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BEHAVIOUR OF 15Kh2MFA RPV STEEL UNDER HIGH NEUTRON FLUENCES

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ABSTRACT

Paper describes results from testing WWER-440 reactor pressure vessel specimens manufacture from 15Kh2MFAA steel and its welding joint after neutron exposure to very high fluence up to 1.5×10^{25} m^{-2} ($En \geq 0.5$ MeV). No saturation effect has been observed in the shift of the critical temperature of brittleness, T_k, increase in yield strength, dRp0.2, or ultimate tensile strength, dRm. Upper shelf energy, KCVmax, from notch impact testing remains larger than 50 $J.cm^{-2}$. Ratio between dT_k and dRp0.2 is increasing with the increase in fluence from 0.4 to 0.5 for base metal and to 0.6 to weld metal.

INTRODUCTION

WWER (**W**ater-**W**ater-**E**nergetic-**R**eactor) type reactors are, in principle, Pressurized Water Reactors (PWR) but designed and manufactured from Russian type materials and operated according to the former Soviet/Russian rules, standards and requirements.

Design neutron fluence for reactor pressure vessels (RPV) of WWER-440/V-213C type is approx. 2.5×10^{24} m^{-2} with $E \geq 0.5$ MeV that is about five times higher than for other PWR types. Surveillance specimen programs for WWER-440/V-213C type RPVs contain 6 sets of containers with specimens that were, due to their high lead factor, usually withdrawn after 1, 2, 3 and five years of operation. Other two sets were aimed for determination of potential thermal ageing effects and have been withdrawn after 10 to 25 years of operation. Lower parts of these chains contain also specimens for determination of radiation damage – maximum obtained fluence went up to 1.5×10^{25} m^{-2}. Testing of impact notch toughness for determination of transition temperature T_k, static tensile tests and static fracture toughness tests for determination of reference temperature T_0 have been performed and results analyzed.

Detailed description of the Standard surveillance program as well as of Supplementary surveillance programs of WWER-440/V-213 type reactors is given e.g. in [1-7].

It is necessary to mention, that neutron flux and neutron fluence in WWER reactor pressure vessels is determined for neutron with energies larger than 0.5 MeV in contrary with PWR/BWR where threshold energy 1 MeV is applied. Conversion between these two different fluxes/fluencies is not constant and is different for different reactors and different positions – ratio between F(E > 0.5 MeV)/ F(E > 1 MeV for surveillance specimen position is approximately 1.95.

WHAT IS IT A “LARGE FLUENCE”?

There is no official definition of the “large fluence” for any type of reactor. Practically, such definition fully depends on the reactor type (its design fluence) and used material (its resistance against radiation embrittlement). As a realistic definition, fluences up to double of design fluence can be taken as large ones and fluences larger that this double one as “very large” ones.

Such proposal is illustrated in Figure 1: as maximum design fluences for operation of 40 years of most of PWR RPVs (and also WWER-1000) are approx. $5x10^{23}$ m^{-2} (En ≥ 1 MeV), very large fluences can be defined in interval between $1x10^{24}$ m^{-2} and $1.5x10^{24}$ m^{-2} that is practically only design fluence for WWER-440 RPVs for 40 years of operation. Then, very large fluences for WWER-440 RPV materials will start at approx. $2.5x10^{24}$ m^{-2} but this presentation will cover irradiations up to approx. $1.5x10^{25}$ m^{-2} (En ≥ 0.5 MeV).

As in the whole WWER evaluation process only fluences with En ≥ 0.5 MeV are used, this threshold energy will be used in this paper.

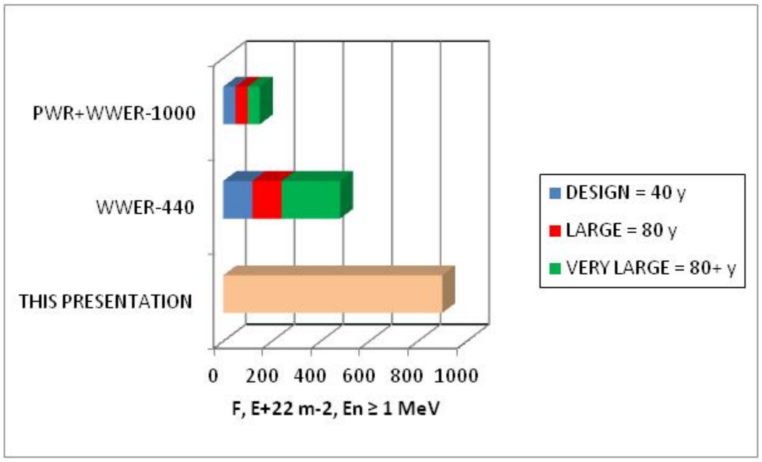

Figure 1. Proposal for definition of large and very large fluences

WWER-440/V-213 RPV MATERIALS

WWER-440/V-213 type reactor pressure vessels are manufactured from the 15Kh2MFA(A) steel of Cr-Mo-V type. Forged rings and submerged arc welding joints in the beltline region are manufacture from the steel with –AA quality, i.e. with lower content of copper and phosphorus impurities, as shown in Table 1 and 2.

Table 1. Requirement for chemical composition of Kh2MFA type base metal and weld metal (in mass %)

MATERIAL	C	Mn	Si	P	S	Cr	Ni	Mo	V
WWER-440 15Kh2MFA	0.13 0.18	0.30 0.60	0.12 0.37	Max 0.025	Max 0.025	2.50 3.00	Max 0.40	0.60 0.80	0.25 0.35
Submerged arc weld Sv-10KhMFT+AN-42	0.04 0.12	0.60 1.30	0.20 0.60	Max 0.042	Max 0.035	1.20 1.80	Max 0.30	0.35 0.70	0.10 0.35
Submerged arc weld Sv-10KhMFT+AN-42M	0.04 0.12	0.60 1.30	0.20 0.60	Max 0.012	Max 0.015	1.20 1.80	Max 0.30	0.35 0.70	0.10 0.35

Table 2. Requirements for content of residual elements in 15Kh2MFAA type base metal and weld metal (max content in mass %)

MATERIAL	P	S	Cu	As	Sb	Sn	P+Sb+Sn	Co
15Kh2MFAA	0.012	0.015	0.08	0.010	0.005	0.005	0.015	0.02

IRRADIATION CONDITIONS

This paper will deal only with surveillance specimen test results from WWER-440/V-213C type RPVs that were manufactured by SKODA JS, Czech Republic. Results from irradiations between 1 and 20 years in 4 units are collected and analyzed. Design of the Standard surveillance program for this type of reactors assures that the lead factor for tensile and Charpy impact specimens from base metal is about 12 and for weld metals even close to 15. Thus, irradiation for more than 5 years is not any more relevant to the design fluence and irradiations for e.g. 20 years would represent fluences equal to more than 250 years of operation. Supplementary and Modified surveillance programs have been designed and realized in these reactors to reach lower lead factor in the range between 2 and 5.

Irradiation temperature of surveillance specimens is close to the inlet water temperature, i.e. in the range of 270 to 275 °C.

EMBRITTLEMENT TREND CURVES

Several Embrittlement Trend Curves (ETC) exist for this type of material but all only for the shift in the critical temperature of brittleness, dT_k, i.e. based on results from testing Charpy V-notch specimens by impact bending.

Original ETC was given in [8] and upgraded in [9]. In both these documents the same format of the ETC was applied :

$$dT_k = A_F \, . \, (F/10^{22}\ m^{-2})^n \qquad (1)$$

where

A_F is coefficient of radiation embrittlement, °C

F is fluence of neutrons with energies larger than 0.5 MeV and n is exponent, in this case 1/3.

Values of A_F, n and σ for base metals and weld metals are given in tables and represent the upper boundary opf all results obtained after irradiation in experimental reactors, i.e. with lead factor of the order of 100. This predictive formula is valid for shifts in dT_k for fluences up to $3x10^{24}\ m^{-2}$.

Later, based on results from surveillance specimen test results, new formulae were developed in [10] and [11] taking into account content of main impurities – copper and phosphorus. In these cases, A_F depends on content of Cu and P and exponent n has been between 0.5 and 0.6.

Unfortunately, these ETCs have been developed only for the shift in transition temperature, in the case of WWER RPVs for critical temperature of brittleness. No ETC exist for changes of tensile properties – yield strength and ultimate tensile strength as well as for fracture toughness transition temperature, e.g. reference temperature T_0. As decrease of the upper shelf energy of notch impact toughness KCV is not substantial for 15Kh2MFA(A) materials within the design fluence, no ETC has been yet developed for such changes.

VERLIFE procedure [11] applies this simple formula (1) of power law also into ETC as for the shift in transition temperatures (either from Charpy impact or static fracture toughness) as also for static tensile properties (yield strength, ultimate tensile strength) from surveillance specimen test results (for a given irradiation temperature):

$$dS = A_S \, . \, (F/10^{22}\ m^{-2})^n \qquad (2)$$

where A_S is coefficient depending on chemical composition of the tested material and tested material property S, °C

F is fluence of neutrons with energies larger than 0.5 MeV and n is experimentally determined exponent,

S is a material property – yield strength, Rp0.2, ultimate tensile strength, Rm, critical temperature of brittleness,T_k, or reference temperature T_0.

Experimentally determined trend curves – fluence dependence of the change os the material property – from the database of surveillance specimen test results of WWER-440/V-213C type reactors are shown in Figures 2 to 9.

Changes in tensile properties – yield strength, Rp0.2, and ultimate tensile strength, Rm – can be described with the equation (2) without any tendency to saturation. As usual, increases in yield strength are larger than in ultimate tensile strength which is more pronounced for testing at room temperature than in the irradiation temperature +265 °C where increases are somewhat smaller than for room temperature testing. In the same time, there is practically no difference between behaviour of base metals and weld metals – changes are very similar.

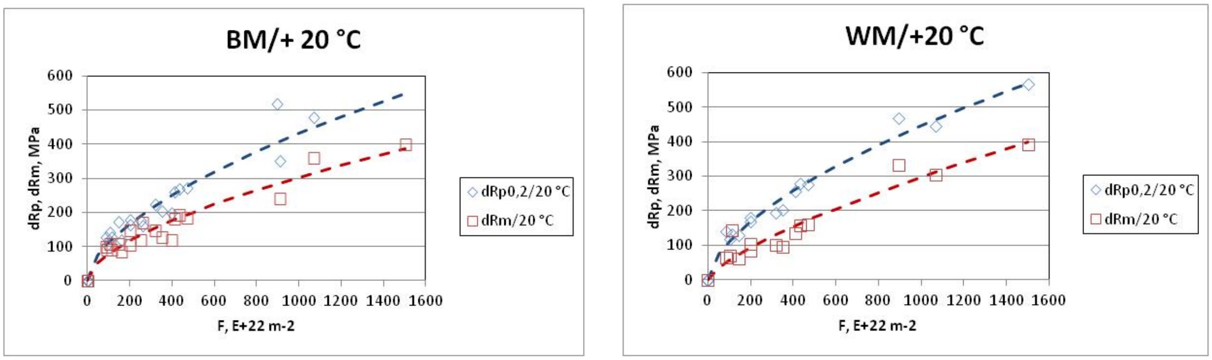

Figure 2. Fluence dependences of changes in yield strength, Rp0.2 and ultimate tensile strength, Rm, tested at room temperature for base metal (BM) and weld metal (WM) of 15Kh2MFAA steel

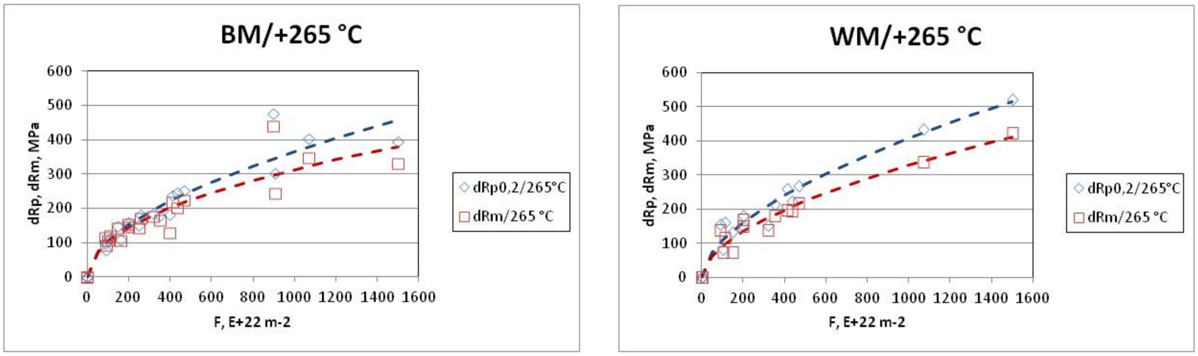

Figure 3. Fluence dependences of changes in yield strength, Rp0.2 and ultimate tensile strength, Rm, tested at 265 °C for base metal (BM) and weld metal (WM) of 15Kh2MFAA steel

Figures 4 to 7 summarize changes in plastic properties from tensile testing – uniform elongation, Am, total elongation, A10, and reduction of area, Z. In this case, there is quite different behaviour between results from room temperature and 265 °C testing even though there is a strong decrease of properties in both temperatures – all plastic properties after testing at room temperature are reaching practically zero value at fluences approximately $1.0\text{x}10^{25}$ to $1.2\text{x}10^{25}$ m^{-2} while these properties still have non-zero values for testing at 265 °C even for the highest neutron fluence. Such effect can be connected with the results of fluence dependence of the transition temperature T_k, i.e. room temperature plastic properties are approaching zero values for transition temperatures in the range of 200 to 250 °C.

Relatively small values of elongation can be explained with the length of test specimens where 10-times diameter (3 mm) was chosen in all surveillance programs instead of standard 5-times.

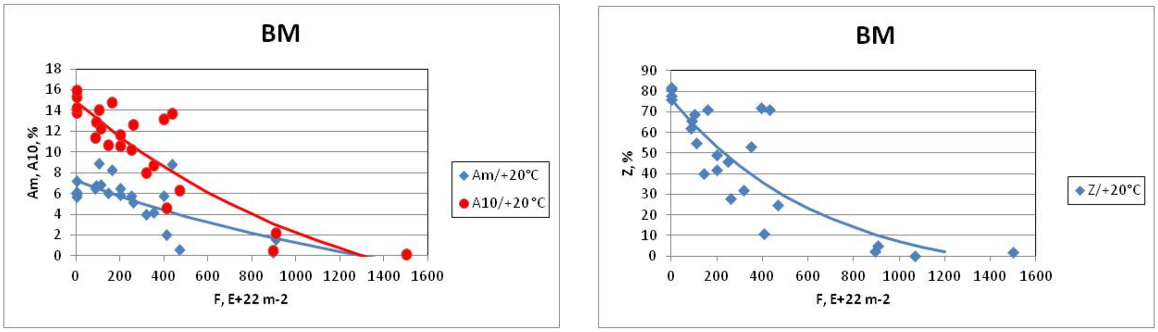

Figure 4. Fluence dependences of changes in uniform elongation, Am, total elongation, A10, and reduction of area, Z, tested at room temperature for base metal (BM) of 15Kh2MFAA steel

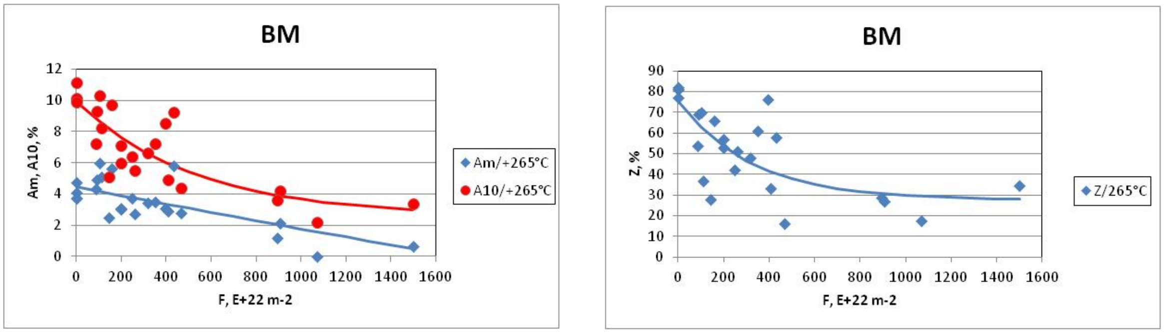

Figure 5. Fluence dependences of changes in uniform elongation, Am, total elongation, A10, and reduction of area, Z, tested at 265 °C for weld metal (WM) of 15Kh2MFAA steel

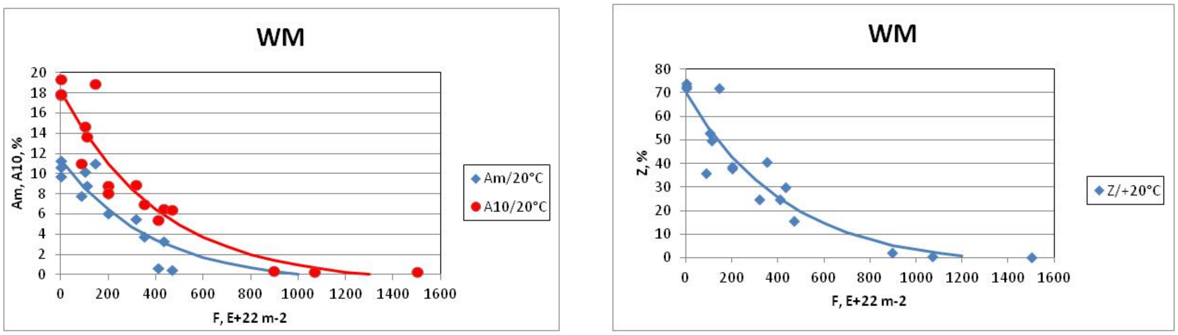

Figure 6. Fluence dependences of changes in uniform elongation, Am, total elongation, A10, and reduction of area, Z, tested at room temperature for weld metal (WM) of 15Kh2MFAA steel

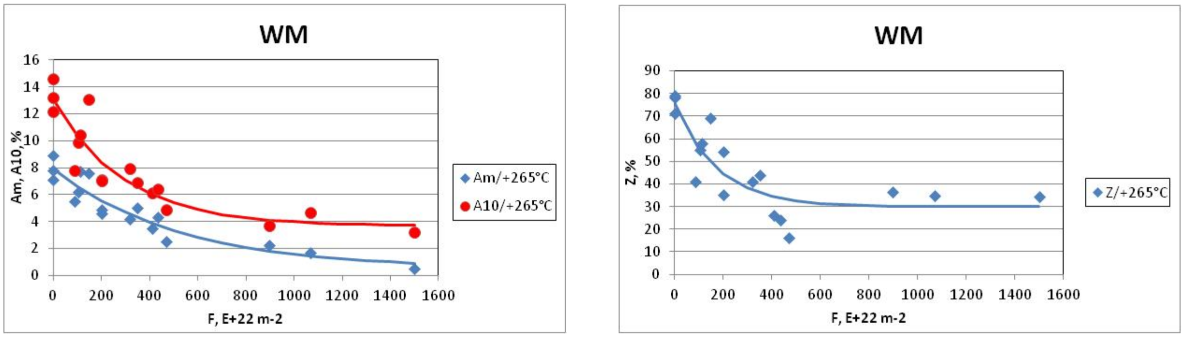

Figure 7. Fluence dependences of changes in uniform elongation, Am, total elongation, A10, and reduction of area, Z, tested at 265 °C for weld metal (WM) of 15Kh2MFAA steel

Figures 8 and 9 summarize results from testing Charpy V-notch impact toughness of base metal and weld metal. Fluence dependence of the shift in the critical temperature of brittleness, dTk, can be again well described with equation of (2). Again, there is no tendency for any saturation up to the highest fluences. Some small drops for the highest fluences can be explained by the fact that testing was performed in the range of the irradiation temperature and thus can be affected by some annealing during the holding of specimens at test temperature.

Decrease of the upper shelf notch impact toughness, KCVmax, has some exponential dependence, like in plastic properties during tensile testing but KCVmax remains at no-zero values even for the highest fluences – its value is approximately 100 J.cm^{-2} that is still larger than required 50 ft-lb (85 J.cm^{-2}). Thus, even for strongly embrittled conditions with transition temperature T_k close to irradiation temperature (250 to 270 °C), upper shelf energy is still sufficiently high and for design fluencies its decrease is practically negligible.

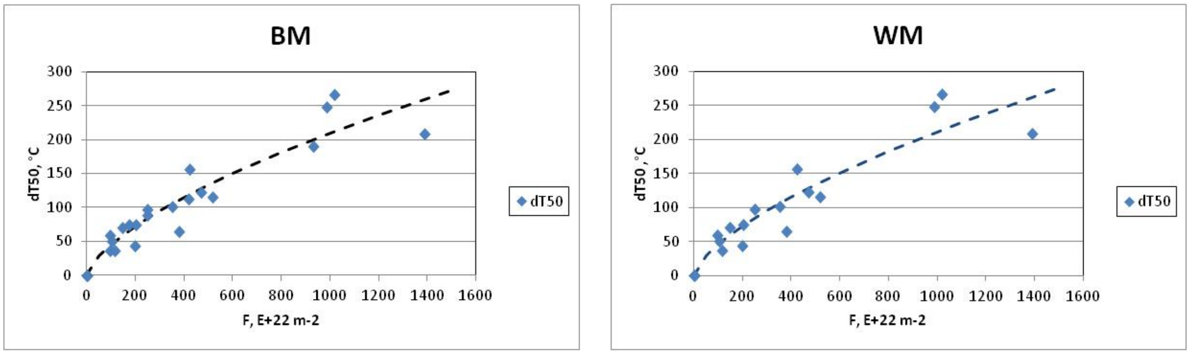

Figure 8. Fluence dependences of changes in critical temperature of brittleness, T_k, for base metal (BM) and weld metal (WM) of 15Kh2MFAA steel

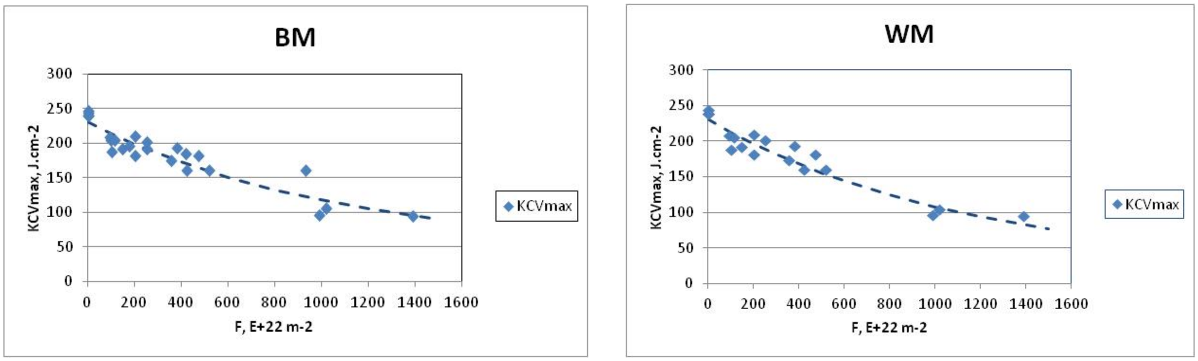

Figure 9. Fluence dependences of changes in upper shelf energy, KCVmax for base metal (BM) and weld metal (WM) of 15Kh2MFAA steel

CORRELATION BETWEEN PROPERTIES

In some cases, correlations between changes in transition temperatures and tensile properties (yield strength) are evaluated. Such correlation is then often used in studies when large amount of parameters are involved and/or there is not enough material for Charpy impact specimens and only tensile specimens or even only hardness testing is performed (under assumption that some linear correlation between changes in hardness and yield strength increase exists).

Widely used correlation [12] between CVN transition temperature shifts and room temperature yield strength increases shows the relationship:

$$\Delta T_{CVN} = 0.70 \times \Delta Rp0.2 \qquad (3)$$

where ΔT_k is in °C and $\Delta Rp0.2$ is in MPa.
The coefficient of 0.70 is the same as the value of 0.70 published in [13] for ΔT_{41J} and $\Delta Rp0.2$. Moreover, [14] published similar results specifically for 'low upper shelf' welds with coefficients ranging from 0.4 to 0.9 for seven different welds and an average value of 0.65, very close to the 0.70 value shown in Equation (3).
Figure 10 shows evaluated results from testing tensile and impact specimens as described in Figures 2 to 9. In this case, mean trend curves have been used for calculation of the ratio between transition temperature shift and yield strength increase, dT50/dRp. This approach has been preferred instead of calculations for each individual fluence as some scatter, especially for small neutron fluences, was obtained.

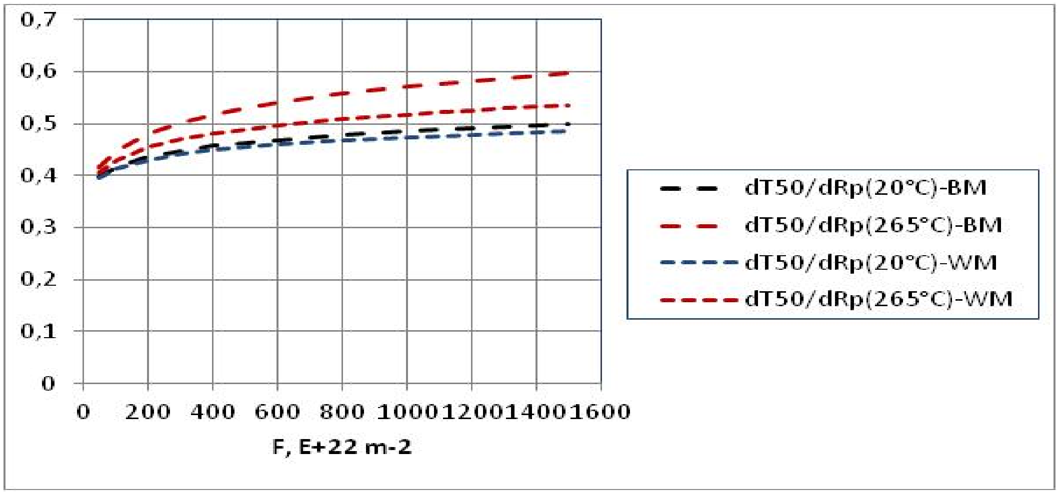

Figure 10. Fluence dependence of the ratio between shift in critical temperature of brittleness and increase in yield strength, dT50/dRp, for base metal (BM) and weld metal (WM) for tensile testing at room temperature and at 265 °C

Results in Figure 10 are interesting from two points – first, that this ratio is increasing with the increase of fluence even though only in a range between 0.4 and 0.5 when using room temperature yield strength, and second, that this ratio is increasing faster for yield strength at 265 °C from 0.4 up to 0.6 – this could be caused by changes in plastic properties. Nevertheless, this ratio is smaller than it is referred in [12] and [13] which can be caused by different type of the steel with higher strength properties and different ratio between yield strength and ultimate tensile strength.

CONCLUSION

Evaluation of results from testing RPV surveillance specimens of WWER-440/V-213C type from 15Kh2MFAA (Cr-Mo-V) steel and weld metal irradiated to very high fluencies – up to $1.5x10^{25}$ m^{-2} (En ≥ 0.5 MeV) showed that no saturation effect can be observed either for increase of tensile properties (yield strength, Rp0.2 and ultimate tensile strength, Rm) or for the shift of transition temperature – critical temperature of brittleness, T_k from Charpy V-notch impact testing. In the same time, plastic properties at tensile testing at room temperature (uniform elongation, Am, total elongation, A10 and reduction of area, Z) are strongly decreasing and reaching zero at fluences larger than 1 to $1.5x10^{25}$ m^{-2}. On the contrary, these properties at testing at 265 °C still remain non-zero even for the largest irradiations.

Transition temperature T_k after such very high fluence irradiation is reaching the irradiation temperature, nevertheless its trend curve for design and extended life fluencies confirms very high resistance of this steel and weld metal against radiation embrittlement that is also confirmed by high values of upper shelf energy KCVmax that remains still larger than 50 ft-lb (85 $J.cm^{-2}$) even for the largest irradiation.
Ratio between transition temperature shift and yield strength increase is slightly dependent on neutron fluence – with increasing fluence its value is increasing from 0.4 to 0.5 for yield strength tested at room temperature and from 0.4 to 0.6 for yield strength tested at 265 °C.

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