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Interim results of the reactor pressure vessel materials evaluation within the framework of the implemented Advanced Surveillance Specimen Programme

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Abstract: The reactor pressure vessel (RPV) is the most critical component of every nuclear power plant (NPP) and continuous evaluation of its mechanical properties is a necessity for long and safe operation. Standard tests require a collection of large-dimension samples coming from the precious and archive materials, usually produced as control segments. Since SPT testing samples are quite small, high activity of irradiated materials is no longer an issue. The SPT technique therefore represents a very useful and effective method applied for characterization of mechanical properties such as ultimate tensile strength (R_m), yield strength (R_e), and fracture appearance transition temperature (FATT). Monitoring of structural components in nuclear power plants receives much attention, particularly, in the context of long term operation (LTO) of current plants where the amount of material available for destructive testing is considerably limited.

Keywords: reactor pressure vessel; small punch test; surveillance specimen programme; irradiation;

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1. Introduction

This paper gives an overview of the mechanical SPT test results, acquired within the evaluation of SPT samples that were irradiated in the commercial nuclear power reactor at NPP Bohunice, unit no.4, for a period equal to seven fuel-campaigns. Herein presented results are just partial that participate and correspond to a very complex reporting system for all irradiated samples of the irradiation chain, as a part of currently running Advanced Surveillance Specimen Programme (ASSP). To evaluate mechanical properties of the RPV materials within irradiation chain of the ASSP, SPT samples of the following materials were chosen and tested:

1. HAZ-I of weld no.4 from the RPV,
2. HAZ-II of weld no.4 from the RPV,
3. Underclad HAZ-I of the RPV,
4. Underclad HAZ-II of the RPV,
5. Transversely-orientated underclad HAZ from the RPV,
6. Original weld metal from RPV of unit no.4,
7. Austenitic cladding (AC)-I from the RPV,
8. Austenitic cladding (AC)-II from the RPV,
9. Transversely-orientated AC from the RPV,
10. Austenitic type 08Ch18N10T corrosion resistant steel of reactor internal components.

2. Materials and Methods

2.1 Advanced Surveillance Specimen Programme

ASSP is specially designed for monitoring of the neutron irradiation effects on RPV materials' mechanical properties that change due to the operation. Project ASSP meets the requirements of the national supervisory by Nuclear Regulatory Authority of the Slovak Republic (NRASR), IAEA's recommendations and the need of Slovak NPPs operator operated nuclear power reactors of the VVER 440/213 type. During the ASSP realization, irradiation induced changes are continuously compared with the results obtained in the initial state and after defined time of irradiation, in this case, precisely after seven fuel-campaigns. The presented results serve for demonstration of the real RPV state during exposure up to the end-of-life neutron irradiation fluencies, still considered under the LTO. The ASSP represents one of the most important parts for the currently operating NPPs in Bohunice-3 and 4, Mochovce-1 and 2 units, in light of their continuous LTO support [1, 2]. A design of the ASSP program is based on long-term experience in the field of monitoring of radiation degradation to VVER-440 type RPVs not only in Slovakia but also in the world and represents the fifth generation of Surveillance Specimen Programs (SSPs) in

Slovakia. The philosophy of this program is based on the need to continuously monitor trends in changes of the properties of RPV structural materials throughout their planned life.

The RPV is the most important part of the design in terms of operational safety of NPP. The current objective for the majority of nuclear power plants is the planned LTO. For LTO it is important to know the mechanical properties of RPV materials and their changes due to operation. The ASSP in four NPP units presents continuation and completion of the originally designed Standard Surveillance Specimen Program (SSSP) and Extended Surveillance Specimen Programme (ESSP). The main aim of the ASSP monitoring program is to acquire reliable technical argumentations for the power plant long term operation by performing continuous monitoring of RPV materials irradiation embrittlement.

The effect of irradiation depends on the type and state of the crystal lattice of an irradiated material. Predominant effects also have characteristic parameters of the real irradiation environment. These parameters include the quantities describing RPV ionizing radiation where the most important parameters are [3, 4]:

- Neutron fluence,
- Irradiation temperature.

2.2 Experimental materials

Mentioned important parameters and irradiation induced changes in materials' mechanical properties during ASSP application are to be measured and evaluated. The aim of this paper is to present the partial results of mechanical properties in the as-irradiated state and evaluated by SPT method and to bring comparison between the results of experimental materials used. The specimens used in this paper were prepared from ten main experimental material types of the RPV and internal components. The representative microstructures and SPT orientation of the above mentioned materials, taken from the reference RPV material "control segment" of identical chemical composition and production technology as for the operated RPV unit, can be seen in the next Figure 1. Samples of the original weld metal were taken from pre-prepared surveillance programme Charpy-V impact test specimens by using electro-discharge wire cutting machine. Samples were irradiated at a max. temperature of 285°C and to a neutron fluence of up to 3.81×10^{24} [n/m^2].

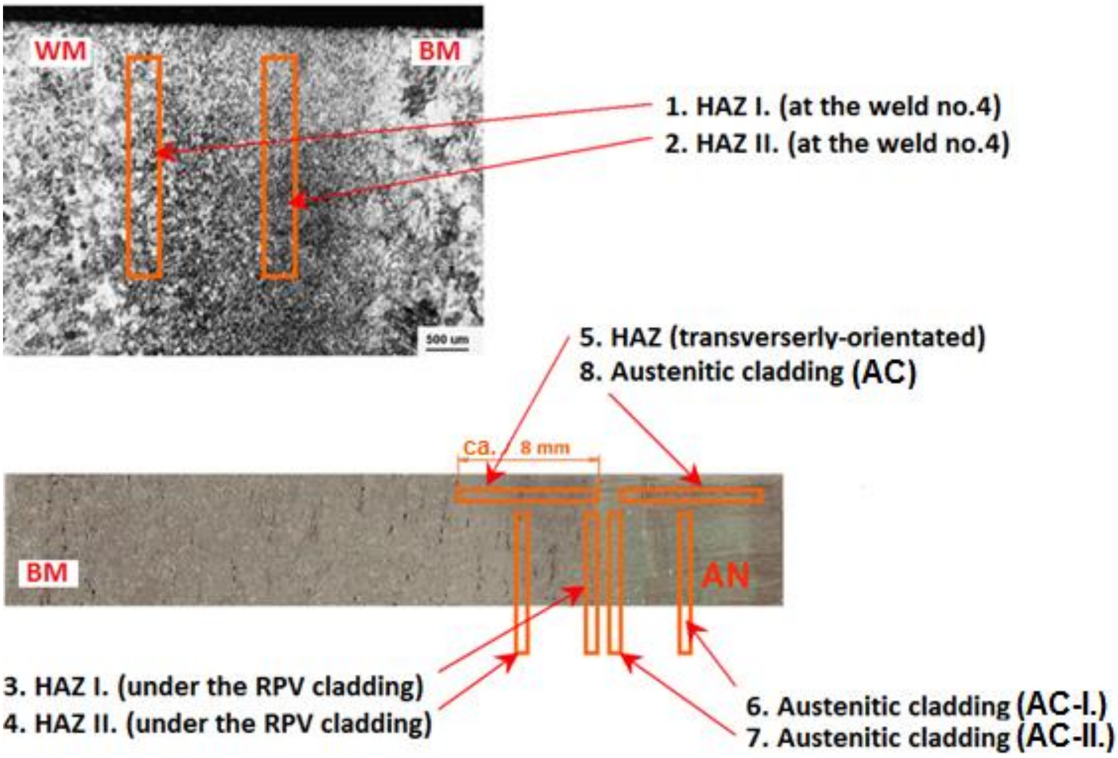


Figure 1. Sampling scheme for HAZ and AC SPT type samples from RPV and internal components**.**

In the ASSP program two different types of specimens to analyze and monitor RPV steel radiation degradation are used. They are:

- Insert-type specimens for reconstitution to the original standard specimens to assess static fracture toughness and Charpy-V impact toughness of materials,
- Small punch test specimens (SPT).

The ASSP program includes in addition to RPV material irradiation damage monitoring, the measurements of irradiation temperature and neutron fluence inside of irradiation capsules as well. Irradiation capsules are filled with samples made of the original material with specified geometry and also melting monitors as well as neutron fluence activation monitors (see Figure 2).

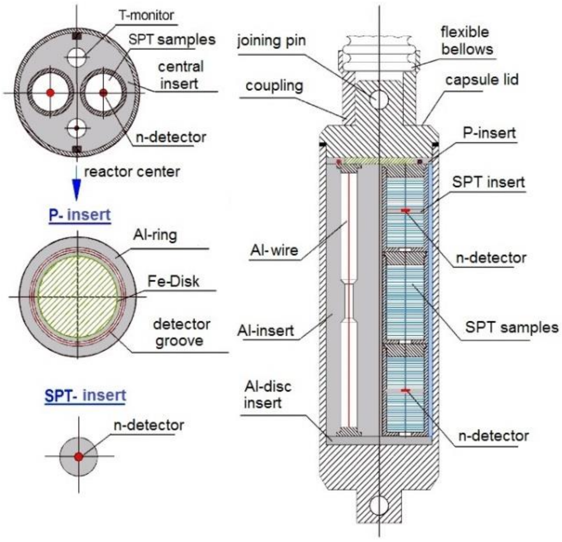


Figure 2. SPT irradiation capsule with samples, detectors, and all other related structural parts.

The design of irradiation chains, measuring of irradiation temperature and neutron fluence is based on the experience from the realized surveillance specimen programs. The innovations in this project are [5]:

- Besides the standard tests of mechanical properties there was included in the material degradation monitoring also the new testing method - Small Punch Test, all the SPT samples are inserted into the special capsules, as can be seen in Figure 2 above,
- Preparation of SPT type samples in order to monitor the new RPV materials that were formerly not included within any of the previous SSP generations. This idea has given us a possibility to assess mechanical properties of mostly irradiated RPV structural parts made of underclad HAZ, austenitic cladding (AC), and austenitic type 08Ch18N10T corrosion resistant steel of reactor internal components.

2.3 Small Punch Test

The standard tests need relatively high amount of the original RPV material and after irradiation, the samples must be tested in the special hot laboratories due to their very high induced activity. In order to study irradiation damage, small samples are preferred because there are limitations of sample size in irradiation channels and great lack of original RPV materials. SPT practice requires a small volume of tested materials what substantially reduces the total activity of the individual irradiated specimen. There's no need for special hot cells when testing SPT sample, a simple lead brick shielding of a testing machine is adequate [6, 7]. Because there is a lack of RPV experimental materials, the great advantage is using the SPT methods for evaluation of their basic mechanical properties [8].

The principle of SPT testing procedure used in VUJE, a.s. is penetration of a disk specimen by a hemispheric rod. The small punch experimental configuration is presented in the Figure 3. The disk shaped specimen is 8 mm in diameter and 0.5 mm in thickness. The specimen holder consists of a lower and upper die and holder body. Using this specimen holder, the specimens are prevented from cupping upward during punching, and therefore, plastic deformation is concentrated in the region below the punch rod. Using relatively simple system with recorders of the load and deflection values, we can obtain the following data of basic mechanical properties [6, 7]:

- The yield stress $\mathbf{R_e}$ and ultimate tensile strength $\mathbf{R_m}$, which are well correlated with the parameters $\mathbf{P_y}$, $\mathbf{P_m}$, and $\mathbf{d_m}$ which is displacement at maximum load $\mathbf{P_m}$ (see Figure 4),

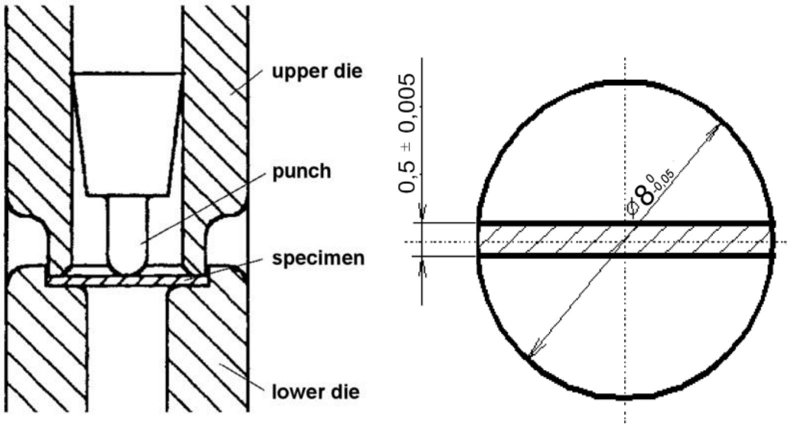
- Ductile-to-brittle transition temperature (DBTT) measured by using the Charpy-V impact test is determined as the fracture appearance transition temperature (FATT at a value of 50-% of shear fracture portion). $FATT_{50\%}$ can be estimated from the results of temperature dependence of small punch energy determined from the area under the load-deflection curve up to the fracture load at displacement, $\mathbf{d^*}$**,** corresponding to the specimen fracture. The $FATT_{50\%}$ correlates to transition temperature of SPT tests, $DBTT_{SPT}$, according to the following equation (1):

$$DBTT_{SPT} = \alpha \times FATT_{50\%} \quad (1)$$

where α is a correlation coefficient of approximately of 0.4, or, in the range of 0.35 up to 0.45. The α coefficient is an empirically derived constant to a very particular tested material. A sufficiently large number of SPT specimens (approx. 20 pcs) from reference materials allowed also evaluating a transition temperature of ferritic steels. The testing procedure, parameters, and the estimation of transition temperature were performed in accordance with [9]:

- Type of puncher - rod or ball of a diameter of 2 mm,
- Punch displacement velocity: 0.5 mm/min for tensile tests, 2 mm/min for tests performed at low and high temperatures,
- SPT specimen geometry: diameter 8.00 - 0.05 mm, thickness 0.500 ± 0.005 mm,
- Total number of SPT specimens used to determine transition temperature - 20 pcs per SPT energy-temperature curve.

To prepare SPT samples the method of an electrical discharge machining (EDM Cutting) followed by wet grinding on abrasive paper with a grit size of P320 unto P1200 is used. By this way the VUJE, a.s. laboratories have prepared several thousands of SPT specimens.



(a) **(b)**

Figure 3. (**a**) Schematic of the setup for the SPT; (**b**) SPT specimen geometry with given tolerances [8].

The testing is usually performed on a standard tension test machine, equipped with load and crosshead feed gauges and a data recorder for the registration of load-deflection curves. Special testing rigs, depending on the testing temperature, are used for the realization of SPT tests. Tests at low temperatures are carried out in a special thermo-insulated chamber. The specimen is cooled using liquid nitrogen vapors or directly by liquid nitrogen. The temperature of the specimen is measured by a calibrated thermocouple. For tests at elevated temperatures a special furnace is used. The SPT method is also used for such evaluation of mechanical properties for lifetime predictions of service components by the authors [10–12].

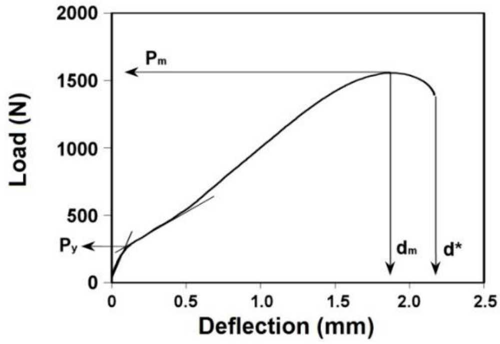


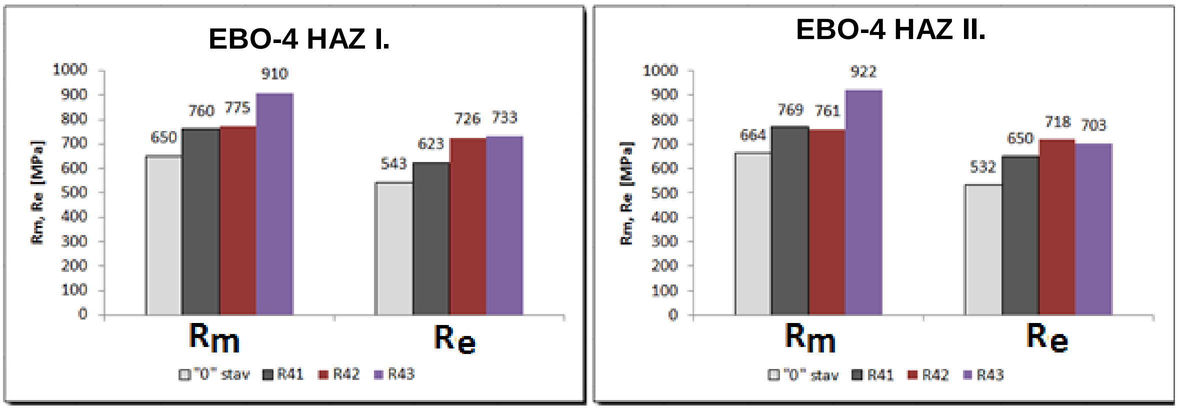
Figure 4. Typical SPT load-deflection curve [8, 9].

3. Results

In the following part of the paper, there are summarized results of the SPT evaluation applied to the as-irradiated state of materials in the frame of the ASSP. For the ASSP project there were prepared 1500 pieces of SPT samples per reactor unit totally and of that number the 750 pieces have already been tested, and other 750 pieces of different types of RPV materials are planned to be tested in as per ongoing program schedule. There are presented the SPT results of tensile evaluated properties and transition temperature determination for steels exhibiting transition behavior (carbon and low carbon steel). For the austenitic steels and their welds, which do not have a ductile-brittle transition, the temperature dependence of SPT energy has been determined. Partial results of determined tensile properties are clearly summarized in the following Table 1. In this table, the values are found after irradiating for a period of effective 7 fuel-campaigns. The graphical demonstration of the changes that occurred as a result of neutron irradiation is given in Figures 5 and 6. It can be seen from the figures that after the irradiation, the strength characteristics of all the evaluated materials slightly increased [5].

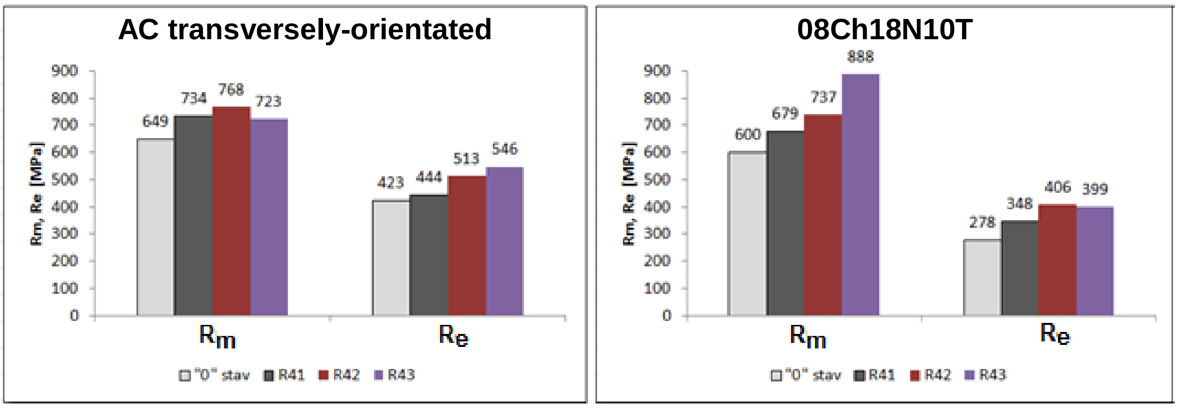
Table 1. Tensile properties evaluated using SPT tests before and after irradiation of R 4BZ3 chain [5].

Material	**“0“-state**		**Chain R 4BZ3**		**Figure**
	R_m	**R_e**	**R_m**	**R_e**	
	[MPa]		**[MPa]**		
HAZ-I of weld no.4 from the RPV	650	543	910	733	*5a*
HAZ-II of weld no.4 from the RPV	664	532	922	703	*5b*
Underclad HAZ-I of the RPV	648	509	1097	856	-
Underclad HAZ-II of the RPV	548	389	927	667	-
Transversely-orientated underclad HAZ from the RPV	570	404	947	691	-
Original weld metal from RPV of unit no.4	551	399	784	618	-
Austenitic cladding (AC)-I from the RPV	618	387	820	526	-
Austenitic cladding (AC)-I from the RPV	634	379	807	468	-
Transversely-orientated AC from the RPV	649	423	723	546	*6a*
Austenitic type 08Ch18N10T corrosion resistant steel of reactor internal components	600	278	888	399	*6b*



(**a**) (**b**)

Figure 5. (**a**) Change in tensile and yield strengths of HAZ I.; (**b**) Change in tensile and yield strengths of HAZ II. [5]



(**a**) (**b**)

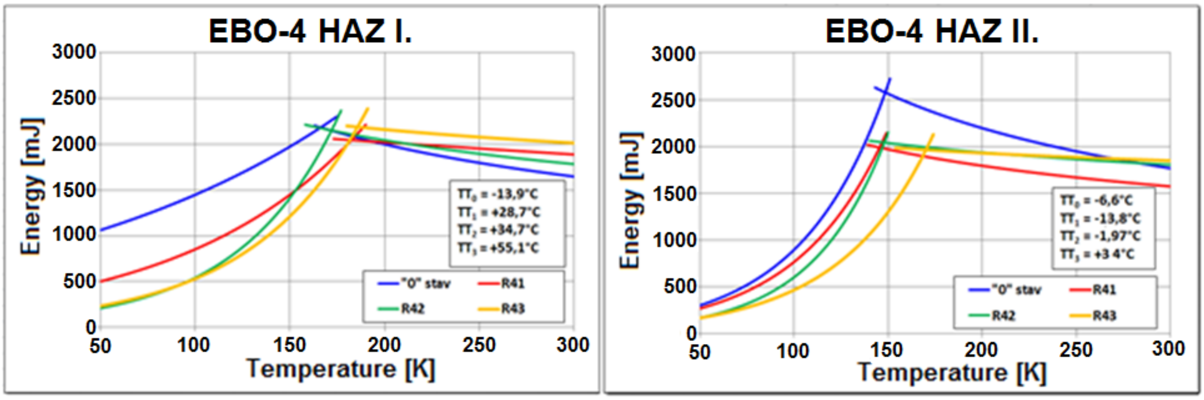
Figure 6. (**a**) Change in tensile and yield strengths of AC; (**b**) Change in tensile and yield strengths of 08Ch18N10T [5].

The $DBTT_{SPT}$ transition temperature values determined by the SPT test for ferritic materials are summarized in Table 2. The SPT energy as a function of temperature for these materials is shown in Figure 7, and for the austenitic materials in the Figure 8. The transition temperature of ferritic steels rises with increasing irradiation level. For austenitic steel 08Ch18N10T in contrast there is no transition temperature and no effect of the irradiation; the SPT energy decreases with increasing temperature [5].

Table 2. Results of $DBTT_{SPT}$ evaluated using SPT tests after irradiation of R 4BZ3 chain [5].

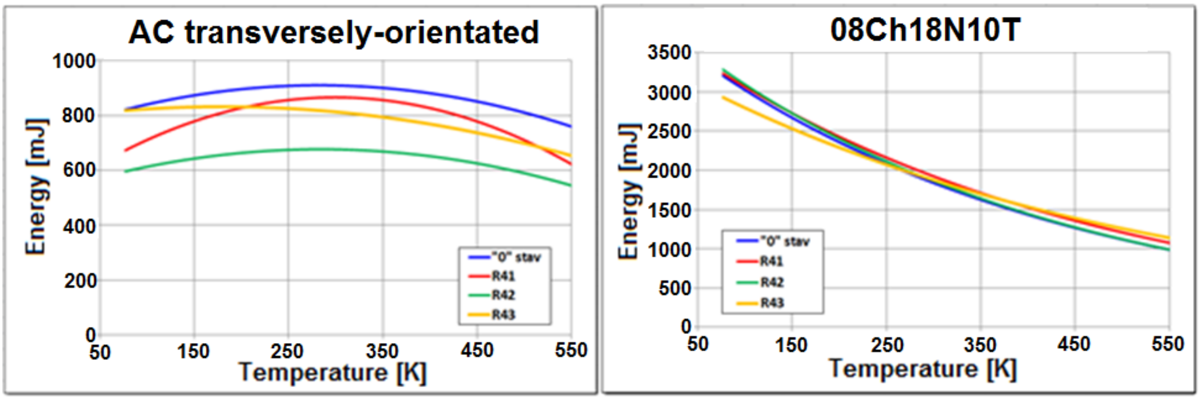
Material	**Transition temperature [°C]**		**Figure**
	“0“-state	**R 4BZ3**	
HAZ-I of weld no.4 from the RPV	-13.9	55.1	*7a*
HAZ-II of weld no.4 from the RPV	-6.6	34.0	*7b*
Underclad HAZ-I of the RPV	-24.2	59.4	-
Underclad HAZ-II of the RPV	-24.6	50.1	-
Transversely-orientated underclad HAZ from the RPV	-25.7	43.5	-

Original weld metal from RPV of unit no.4	14.4	74.6	-
Reference weld metal	-2.2	-	
Note: R41 - 1 fuel campaign, **R42** - 3 fuel campaigns, **R43** - 7 fuel campaigns			



(**a**) (**b**)

Figure 7. (**a**) Rise in $DBTT_{SPT}$ of HAZ I.; (**b**) Rise in $DBTT_{SPT}$ of HAZ II. [5].



(**a**) (**b**)

Figure 8. (**a**) SPT energy run for AC; (**b**) SPT energy run for 08Ch18N10T [5].

4. Discussion

By comparing the SPT experimental results of tensile properties for four representative materials with the values of mechanical properties as-tested by exactly the same SPT procedure, but in four different states,"0"-state and three irradiation levels (cf. Figures 5 and 6); it can be discussed the following:

- the values of tensile strengths for HAZ-I and HAZ-II confirmed the expected changes that are clearly manifested by the incremental trend in both Figures 5a and 5b,
- considering all the results, changes in the yield strengths for HAZ-I and HAZ-II as a result of irradiation by neutrons can also be well noticed, and the increase of R_e is still around 30%,
- changes in the values of tensile strengths for austenitic cladding AC and 08Ch18N10T type steel also confirmed the expected incremental behavior for both materials as given in Figures 6a and 6b,
- after the irradiation at different neutron fluences, the austenitic cladding AC in Figure 6a generally revealed slightly higher tensile and yield strengths than that of the 08Ch18N10T type steel in Figure 6b, nevertheless, the maximum tensile strength reached value was recorded for this type of structural material,
- the transition temperature curves shown in Figure 7 for the both HAZs indicate the larger shifts ascertained and the established values presented in Table 2, confirmed this as to the underclad HAZ-I and transversely-orientated underclad HAZ as well,

- the SPT energy curves for austenitic type in-vessel structural materials, as given in Figure 8, still document very high irradiation resistance to neutron induced damaging processes under the VVER-440/213 type reactor operating conditions,
- in terms of energy change, titanium-stabilized austenitic type 08Ch18N10T corrosion resistant steel can in overall be characterized as less sensitive to irradiation than the material of austenitic cladding AC, most probably for the reason of microstructural differences as claddings are in fact two-layered weldments, produced by using two different material weld tapes.

5. Conclusions

- In general, the tensile properties are higher for all HAZ types then for other material types tested,
- Further monitoring of materials properties continuous as per defined irradiation schedule,
- The most irradiation sensitive is the material of HAZ-I, and conversely the most irradiation resistant are the austenitic-type materials used for in-core and in-vessel RPV structures, such as claddings,
- The published results achieved in the evaluation of irradiated materials states are an essential part of the ASSP program and are used as the input data in calculation so as to determine the residual lives of all operating RPVs,
- The ASSP project is approved by the NRASR according to IAEA's recommendations, and has already been launched for all RPVs of the NPP Bohunice, and Mochovce units 1 and 2.

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