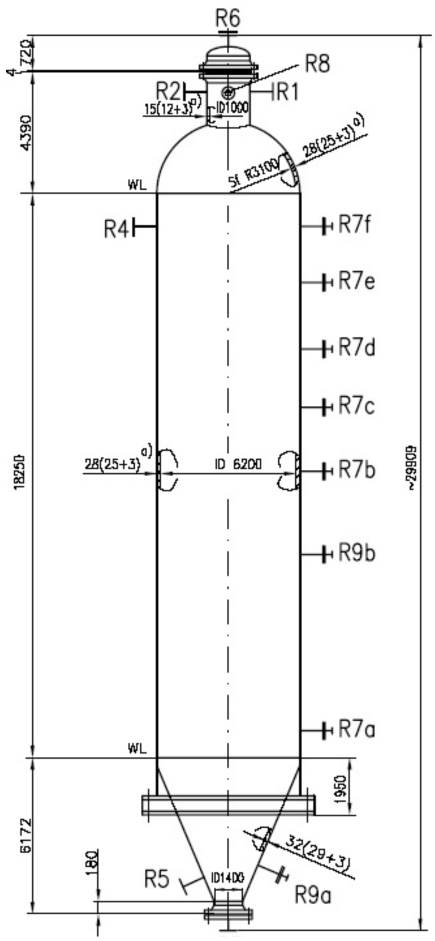



Figure 1. The shape and geometrical dimensions of coxing box.
Slika 1. Oblik i dimenzije komore za koksovanje.

## MATERIALS AND METHODS

Chemical composition and mechanical characteristics of 16Mo5 and X6CrAl13 steels are given in Tables 2 and 3.

Experimental programmes were done using installations, designed and made in ISIM (Fig. 2), /1, 2/. The control programme, signal acquisition for temperature, force and strain, as well as the data processing programme were produced by the Automation Department of the Politehnica University Timişoara, according to ISIM's specification.

The installation is endowed with five interchangeable elastic elements (arcs) with different rigidity in the range 60–300 kN/mm, which provides five imposed levels of the total (or plastic) strain amplitude for the same size of the testing specimen. The installation runs by cyclic loading of a tubular cylindrical specimen or with the calibrated cylindrical section (Fig. 3) with compression mechanical stresses in the heating semi-cycle and tensile in the cooling one. The size on the working section of the specimen is $\phi 13/\phi 12$ and the fixing ends are M16.

A diametral transducer was also developed at ISIM for the thermal fatigue testing and non-isothermal low-cycle fatigue. The elements in contact with the heated specimen were made out of quartz bars and an inductive moving transducer, connected with an amplification bridge was used as a sensitive element. The diametric transducers are used to transform this in axial strain as recommended in the ASTM E 606 /7/. The procedures from /5/ were also used. The advantage is that it takes into account the temperature variation of the elasticity modulus ($E$) and of the Poisson coefficient ($\nu$).

Table 2. The chemical composition (%) (of liquid steel)
Tabela 2. Hemijski sastav (%) (rastopljenog čelika)

| Steel grade | C | Mn | Si | P | S | Cr | Mo | Al |
|---|---|---|---|---|---|---|---|---|
| 16Mo5 (STAS 2883/3-88) (W 1.5423) | 0.12…0.20 | 0.50…0.80 | 0.15…0.30 | Max. 0.035 | Max. 0.035 | – | 0.45…0.65 | 0.010…0.030 |
| X6CrAl13 SR EN 10088-2:2005 (W1.4002) | Max. 0.080 | Max. 1.0 | Max. 1.0 | Max. 0.040 | Max. 0.015 | 12.00…14.00 | – | 0.10…0.30 |

Table 3. The mechanical characteristics of used steel.
Tabela 3. Mehaničke karakteristike upotrebljenog čelika.

| Steel grade | Tensile strength $R_{m/293}$ (N/mm$^2$) | Yield strength $R_e$, $R_{eH/293}$ or $R_{p0,2}$ (N/mm$^2$) | Yield strength $R_{p0,2/T}$ (N/mm$^2$) | Yield strength $R_{p0,2/T}$ (N/mm$^2$) | Fracture elongation $A_5$ (%) | Charpy energy to 293 K KV (J) |
|---|---|---|---|---|---|---|
| 16Mo5 (STAS 2883 /3-88) (W 1.5423) | 440–540 | Min. 265 | Min. 157 at 723 K | Min. 137 at 773 K | 18 | 31 |
| X6CrAl13 SR EN 10088-2:2005 (W1.4002) | 400–600 | Min. 210 | Min. 230 at 293 K | Min. 190 at 673 K | Min. 17 | Unspecified |

Figure 2. The thermal fatigue testing ISIM's installation.
Slika 2. ISIM instalacija za ispitivanje termičkog zamora.

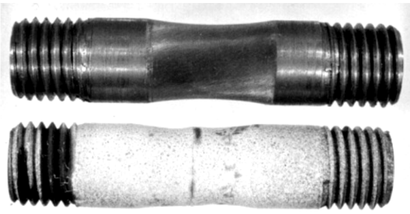


Figure 3. Testing specimen for the thermal fatigue initial state and cracked after testing.
Slika 3. Epruveta za ispitivanje termičkog zamora u početnom stanju i u stanju posle ispitivanja.

The installation is designed to work with two independent testing groups. Each testing group receives the command for the heating semi-cycle by the software from the PC by means of a CAN channel of the interface to the power adjusting system by thyristors of the specimen heating element.

The heating is achieved through radiation from a halogen lamp. Each testing group receives the command for the cooling semi-cycle through the software of the computer. It is made by means of some CAN channels of the interface to the control system of a pneumatic distributor coil, which allows the air access (or the access of an inert gas) on the calibrated section of the testing specimen. The command to hold the time at $T_{max}$ and $T_{min}$ is given through software with the corresponding adjusting of the heating element. As a consequence of the cyclic variation of temperature and of the partial blocking of the ends of the testing specimen, stresses and deformation appear, which exceed the material yield limit in the elastic-plastic field.

## RESULTS AND DISCUSSIONS

### *The result of the inspection after the failure*

After 60.000 hours of exploitation, failure occurred. The welding defects, amplified by the hydraulic pressure test, lead to propagation of initial cracks to macroscopic dimensions. The result was the interruption of operation. Defects were detected by inspection (Figs. 4 and 5).


Figure 4. Coupon 2 – exterior view, with crack.
Slika 4. Presek 2 – spoljni izgled, sa prslinom.

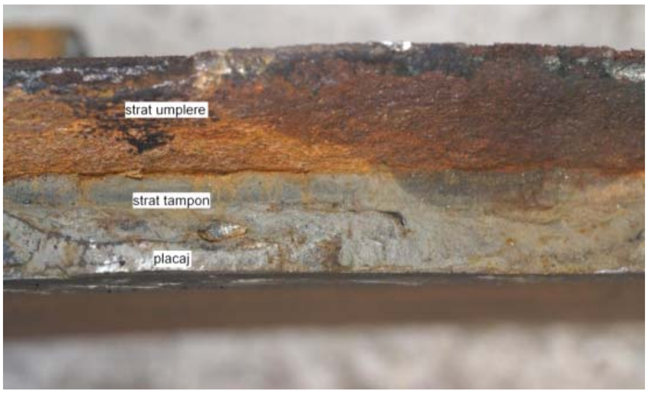



Figure 5. Crack path through weld (ring 2 details, coupon 5).
Slika 5. Putanja prsline kroz šav (detalj na prstenu 2, presek 5).

The programme of the investigation has concentrated on mostly product zones, affected and unaffected by failure.

The actual strength characteristics at normal and exploitation temperature are in conformity to the reference specifications. Steel identified by chemical analyses corresponds to the steel grade indicated by the designer.

Inspected materials presented no significant structural degradation due to exploitation. The toughness and technological tests of the ring material indicated that this material has aged. The aged state is explained by the following characteristics:

– high value of the reported $R_{p0,2}/R_m$ of the base material (16Mo5 steel), in both sampling directions,
– low toughness of the material which is on the acceptability limit in perpendicular direction to the welding,
– high value, over 59%, of the sensibility to aging coefficient.

For a complete characterisation of the base material, 16Mo5 steel, using the experimental quantitative data, long duration creep tests and thermal fatigue tests were done.

The actual metallurgical state of ring materials 2 and 3 did not vary significantly; these result from the structure and mechanical characteristics obtained by short duration tests. The aging sensibility is higher for ring 3.

From supplementary macroscopic examinations, the area presenting cracks was identified as damaged, thus imposing the repair welding between the rings. In the cracking and fracture zone, the tampon layer is in contact with the working medium and it is unprotected to a charge welding compatible with the plate.

The bend test of the welded joint with the plate on the tense fibre shows a low capacity to cold deformation. This can be another complementary cause of the cracks to initiate in the passing zone between the plate and the welding to the plate. The high thickness of the tampon layer characterised by hardness, high mechanical resistance and with the fragile constituents, leads to the propagation of the initial cracks in the corrosion protective layer.

*The remaining life assessment and creep-fatigue analysis – the final creep data*

The results extrapolated to creep with the iRiS-Creep expert system are presented in Fig. 6.

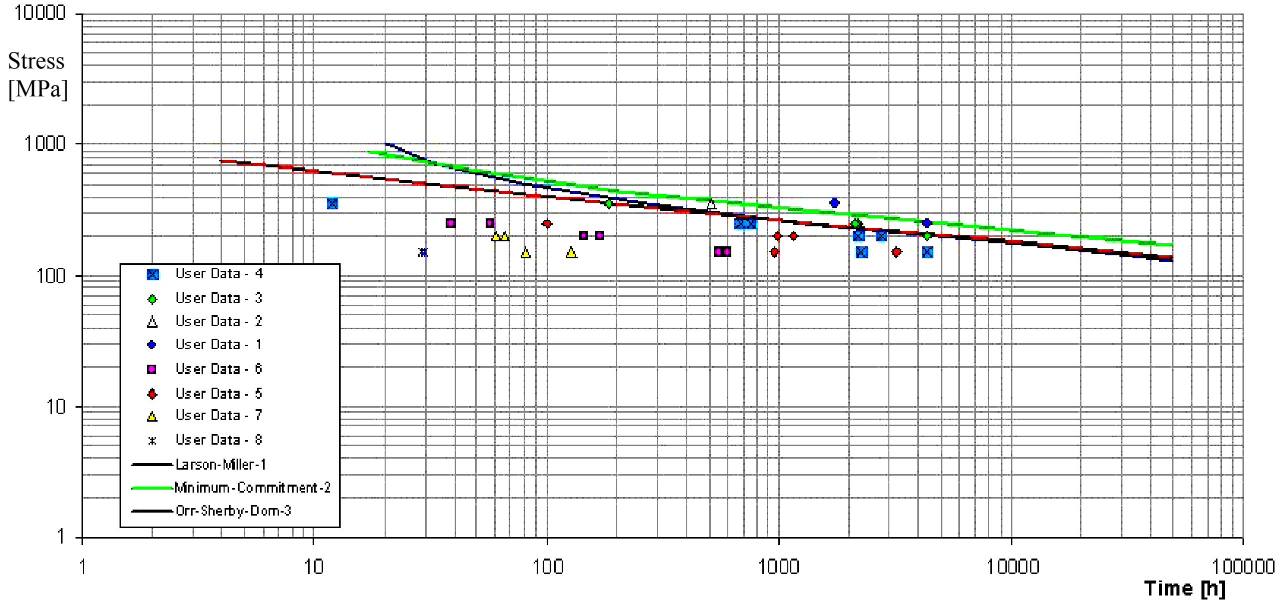



Figure 6. The final creep tests with the extrapolation at 485°C/782 K.
Slika 6. Završna ispitivanja puzanjem sa ekstrapolacijom na 485°C/782 K.

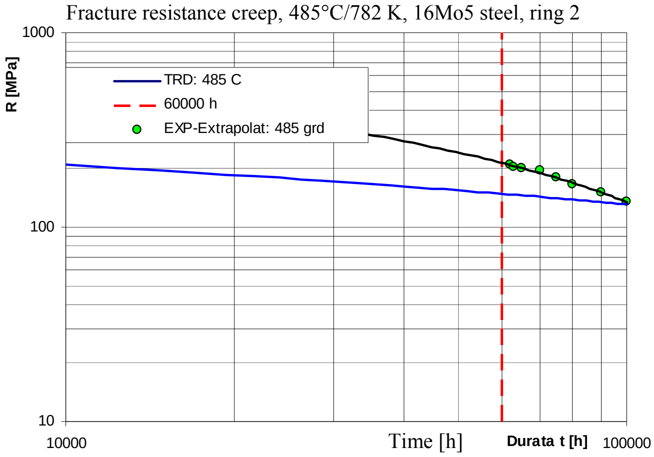



Figure 7. The creep results for ring 2.
Slika 7. Rezultati puzanja za prsten 2.

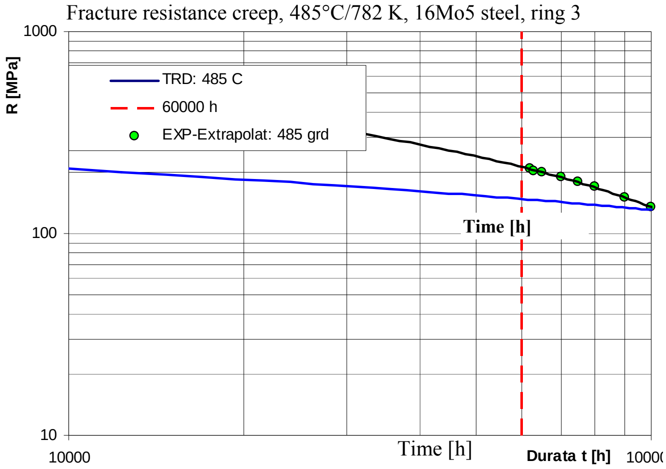


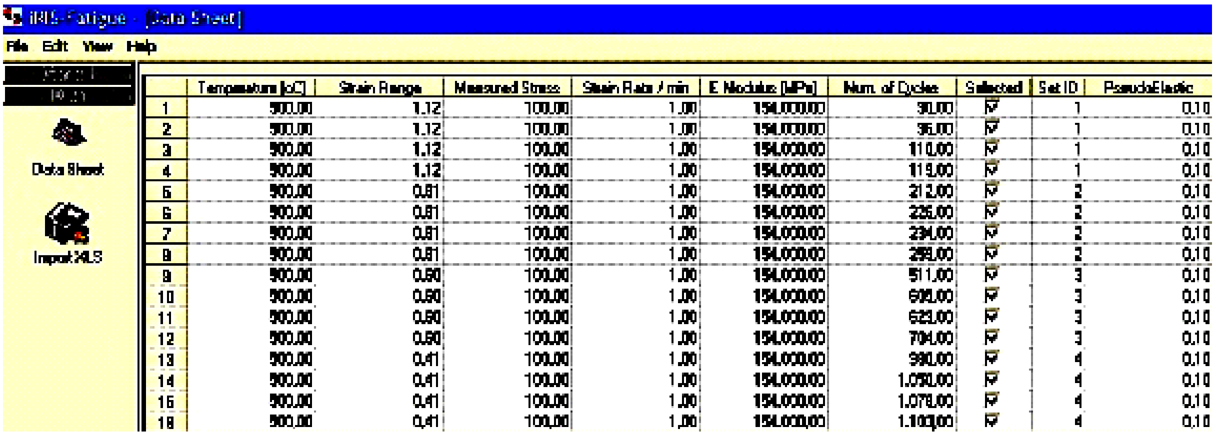

Figure 8. The creep results for ring 3.
Slika 8. Rezultati puzanja za prsten 3.

The conclusions of the remaining life – the final creep data – step 3, are presented in comparison with the TRD curves at 485°C/782 K. The creep fracture curves are experimentally determined on 34 samples from the reactor (rings 2 and 3) (Figs. 7 and 8). The evaluations present the exploitation durations which are less than 60 000 hours.

*Evaluation of remaining life and creep-fatigue analysis*

In research runs of thermal fatigue tests in the regime 333 → 773 K on 16 samples and results introduced in the module iRiS-Fatigue of the expert system are presented in Fig. 9. Tests were made on the IIOT-2 installation designed and produced by ISIM Timisoara, /1, 2/, respecting the requirements of the test standard ASTM E606 and of statistic calculation /6, 7, 8/. In Fig. 10, results from the expert system for the projection curve determination TRD 301 method, are presented.

The life remaining assessment was obtained by using the iRiS expert system. For remaining life, in respect, creep and fatigue exhaustion, the modules of the expert system similar to the step 1 were used.




| | Temperature [oC] | Strain Range | Measured Stress | Strain Rate / min | E Modulus [MPa] | Num. of Cycles | Selected | Set ID | PseudoElastic |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 500,00 | 1,12 | 100,00 | 1,00 | 154.000,00 | 90,00 | ☑ | 1 | 0,10 |
| 2 | 500,00 | 1,12 | 100,00 | 1,00 | 154.000,00 | 96,00 | ☑ | 1 | 0,10 |
| 3 | 500,00 | 1,12 | 100,00 | 1,00 | 154.000,00 | 110,00 | ☑ | 1 | 0,10 |
| 4 | 500,00 | 1,12 | 100,00 | 1,00 | 154.000,00 | 119,00 | ☑ | 1 | 0,10 |
| 5 | 500,00 | 0,81 | 100,00 | 1,00 | 154.000,00 | 212,00 | ☑ | 2 | 0,10 |
| 6 | 500,00 | 0,81 | 100,00 | 1,00 | 154.000,00 | 226,00 | ☑ | 2 | 0,10 |
| 7 | 500,00 | 0,81 | 100,00 | 1,00 | 154.000,00 | 234,00 | ☑ | 2 | 0,10 |
| 8 | 500,00 | 0,81 | 100,00 | 1,00 | 154.000,00 | 259,00 | ☑ | 2 | 0,10 |
| 9 | 500,00 | 0,60 | 100,00 | 1,00 | 154.000,00 | 511,00 | ☑ | 3 | 0,10 |
| 10 | 500,00 | 0,60 | 100,00 | 1,00 | 154.000,00 | 606,00 | ☑ | 3 | 0,10 |
| 11 | 500,00 | 0,60 | 100,00 | 1,00 | 154.000,00 | 623,00 | ☑ | 3 | 0,10 |
| 12 | 500,00 | 0,60 | 100,00 | 1,00 | 154.000,00 | 704,00 | ☑ | 3 | 0,10 |
| 13 | 500,00 | 0,41 | 100,00 | 1,00 | 154.000,00 | 990,00 | ☑ | 4 | 0,10 |
| 14 | 500,00 | 0,41 | 100,00 | 1,00 | 154.000,00 | 1.050,00 | ☑ | 4 | 0,10 |
| 15 | 500,00 | 0,41 | 100,00 | 1,00 | 154.000,00 | 1.078,00 | ☑ | 4 | 0,10 |
| 16 | 500,00 | 0,41 | 100,00 | 1,00 | 154.000,00 | 1.100,00 | ☑ | 4 | 0,10 |

Figure 9. Thermal fatigue results.
Slika 9. Rezultati termičkog zamora.

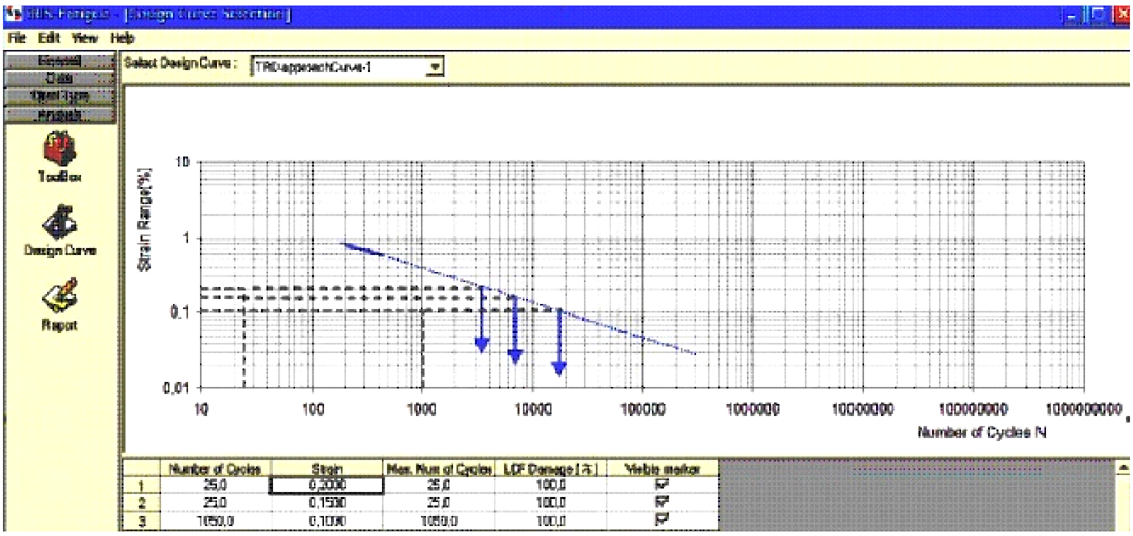



Figure 10. The projection curve to thermal fatigue from the thermal fatigue tests, according to TRD 301 method.
Slika 10. Projektna kriva za termički zamor na osnovu ispitivanja termičkog zamora, po metodi TRD 301.

Remaining life assessment /3, 4/ according to the iRiS Power expert system was realised using the analytical relation in order to check the loading capacity of the under-pressure recipient (ASME Code Selection VIII):

$$t_{min} = P \cdot R / (S \cdot E - 0.6 \cdot P) \quad (1)$$

where: $t$ is the minimum thickness (25 mm); P – interior pressure (0.5 MPa); $R$ – minimum interior radius (3100 mm); $E$–weld efficiency (1 according to ASME Code Section VIII, p. 108); $S$ – maximum allowed tensile stress (62.3 MPa).

The maximum strains are less than 0.2% from yield strength and the allowed calculated tensile stress ($S$ = 62.3 N/mm$^2$) does not exceed the fatigue limit 213 N/mm$^2$, determined from data presented in phase 3 (preliminary).

Results of the remaining life assessment from creep tests are presented in Figs. 11 and 12, in comparison to the TRD curves at 485°C/782 K, of fracture resistance creep curves determined experimentally on 27 samples from the reactor. The evaluations allude to the exploitation durations which are less than 60 000 hours.

Preliminary conditions for remaining life assessment are:

- Results obtained are for steel 16Mo5 with samples for rings 2 and 3 from the coxing box and without considering material flaws. In the evaluations the influence of lining, welding, and of the flaws were not considered.
- Actual creep characteristics to exploitation temperature (465°C/758 K) are according to those from the reference after exploitation duration of 60,000 hours. It is considered that the degradation by thermal fatigue is reduced, the number of remaining cycles resulted from the comparison of the projection curves for the marker 3 is maximum 1000 cycles (start-stop).

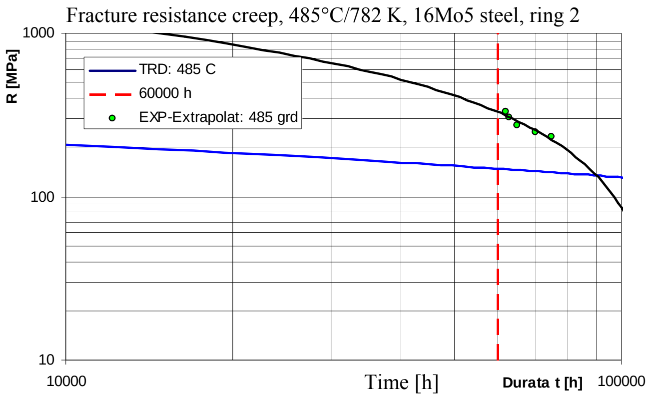



Figure 11. Creep results for ring 2.
Slika 11. Rezultati puzanja za prsten 2.

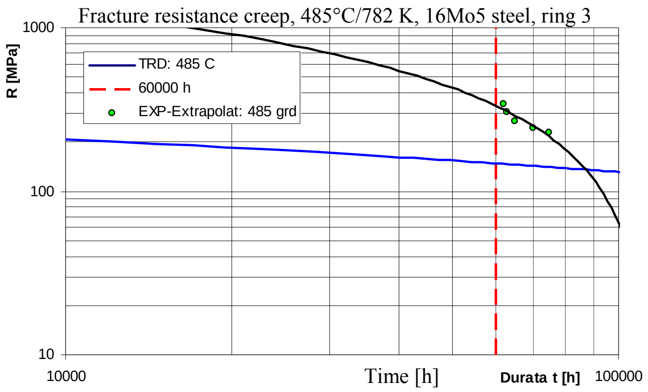



Figure 12. The creep results for the ring 3.
Slika 12. Rezultati puzanja za prsten 3.

- The results for this step are conservative. By analysing creep-fatigue behaviour on the obtained results it is estimated that the reactor material 16Mo5 can be utilised under safety conditions at least 25,000 hours with an effective maximum tensile stress 62.3 MPa.

## CONCLUSIONS

The experience in ISIM, gathered in previous researches /10/ enabled to perform this complex and requiring task of creep-fatigue interaction assessment.

The obtained results are for the 16Mo5 steel, rings 2 and 3, from the coxing box without the possible material flaws undetected at exterior inspections. In the evaluations, the influence of lining, welding, and flaws were not considered.

Actual creep characteristics to exploitation temperature (465°C/758 K) are according to those from the reference after exploitation duration of 60,000 hours.

It is considered that the degradation by thermal fatigue is reduced, the number of remaining cycles resulted from the comparison of the projection curves for the marker 3 is maximum 1000 cycles (start-stop).

Analysing the creep results, Figs. 11 and 12, it is evident that the inspected material has creep characteristics superior to the TRD projection curve for other 40 000 exploitation hours in respect to the designed condition.

Analysing creep-fatigue behaviour, based on the obtained results, it is estimated that the reactor material 16Mo5 can be used under safety conditions at least 40 000 hours with an effective maximum tensile stress 62.3 $N/mm^2$.

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