

INVESTIGATION OF THE THERMAL AGEING EFFECTS ON WWER-1000 MATERIALS FOR UP TO 60 YEARS OF OPERATION

ISTRAŽIVANJE UTICAJA TERMIČKOG STARENJA NA WWER-1000 MATERIJALE DO 60 GODINA EKSPLOATACIJE

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Keywords

- thermal ageing
- long term operation of nuclear power plant
- transition temperature
- small punch test

Abstract

Ensuring the reliable performance of Water-Water Energetic Reactors (WWER) and justifying their service life extension to 60 years and beyond requires a comprehensive understanding of thermal ageing in primary circuit materials. This study investigates the degradation of mechanical properties selected to represent both austenitic and ferritic steels used in safety-critical components, specifically 08Ch18N10T after 28 years of operation, 38KhN3MFA after 30 years, and unirradiated 10GN2MFA. To simulate a 60-year service life, accelerated thermal ageing is performed at 450 °C using the Arrhenius equation for duration calibration. The experimental programme uses conventional tensile and instrumented Charpy V-notch testing alongside miniature Small Punch Testing (SPT) and hardness measurements. To optimise material use, a specialised alignment and welding device is developed and manufactured for the Charpy specimen, followed by successful validation and approbation of the process. This approach ensures that the mechanical properties of specimens remain unaffected by the welding heat, allowing for an accurate assessment of impact toughness.

INTRODUCTION

In many cases, due to the impossibility of reproducing the conditions of actual equipment operation in terms of compliance, for example, time limits or the action of aggressive environments, an alternative approach using artificial ageing is used. Artificial ageing is the process of artificially reproducing the effects of material ageing in laboratory conditions. This process may include the use of chambers for simulating the environment, installations for testing atmospheric influences, etc. /1/.

The main purpose of artificial ageing is to study changes in the structure and mechanical properties of a material as a result of thermal exposure. Since under real operating conditions, a structural element is subjected to various influences, such as temperature, mechanical loads, radiation and aggressive environments, artificial ageing allows the influence of

Ključne reči

- termičko starenje
- dugotrajni rad nuklearne elektrane
- prelazna temperatura
- minijaturno ispitivanje probijanjem

Izvod

Obezbeđenje pouzdanog rada energetskih reaktora hladnih vodom (WWER) i opravdavanje produženja njihovog radnog veka na 60 i više godina zahteva sveobuhvatno razumevanje termičkog starenja materijala primarnog kola. U radu se ispituje degradacija odabranih mehaničkih osobina čelika, koje se odnose na austenitne i na feritne čelike koji se koriste u bezbednosno kritičnim komponentama, posebno 08Ch18N10T posle 28 godina rada, 38KhN3MFA posle 30 godina, i za neozračeni 10GN2MFA. Za simulaciju radnog veka od 60 godina, izvedeno je ubrzano termičko starenje na 450 °C primenom Arenijusove jednačine za kalibraciju roka trajanja. Eksperimentalni program obuhvata konvencionalno ispitivanje zatezanjem i instrumentirano ispitivanje sa Šarpi V-zarezom, uz minijaturno ispitivanje probijanjem (SPT) i merenje tvrdoće. Radi optimizacije upotrebljenog materijala, razvijen je i proizveden specijalan uređaj za centriranje i zavarivanje, za Šarpi epruvete, nakon čega je usledila uspešna provera i odobravanje postupka. Ovaj pristup osigurava nepromenljivost mehanička osobina uzoraka usled uticaja toplote zavarivanja, čime se omogućava tačna procena udarne žilavosti.

each factor to be considered separately, if that factor is the subject of the study.

The main parameters of artificial temperature ageing are:

- *Ageing temperature.* The temperature range for artificial ageing varies between 250 and 550 °C, as this is the range in which the processes of microstructural change in steels are most active. The choice of ageing temperature depends on the type of steel and its behaviour at elevated temperatures.
- *Duration of ageing.* Depending on the research task, the duration of ageing can vary from several hundred to several thousand hours. The typical time interval for ageing steel in laboratory conditions is from 100 to 5,000 hours. This time is equivalent to 30-40 years of operation in real-world conditions.
- *Environment.* An important parameter is the environment in which the material ages. For some types of materials,

additional factors such as atmospheric humidity or vacuum may be important.

- *Cooling mode.* At the end of the temperature ageing process, a specific cooling mode may be applied, which also affects the final properties of the material.

A special case of artificial ageing is accelerated ageing of materials. Accelerated ageing is becoming increasingly important because it provides test results much faster, saving time and resources. The basic concept of accelerated ageing is to ensure a faster change in material properties over time. This is achieved by applying several requirements, which include: eliminating rest periods, ignoring lower load levels, and increasing the level of the main influencing factor which is equivalent to reducing the duration of its action.

In thermally accelerated ageing, acceleration is achieved by increasing the temperature. In this process, sufficient energy is introduced to activate the ageing process, which is not relevant in real operating conditions. Therefore, it is critically important that the accelerated ageing process be thoroughly tested, /1/.

Accelerated artificial temperature ageing is a method widely used to simulate long-term changes in structural materials used in nuclear reactors. This method makes it possible to simulate long-term thermal ageing processes in materials that occur over decades by significantly accelerating thermal processes over a relatively short period of time in laboratory conditions. This allows the change in material properties due to ageing to be assessed and its behaviour under operating conditions to be predicted.

Extensive research has been conducted globally to model these degradation processes. Currently, there are at least three well-established models for predicting changes in J-R curves as a result of thermal ageing: the Argonne /8/, French/EDF /5, 6/, and Japanese /7/. Accelerated artificial ageing is carried out at elevated temperatures (usually between 400 °C and 550 °C) which exceed the operating temperatures of reactor installations. The temperature and duration of exposure of the material to these conditions are usually determined depending on the specifics of the material under study and the purpose of the experiment.

According to /9/ and other national and international standards, the standard ageing method for nuclear steels is ageing at 450 °C for 100 to 5000 hours. This approach allows simulating processes that occur over decades in real conditions. The paper /4/ presents the results of studies on accelerated artificial temperature ageing of reactor steels at temperatures of 400 °C and 450 °C which simulate operating conditions lasting 30,000 and 20,000 hours, respectively, for BM, WM, and HAZ materials.

Mechanical tests are used to analyse the properties of the material after the artificial ageing process. This is the most informative and direct method of assessing the effect of ageing on changes in mechanical characteristics of the material.

Analysis using this method is based on experimental research methods in the mechanics of deformable solids /2/. During its application, various mechanical tests are carried out on appropriate certified experimental equipment in accordance with relevant standards. They usually include tests

for static tensile strength, impact toughness, static or cyclic crack resistance, as well as hardness of materials in their initial state, and after thermal ageing. The result of such studies is an assessment of changes in the basic mechanical properties and crack resistance characteristics of the steels under study due to the effects of thermal ageing.

The main objective of this study is to experimentally evaluate the influence of thermal ageing on the mechanical and fracture properties of key structural steels used in WWER primary circuit components, and to assess the implications for 60 years of reactor service life. The materials investigated include:

- main circulation piping steel (10GN2MFA) in its as-received (non-operated) condition;
- pressuriser surge line (08Ch18N10T) after 28 years of actual operation in a WWER-440 Unit;
- reactor flange fastening elements (38KhN3MFA) after 30 years of actual operation in a WWER-1000 unit.

These components are selected due to their high operational relevance, exposure to long-term thermal loading, and their role in ensuring NPP safety. The research seeks to establish correlations between time of thermal exposure and the macroscopic mechanical behaviour of the materials.

METHODOLOGY

Material

The materials selected for testing (Fig. 1) are unirradiated 10GN2MFA in its as-received (non-operated) condition, austenitic stainless steel 08Ch18N10T after 28 years of actual operation in a WWER-440 unit and 38KhN3MFA after 30 years of actual operation in a WWER-1000 unit. Mechanical properties according to the TU and GOST are presented in Table 1.

Table 1. Mechanical properties of selected materials.

Model alloy	20 °C, not less				350 °C, not less			
	R_m , MPa	$R_{p0.2}$, MPa	A_5 , %	Z , %	R_m , MPa	$R_{p0.2}$, MPa	A_5 , %	Z , %
08Ch18N10T	490	196	38	50	353	177	25	45
38KhN3MFA	981	880	11	35	834	746	11	40
10GN2MFA	590	392	16	55	490	295	14	50

Experimental equipment

A laboratory oven is used for the artificial thermal ageing process, which ensures temperature stability within ± 4 °C.

To accelerate the thermal ageing process, the Arrhenius equation /3/ is used in the form:

$$\frac{t_1}{t_2} = \exp \left[\frac{Q}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \right], \quad (1)$$

where: t_2 is time of accelerated ageing; t_1 is required service life; Q is activation energy in 100 kJ·mol⁻¹; T_2 is temperature of accelerated ageing (450 °C); T_1 is service temperature; and R is the gas constant (8.368 J·mol⁻¹).

Based on this relationship, the equivalent duration of laboratory thermal exposure is calculated for each investigated material. The specific parameters of ageing regimes are summarised in Table 2.



Figure 1. Materials selected for testing: a) pressuriser surge line 08Ch18N10T; b) WWER-1000 - reactor flange fastening parts 38KhN3MFA; c) WWER-1000 - main circulation piping 10GN2MFA.

Table 2. Calculated thermal ageing parameters equivalent to long-term operation periods.

Model alloy	t_1 (hours)	t_2 (hours)	T_1 (°C)	T_2 (°C)
08Ch18N10T	233600	1240	276	450
38KhN3MFA	219000	252	240	450
10GN2MFA	438000	3994	290	450

The experimental programme is designed to characterise mechanical properties using a combination of conventional and miniature testing techniques: uniaxial tensile testing, Charpy V-notch impact testing, small punch testing (SPT), and hardness measurements, enabling evaluation of strength and toughness over different material scales (Fig. 2).

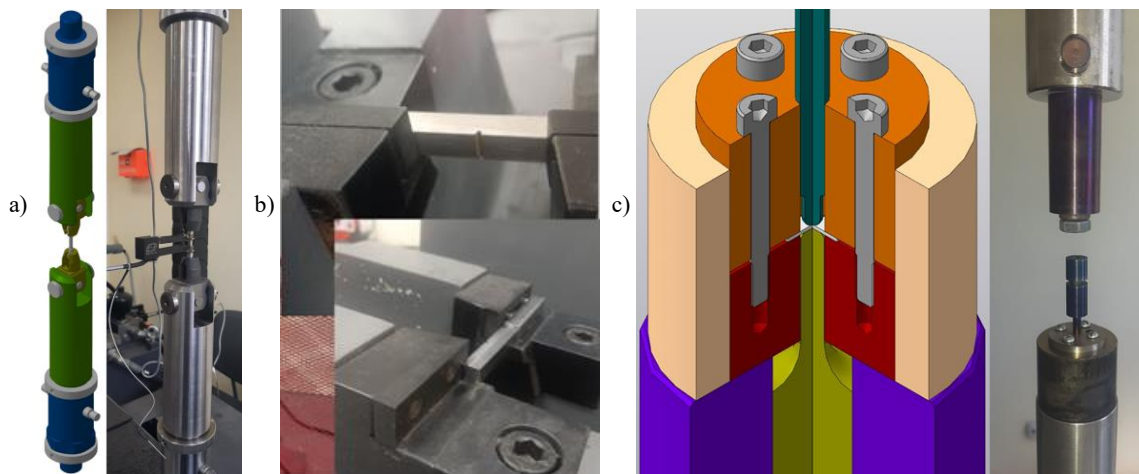


Figure 2. Types of testing: a) tensile testing; b) impact testing; c) SPT testing.

Tensile tests are performed using a servo-hydraulic universal testing machine with a maximal load capacity of 100 kN. Specimen elongation is measured using a clip-on extensometer with a gauge length of 12.5 mm. For the experimental campaign, dedicated grips are designed and manufactured (Fig. 2). The developed gripping system enables tensile testing over a wide temperature range, including both low- and high-temperature conditions.

All tensile tests are conducted at room temperature. For each material type, at least three specimens are tested to ensure the repeatability of results. Specimen geometry and

corresponding technical drawings, as well as representative specimens before and after testing, are presented in Fig. 3.

The impact toughness of the investigated materials is evaluated by means of Charpy V-notch impact testing. The experiments are carried out using an instrumented pendulum impact testing machine with a maximum impact energy of 300 J (Fig. 2). The standard Charpy specimen after the experiment with V-notch geometry is presented in Fig. 4. The area highlighted in red indicates ductile fracture (stable crack growth), while the area highlighted in green corresponds to brittle fracture (unstable cleavage).

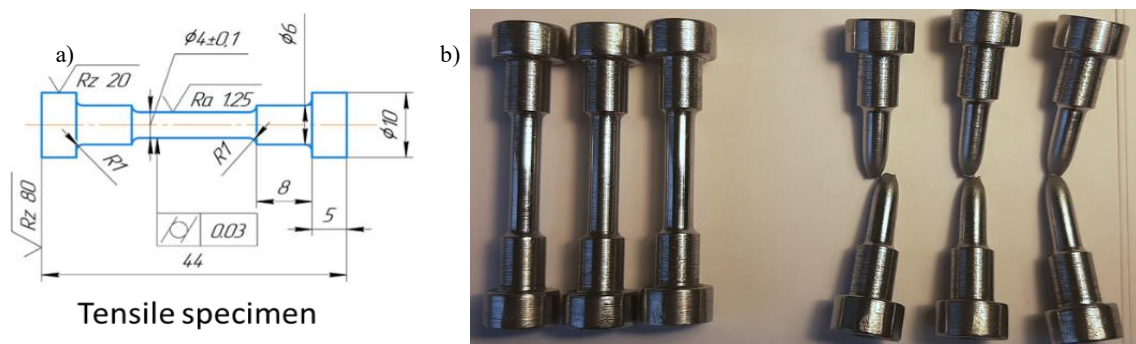


Figure 3. a) Drawing of the specimen and; b) specimens before and after the experiment.

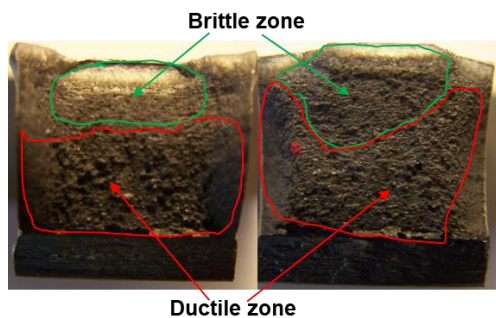


Figure 4. Charpy V-notch specimens after the experiment.

To optimise the use of limited volume of available material, a specialised technique for Charpy V-notch specimens is implemented. The alignment device is designed and manufactured specifically for the precision reconstruction of these specimens. The process involved utilising one broken specimen half (insert) and two side studs (end-pieces) made of a material with mechanical properties closely matching those of the investigated steel. Components are laser beam welded, which ensures a minimal heat-affected zone (HAZ) and prevents any thermal degradation of original properties. The alignment and welding jig, as well as specimens reconstructed from broken halves, are shown in Fig. 5.



Figure 5. Charpy V-notch specimens: a) specialised alignment and welding jig; b) specimens reconstructed from broken halves.

To ensure the integrity of the base material during the process, a comprehensive verification of the welding procedure is conducted. This includes real-time temperature monitoring to confirm that the thermal cycle does not exceed the critical limits for the investigated steels. The spatial arrangement of the thermocouples during this verification stage, used to record the temperature distribution near the insert, is presented in Fig. 6. This validation step confirms that the mechanical properties of the central part of the specimen remain unaffected by welding heat, which is essential for

accurate impact toughness assessment after long-term operation simulation.

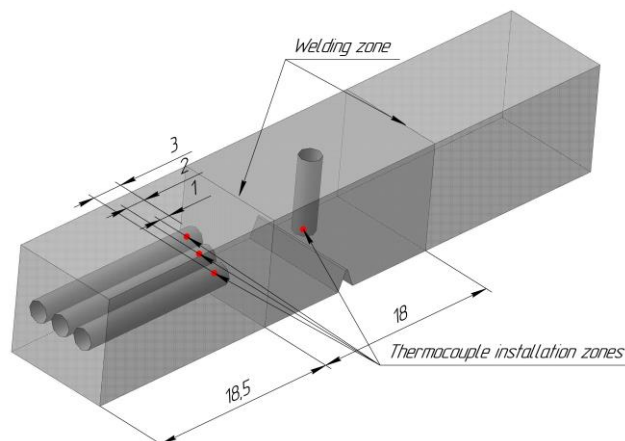


Figure 6. Schematic representation of thermocouples positioning for welding procedure verification.

Small punch tests (SPT) are performed using a dedicated experimental setup specifically developed for miniature specimen testing. Similar to tensile experiments, a specialised gripping system with adapters is designed and manufactured to ensure accurate positioning and stable fixation of the specimens during loading (Fig. 2). The testing assembly consists of upper and lower dies between which the disc-shaped specimen is rigidly clamped. A hemispherical punch is used to apply the load to the centre of the specimen, while a guide bushing ensures proper alignment of the punch and minimises lateral displacement during the test.

The experimental configuration also includes a provision for mounting an extensometer to measure the central deflection of the specimen during loading. The load-displacement curves are continuously recorded throughout the test and used for further analysis of material behaviour. Representative load-displacement diagrams before and after thermal ageing are presented in Fig. 7.

Hardness testing is performed using a TM-40 hardness tester. Prior to hardness measurements, the metal surface is carefully prepared to ensure reliable and reproducible results. The preparation procedure includes mechanical grinding and polishing in order to obtain a smooth and clean surface free from oxides and surface irregularities that could affect the measurement accuracy.

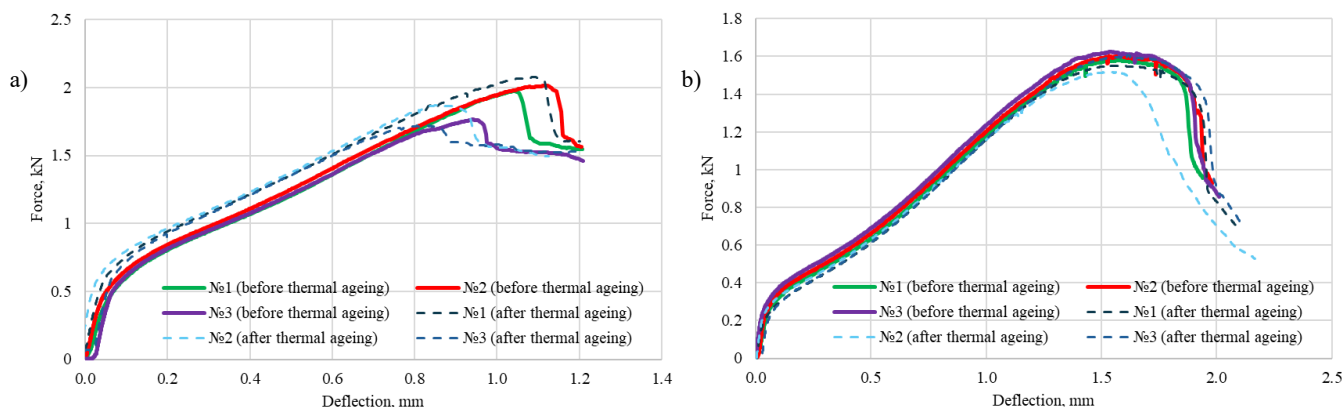


Figure 7. Representative load-displacement diagrams before and after thermal ageing: a) reactor flange fastening elements (38KhN3MFA); b) main circulation piping steel (10GN2MFA).

Hardness values are initially determined according to the Vickers scale (HV). Several measurements are carried out for each material condition to minimise experimental scatter and to obtain representative average values.

Subsequently, in accordance with /10/, the measured Vickers hardness values are converted into Brinell hardness values (HB). The conversion procedure is performed using standardised correlations specified in the above-mentioned document. Finally, based on the relationships provided in /10/, the main mechanical properties of the investigated materials are estimated from hardness values. These include ultimate tensile strength, yield strength, relative elongation, and reduction of area. The obtained results are used for a preliminary assessment of the mechanical performance of the materials and for comparison with experimental tensile data.

RESULTS AND DISCUSSION

The evaluation of thermal ageing effects on WWER-1000 materials after a simulated 60-year service life reveals distinct degradation patterns depending on the steel's microstructure and alloying. The study focuses on mechanical strength and impact toughness.

Austenitic stainless steels: pressuriser surge line

The results for the austenitic stainless steel used in the pressuriser surge line demonstrate high structural stability under thermal exposure.

- **Tensile Properties:** the mechanical properties diagrams (Fig. 8) before and after ageing show almost no deviation, indicating that yield strength and ultimate tensile strength are not significantly affected by long-term thermal treatment.
- **Impact toughness:** analysis of impact toughness results shows that thermal ageing leads only to a slight reduction in the Upper Shelf Energy (USE) (Table 3). However, these changes are minimal and do not compromise the overall fracture resistance of the material.

Ferritic steels: main circulation piping and reactor fasteners

Ferritic components, including the main circulation piping (MCP) and reactor flange fastening parts (studs and nuts), exhibit a much higher sensitivity to thermal ageing.

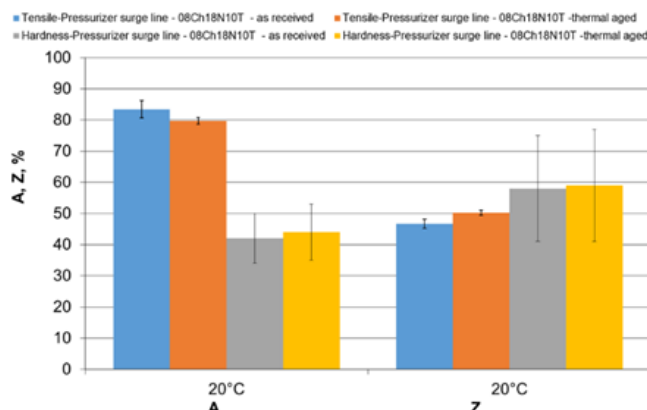


Figure 8. Results of tensile, SPT and hardness for pressuriser surge line.

Table 3. Results of Charpy impact for Pressurizer surge line - 08Ch18N10T.

State	Test temp. [°C]	Impact energy [J]
after 28 years in operation	24	160.4
	276	220.9
after 28 years in operation + artificial thermal ageing	24	148.0
	276	186.3

- **Mechanical degradation:** in contrast to austenitic steels, a general decrease in mechanical properties is observed (Fig. 9). Experimental data confirm that these materials undergo embrittlement over time.
- **Toughness and brittleness:** impact toughness tests (Table 4) reveal a clear degradation trend:
 - A substantial reduction in the USE.
 - A significant increase in the ductile-to-brittle transition temperature (DBTT).
- **DELISA-LTO Findings:** these results, obtained within the DELISA-LTO project, highlight that the ferritic matrix is susceptible to microstructural changes (likely phosphorus segregation or carbide precipitation) that shift the material towards a more brittle state during the long-term operation (LTO) period.

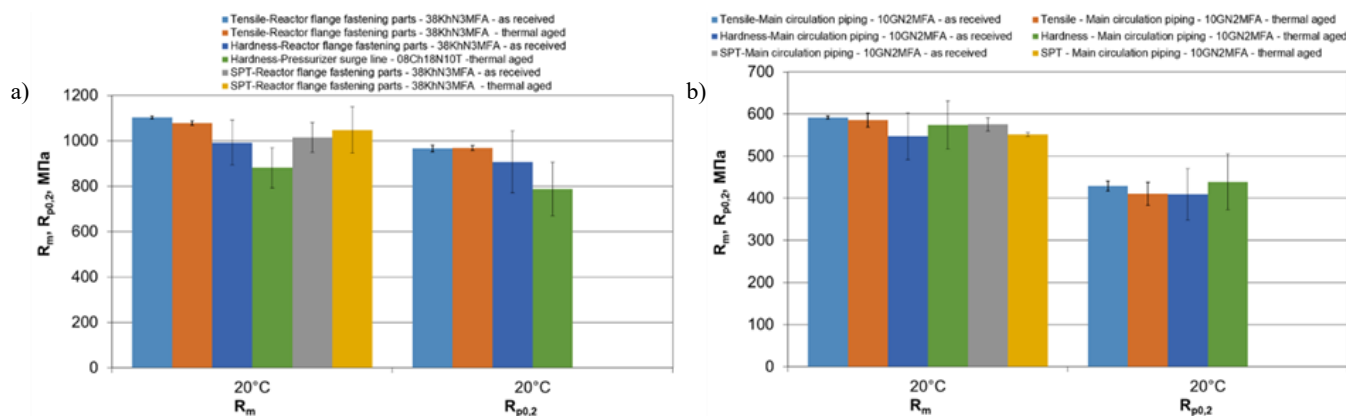


Figure 9. Results of tensile, SPT and hardness for: a) studs and nuts; b) main circulation piping.

Table 4. Charpy impact toughness tests for reactor flange fastening elements (38KhN3MFA) - after 30 years in operation.

Material	Service life, years	T_k [°C]	USE [J]
Reactor flange fastening elements (38KhN3MFA)	30	-56	99
	60	-2	90
Main circulation piping steel (10GN2MFA)	0	-66	260
	60	-71	244

CONCLUSIONS

Thermal ageing has been observed so far for WWER-440 and WWER-1000 RPVs.

The existing Ukrainian practice of monitoring thermal ageing in primary circuit components, which relies on correlation formulas derived from hardness measurements, currently lacks the precision to definitively confirm or deny the presence of thermal ageing. The high level of uncertainty associated with these indirect methods necessitates the transition to more sensitive experimental techniques and updated regulatory frameworks, such as SOU-N NAEK 133:2023.

Obtained results provide a quantitative assessment of thermal ageing effects for a 60-year equivalent service life:

- *Austenitic stainless steel (08Ch18N10T)*: this material exhibits high phase stability. Changes in mechanical properties (yield and tensile strength) are negligible (< 0.5 %), while the upper shelf energy (USE) shows a minor reduction of approximately 5 %.
- *Ferritic alloyed steels (10GN2MFA and 38KhN3MFA)*: both steels show a more pronounced response to thermal exposure. Mechanical properties decrease by approximately 3 %.
- *38KhN3MFA (reactor nuts)*: demonstrate the highest sensitivity to ageing, with a 10 % reduction in USE and a significant ductile-to-brittle transition temperature (DBTT) shift from -56 °C to -2 °C.
- *10GN2MFA (main coolant pump)*: the USE decreases from 260 J to 240 J, while the DBTT remains relatively stable, with a marginal shift from -66 °C to -71 °C.

New experimental methods, such as SPT and hardness, after comprehensive validation, may be useful tools for monitoring thermal ageing effects on NPP components.

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REFERENCES

1. Kanngiesser, I., Artificial Aging: Predicting Material Behavior, BINDER GmbH, 2022.
2. Strizhalo, V.O., Borodii, M.V., Experimental Methods in Mechanics of Deformable Solids, Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, 2022, 306 p.
3. Arrhenius, S. (1889), *Über die Reaktionsgeschwindigkeit bei der Inversion von Rohrzucker durch Säuren (On the reaction velocity of the inversion of cane sugar by acids)*, Zeitschrift für Physikalische Chemie, 4U(1): 226-248. doi: 10.1515/zpch-1889-0416
4. Joly, P., Roch, F., Primault, C. (2013), *Effect of thermal ageing on properties of pressure vessel low alloy steel*, In: Proc. of the ASME 2013 Pressure Vessels & Piping Conference PVP2013, Paris, France, 2013, paper no: PVP2013-97643, V007T07A025; 8 p. doi: 10.1115/PVP2013-97643
5. Ligneau, N., Page's, C., Akamatsu, M., et al. (2009), *Integrity and life assessment of cast duplex stainless steel elbows used in the primary loops of PWRs*, In: Proc. of the ASME 2009 Pressure Vessels & Piping Conference PVP2009, Prague, Czech Republic, 2009, paper no: PVP2009-77731; 9 p. doi: 10.1115/PVP2009-77731
6. Faigy, C. (2012), *Ageing management of cast stainless steel components in French PWRs*, In: Proc. of the ASME 2012 Pressure Vessels & Piping Conference PVP2012, Toronto, Ontario, Canada, 2012, paper no: PVP2012-78843; 8 p. doi: 10.1115/PVP2012-78843
7. Kawaguchi, S., Nagasaki, T., Koyama, K. (2005), *Prediction method of tensile properties and fracture toughness of thermally aged cast duplex stainless steel piping*, In: Proc. of the ASME 2005 Pressure Vessels & Piping Conference PVP2005, Denver, Colorado, USA, 2005, paper no: PVP2005-71528; 7 p. doi: 10.1115/PVP2005-71528
8. Chopra, O.K., Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems, U.S. Nuclear Regulatory Commission Report NUREG/CR-4513, Rev. 1, ANL-93/22, 1994.
9. ASTM E185-13 (2013) Standard Practice for Design of Surveillance Programs for Light-Water Moderated Nuclear Power Reactor Vessels, ASTM International.
10. SOU-N NAEK 133:2023. Engineering, Scientific and Technical Support. Methodology for Determining the Mechanical Properties of Metal Based on Hardness Test Results (in Ukrainian), SE 'NNEGC Energoatom', Kyiv, Ukraine, 2022.

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