TAREG 2.01/00 Project, "Validation of neutron embrittlement for VVER 1000 and 440/213 RPVs, with emphasis on integrity assessment"

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Abstract

The irradiation embrittlement and integrity of the VVER reactors has been an important issue in many EC supported TACIS and PHARE projects since 1990. In the EC annual program 2000 two TACIS projects (TAREG 2.01/00 and 2.01/03) were approved on the issue in order to improve the neutron irradiation embrittlement databases, elaborate new trend curves for the embrittlement and to assess the integrity of the RPVs (Reactor Pressure Vessel) by analysing PTS transients (Pressurized Thermal Shock) for some selected Russian and Ukrainian VVER 1000 and 440/213 NPPs. In this paper the TAREG 2.01/00 project is briefly described with some details from the twin project 2.01/03, which served as a materials testing project, providing inputs for the 1st project. As a result of the project new trend curves for neutron irradiation embrittlement were elaborated, based on upgraded and more reliable surveillance results databases. The PTS study shows that the integrity of the selected VVER RPVs can be ensured to the end of RPV design life.

1. Introduction

The core region of a nuclear RPV (Reactor Pressure Vessel) gets brittle during operation due to strong neutron irradiation from the reactor core. The embrittlement of the material is followed up by a surveillance program which includes irradiation of test specimens made from the same material as the base- and weld metal of the RPV core region. The specimens are withdrawn with scheduled intervals during operation and tested in hot cells in order to determine the changes in mechanical- and especially fracture toughness properties.

The 1st generation of the VVER 440 NPPs (VVER 440/ V-230) did not have any surveillance program. Loviisa 1 NPP owned by Imatran Voima OY, today Fortum LTD, was the 1st VVER 440 NPP with a surveillance program. This plant is a 2nd generation VVER 440 of type V-213. The 1st surveillance set in Loviisa 1 was withdrawn from the reactor and tested in 1980. The 1st test results were surprising showing that the embrittlement rate is almost 3 times higher than expected [1]. The utility management as well as the safety authorities were very much concerned of the surveillance results which could remarkably limit the operating life of the RPV.

Fortum immediately decided to tackle the problem and make necessary modifications at the plant in order to mitigate the embrittlement and reduce the risk of brittle failure of the RPV. The reactor core was reduced by replacing 10% of the fuel elements at the periphery position with dummies. With this modification the neutron fluence in the worst azimuthal direction was reduced by a factor of 6. The temperature of the ECCS accumulators (emergency core cooling system) was increased from room temperature to 100 ^{o}C and of the ECCS tank to 60 ^{o}C. The capacity of the ECCS pumps was simultaneously decreased. The aim was at slowing down the cooling and reducing the thermal stresses in a possible PTS (Pressurized Thermal Shock) event at the plant. In 1996 the toughness properties of the RPV material in Loviisa 1 were recovered by annealing of the RPV core region weld. Since the problem is generic at VVER 440 NPPs, annealing has been carried out already at 16 units. Two units are of the VVER 440 V-213 type (Loviisa 1 and Rovno 1). Similar actions were taken at most of the older VVER 440 NPPs to ensure integrity of the RPV.

The neutron flux at the RPV wall of the VVER 1000 RPV is much smaller than in the VVER 440 due to a larger RPV diameter and water gap between the core and the wall. The core line material of the VVER 1000 RPV is also much cleaner containing a restricted amount of harmful impurities, such as Cu, P, As, Sn and Sb. Accordingly the material was expected to have much better resistance against neutron embrittlement. Nevertheless, the embrittlement of the VVER RPV material was also higher than expected, especially at units with high Ni content in the core region welds. But the embrittlement problem was never as serious as in the VVER 440 type of NPP.

2. TAREG 2.01/00 Project, "Validation of neutron embrittlement for VVER 1000 and 440/213 RPVs, with emphasis on integrity assessment"

The European Commission (EC) was also concerned about the irradiation embrittlement and integrity of the VVER reactors. When the TACIS support programs started in 1990 special attention was given to this issue and many TACIS and PHARE projects were launched in order to support VVER owner countries and ensure safety at the plants. In this paper two recently completed TACIS projects; TAREG 2.01/00, "Validation of neutron embrittlement for VVER 1000 and 440/213 RPVs with emphasis on integrity assessment" and TAREG 2.01/03, "Neutron irradiation embrittlement assessment and validation of embrittlement models for VVER RPVs" are briefly described with priority on the former. European Commission, DG-JRC was the Contractor of the 1st project, while a consortium of NRI Rez and FZR Dresden of the 2nd project. The aim of the 2nd project was mainly to carry out materials testing and generate test results to the JRC project, where they were compiled and used for irradiation embrittlement trend curve elaborations and integrity assessments, etc.

In Russia the Contractors/Sub-Contractors were: RRCKI (Russian Research Centre Kurchatov Institute), CRISM Prometey (Central Research Institute for Structural Materials), EDO Gidropress and Diaprom and in Ukraine KINR (Kiev Institute for Nuclear Research), IPS (Institute for Problems and Strength) and ARMS (Association for Reliability of Machines and Structures). Beneficiaries were Rosenergoatom in Russia and Energoatom in Ukraine. The 1st project commenced with the Kick of Meeting in ST Petersburg in October 2003 and was finished at the end of 2010.

2.1. Upgrading neutron fluence, mechanical properties of surveillance specimens and elaboration of new trend curves

The aims of Tasks 3 (VVER 1000) and 4 (VVER 440/213) were to carry out **more accurate neutron fluence calculations** for the surveillance specimens, carry out an inventory of tested surveillance specimens in order to **select specimen halves for re-constitution and testing** and to elaborate **new trend curves** for irradiation embrittlement based on the upgraded and more reliable database.

The neutron dosimetry procedures applied earlier for neutron fluence evaluation of VVER reactor surveillance specimens in Russia had a number of shortcomings and disadvantages compared to new approaches and capabilities. For upgrading of the neutron fluence evaluation for the **VVER 1000 reactors** new 3-D calculations for each fuel cycle for the surveillance specimen exposure were carried out. The orientation of the surveillance assembly and capsules during exposure was determined by comparing experimental and calculated values of ^{54}Mn activity in specimens. The spectral index, $SI_{0,5/3,0}$

was elaborated for each container taking into account the real orientation. The neutron flux in the surveillance specimens was evaluated by using P_3S_8 approximation of discrete ordinates using the TORT code and library BUGLE-96. The calculation of burn-up increments for the fuel assemblies was carried out using the BIPR-7A code and pin-by-pin burn-up increments in the periphery elements were carried out using code PERMAKA-A. For the inner part of the core an averaged neutron source was used while for the periphery assemblies a pin-by-pin source. In this project neutron fluence calculations were upgraded for the withdrawn surveillance specimens of Balakovo 1, 2, 3 and 4, Zaporozhe1, 2, 3, 4 and 5, Kalinin 1 and 2, Novovoronesh 5, Rovno 3, Khmelnitsky 1 and South Ukraine 1 and 2.

In Ukraine KINR also upgraded their neutron fluence calculations in a similar way but using other calculation codes. KINR applied the MCSS (Monte Carlo) method consisting of the following modules: Transport code Trans, SyconMom, D3mod3 and flux act. The MCSS code package was validated by comparing to benchmarking experiments carried out for Balakovo 1 (10th fuel cycle) in connection with the TACIS 2.01/96 project. The results of the comparison showed that the experimental and calculated results are consistent. Re-evaluation of neutron flux in KINR was completed for NPPs South Ukraine 1, 2 and 3, Khmelnitsky 1 and Zaporoche 6.

For **VVER 440/213 NPPs upgrading of neutron fluence** for selected surveillance specimens of Kola 3, 4 and Rovno 1 and 2 were carried out by the RRCKI. In contrast with earlier procedures the new method takes more accurately into account the real geometry of the internals close to the surveillance position, the influence of the core configuration on the neutron field formulation in the surveillance channel and the dependence of the spectral index ($SI_{0,5/3,0}$) on horizontal level of surveillance specimens. Validation of calculation method has been carried out using experimental results obtained under the EC supported project COBRA. The results of the upgrading for the VVER 440 plant showed that the new neutron fluence values are systematically slightly higher than previously. This can bee seen as a beneficial result since the damage to the irradiated surveillance specimens has actually taken place at higher doses than believed earlier.

Based on the results of upgraded neutron fluence calculations and on the above mentioned surveillance specimen inventory the selection of tested test specimen halves for reconstruction and testing was made. In RRCKI about 500 fracture- and impact toughness specimens from VVER 1000 NPPs (Balakovo 1, Kalinin 1, Novovoronesh 5, Zaporozhe 1-5 and South Ukraine 1) and 120 specimens from VVER 440/213 (Kola 1, 2 and Rovno 1 and 2) were reconstituted and tested. In addition about 112 sub-size Charpy specimens were machined from old tested specimens from the VVER 440/213 NPPs. In KINR 150 fracture- and impact toughness specimens were reconstituted and tested (South Ukraine 1, 3 and Zaporozhe 6). These reconstitution and testing activities were carried out in the TAREG 2.01/03 project; which was launched as a twin project in order to generate new test results as input for this TAREG 2.01/00 project.

The upgraded, more accurate and reliable surveillance databases were compiled for elaboration of new trend curves, that is, material embrittlement as a function of neutron fluence or operation time for the VVER RPVs. In the frame of TAREG2.01/00 project and simultaneously domestic Russian projects the following results were obtained [2,3].

It has been shown that VVER-1000 RPV material is getting brittle during operation due to both neutron irradiation and thermal ageing simultaneously. This is in contrast with the old Russian standard PNAEG-002-86 [4] where embrittlement due to thermal ageing during operation was not considered ($\Delta T_t=0$). Another reason for which we have to consider separately the embrittlement due to thermal aging and neutron irradiation is the fact that the leading factor for the surveillance specimens (SS) is not equal to unity. If leading factor for SS exceeds 1, for the same level of neutron fluence on SS and on wall of the RPV we will have the same level of ΔT_F but values of ΔT_t will be different.

VVER RPV materials embrittlement during operation may be presented as:

(1) $\Delta T_k(F,t) = \Delta T_t(t) + \Delta T_F(F)$, °C

where $\Delta T_k(F,t)$= the median value of the shift of the critical brittle fracture temperature during operation, $\Delta T_t(t)$= the median value of the shift of the critical brittle fracture temperature due to thermal ageing, $\Delta T_F(F)$= the median value of the shift of the critical brittle fracture temperature due to neutron irradiation, t= time, F= neutron fluence .

Conservative value of ΔT_k with probability 95% is calculated by formula:

$$(2) \qquad \Delta T_k^{95}(F,t) = \Delta T_k(F,t) + \omega, \ ^{o}C$$

where ω is the temperature margin. The parameter $\omega = 2\sigma$ (where σ is standard deviation).

In Eq (1) the dependences $\Delta T_F(F)$ is calculated as follows:

$$(3) \qquad \Delta T_F(F) = A_F \ (F/F_0)^n,$$

where A_F and n= embrittlement factors due to neutron irradiation; $F_0 = 1\cdot 10^{22}$ n/m^2 ($E \geq 0,5$ MeV).

For the **VVER 1000 RPV** dependences $\Delta T_t(t)$ and parameters A_F, n, ω are as follows:

$$(4) \qquad \Delta T_t(t) = \left(\Delta T_t^{inf} + b_T \exp\left(\frac{t_T - t}{t_{OT}}\right)\right) \cdot th\left(\frac{t}{t_{OT}}\right), \ ^{o}C$$

where ΔT_t^{inf} = the shift of the critical brittle fracture temperature at $t = \infty$; t_{OT}, t_T, and b_T are material constants, depending of ageing temperature (see Table 1).

Table 1 Constants in Eq(4) for **VVER 1000 RPV** materials

Material	b_T, °C	t_{OT}, hour	t_T, hour	ΔT_t^{inf}, ^{o}C
Base metal	26,2	32700	40700	2
Weld metal with $C_{Ni} \leq 1,3\%$	26,2	32700	40700	2
Weld metal with $C_{Ni} > 1,3\%$	10,1	23200	40900	18

The values of the embrittlement factors A_F and n in Eq(3) and parameter ω in Eq(2) are presented in Table 2.

Table 2 Constants in Eq(2) and Eq(3) for **VVER 1000 RPV** materials

Material	A_F, °C	n	ω, ^{o}C
Base metal	1,45	0,8	38
Weld metal	$\alpha_1 \exp(\alpha_2 \cdot C_{eqv})$, $C_{eqv} = \begin{cases} C_{Ni} + C_{Mn} - \alpha_3 C_{Si}, & \text{if } C_{Ni} + C_{Mn} - \alpha_3 C_{Si} \geq 0 \\ 0, & \text{if } C_{Ni} + C_{Mn} - \alpha_3 C_{Si} < 0 \end{cases}$ $\alpha_1 = 0,703$; $\alpha_2 = 0,883$; $\alpha_3 = 3,885$, C_{XX} = chemical content in weight %.	0,8	20

The formula for the weld metal is valid for the following values of nickel, manganese and silicon content: $1,00 \leq C_{Ni} \leq 1,90$ %, $0,40 \leq C_{Mn} \leq 1,10$ %, $0,20 \leq C_{Si} \leq 0,40$ %.

The equation for A_F for the weld metal shows that Mn, Ni and Si are the main elements having influence on the embrittlement rate due to neutron irradiation. The positive influence of Si content is a new observation. The core region material of the VVER 1000 RPV is quite pure in terms of impurities (Cu and P) and the variation of these impurities is rather insignificant in the core region material. Therefore the influence of impurities on neutron irradiation embrittlement is not assessed. It was also observed, that thermal ageing (ΔT_t) has a significant influence on material embrittlement and must be taken into account for the VVER 1000 RPV integrity assessment.

For the **VVER 440 RPV** dependences $\Delta T_t(t)$ and parameters A_F, n, ω are following:

(5) $\Delta T_t(t)=0, {}^oC$

The values of the embrittlement factors A_F and n in Eq(3) and parameter ω in Eq(2) are presented in Table 3.

Table 3 Constants in Eq(2) and Eq(3) for **VVER 440 RPV** materials

Material	A_F, °C	n	ω, °C
Base metal	$0{,}651 + 358(0{,}046\ C_{Cu} + (C_P - 0{,}002))$	0,483	21,96
Weld metal	$6{,}4 + 610(C_p + 0{,}07C_{Cu} - 0{,}01)$	1/3	20

For **base metal** a formula for A_F is valid for fluence $F \leq 3*10^{24}\ n/m^2$; $C_p \leq 0{,}013\%$ and $C_{Cu} \leq 0{,}11\%$, if $C_P \leq 0{,}002\%$, then it is taken $C_P = 0{,}002\%$.
For **weld metal** a formula for A_F is valid for: $C_P \leq 0{,}013\%$, $C_{Cu} \leq 0{,}11\%$, if $C_P + 0{,}07 \cdot C_{Cu} \leq 0{,}01\%$, then it is taken $C_P + 0{,}07 \cdot C_{Cu} = 0{,}01\%$.

Trend curves for welds metal was earlier elaborated in CRISM Prometey on the basis of test results of the irradiated specimens in the frame of a separate research program [7], where the test specimens were irradiated in research reactor conditions. It was shown that this trend curve gives a good prediction also for the surveillance–specimens tested in this TAREG programs.

For the core region weld different trend curves were elaborated depending on the Cu content. The 1st group is for core welds with $C_{Cu} \leq 0{,}08\%$, the 2nd for welds with $0{,}08 < C_{Cu} \leq 0{,}13\%$ and the 3rd group for $C_{Cu} > 0{,}13\%$. The above equation for the weld metal is valid for the 1st group only.

The trend shows that the embrittlement of the core region weld of the VVER 440/213 RPV depend on the Cu and P content of the material as in the old normative trend curve [8]. The new trend curves given above are based on evaluations carried out in CRISM Prometey and contains also low Cu content welds, which have been irradiated in research reactors as mentioned above. RRCKI elaborated different trend curves, which are based on results from irradiations in power reactors only. For weld metal with low cooper content both obtained dependences give comparable predictions when $C_{Cu} \approx 0{,}04\%$. For $C_{Cu} > 0{,}04\%$, RRCKI dependence gives more conservative estimation as compared with CRISM Prometey dependence and has a slightly more scatter. For base metal RRCKI dependence has different form as compared with CRISM Prometey dependence, predicted in Table 3. Difference in prediction for base metal on the basis of RRCKI and Prometey trend curves is small.

2.2. RPV brittle fracture analyses and integrity assessment

In Task 5, brittle fracture analyses were carried out in order to evaluate the integrity of the RPV for some selected Russian and Ukrainian VVER 1000 and 440/213 NPPs. In these studies the results from the upgraded neutron fluence calculations, the reconstitution and testing carried out in the twin project TAREG 2.01/03 and the new trend curve developments were used. PTS (Pressurized Thermal Shock) calculations were carried out in OKB Gidropress in Russia and in IPS (Institute for Problems of Strength) in Ukraine. The brittle fracture analyses included the following steps:

- Thermo-hydraulic analyses of the reactor coolant system
- Calculation of temperature distribution in the RPV wall due to cooling
- Stress analyses for the RPV core region taking into account both thermal and pressure stresses
- Calculation of stress intensity K_I for postulated defect perpendicular to the maximum stresses
- Calculation of crack growth of the postulated defect during design life (40 years) taking into account design stress variation (heat-up/cool down, hydraulic tests, etc.)
- Determination of the fracture toughness of the core region material after 40 years of operation; taking into account neutron irradiation embrittlement, thermal ageing and fatigue

The brittle fracture analyses were performed according to the Russian standard [6] in both countries. In Russia RPV integrity analyses were carried out for Balakovo 2 (type V-320), Kalinin 1 (V-338) and Kola 3 (type V-213) by OKB Gidropress and in Ukraine for Khmelnitsky 1 (V-320), South Ukraine 2 (V-338) and Rovno 2 (V-213) by IPS. As initiating events for the analyses the following incidents were selected:

- SBLOCA, Small Break Loss of Coolant Accident (VVER 1000)
- MBLOCA, Medium Break LOCA (VVER 1000)
- Inadvertent opening of pressurizer safety valve (VVER 1000)
- Inadvertent opening of pressurizer safety valve with subsequent closing (VVER 440)
- Lift-off of steam generator collector cover (VVER 1000 and 440)
- Steam Line Break before secondary circuit safety valve

The selected transients are the most severe ones for VVER reactors with emphasis on RPV brittle failure according to reactor designer and others. OKB Gidropress used TRAP-97 code for thermo hydraulic analyses. Water mixing in nozzle region and down comer was calculated with code OKBMIX. In the Stress analyses the most up-to date 3D FEM codes were applied. In Russia OKB Gidropress used the MSC.MARC code for temperature fields, stress and fracture mechanic parameters (J-integral) calculations. In Ukraine IPS used the SPACE code for temperature field and stress calculations. The discrete FEM model of the VVER 1000 RPV used by OKB Gidropress is shown as an example in Fig 1 together with the crack model for a postulated sub-surface crack under the cladding.

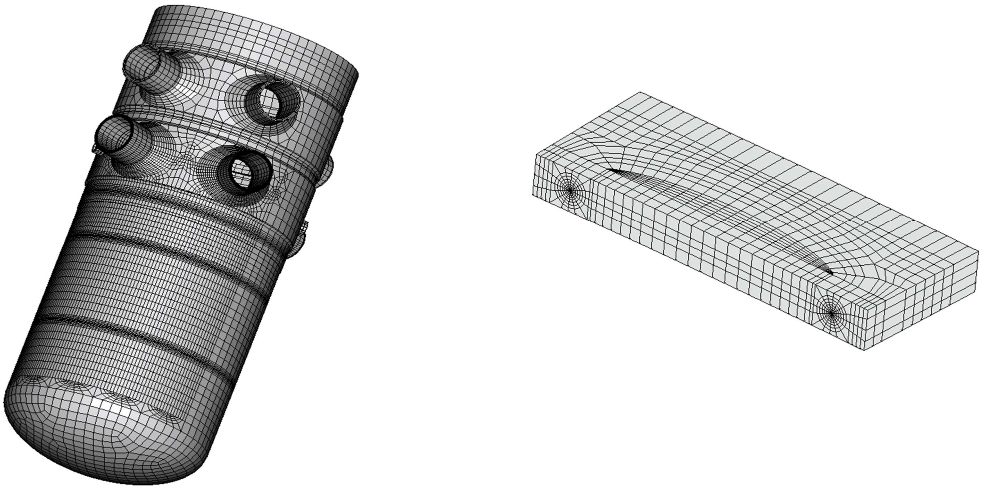

Fig 1. FEM models for the VVER 1000 RPV and postulated sub-cladding crack.

According to the a.m. Russian standard [6] it is allowed to postulate and **analyse only sub-surface flaws** in the RPV wall, provided that the cladding integrity has been proved in periodic ISI (In Service Inspection) with NDT (Non Destructive Testing) e.g. by using ultra sound technique. In addition it is necessary to show that the fracture toughness of the cladding is good enough ($J_C > 65$ N/mm) taking into account neutron exposure. If this fracture toughness request cannot be met, it is still allowed to make more detailed fracture analyses to prove crack stability on the cladding side of the postulated sub-surface crack.

If this cannot be met, it is requested to postulate a **surface crack through the cladding** in the RPV integrity analyses. This could be very punishing in the PTS study due to the contribution of the high tensile stresses evolved in the cladding when cooling. In this project only sub-surface cracks were calculated since the mentioned toughness criteria ($J_C > 65$ N/mm) was met for all selected cases.

In the brittle fracture analyses of the RPV core region the fracture toughness curve, K_{Jc}, of the material after 40 years of operation must be elaborated. According to the Russian standard [7] and [8-9] the "Unified Curve" created by CRISM Prometey shall be used (6).

(6) $K_{Jc\,(med)} = K_{Jc,shelf} + \Omega(1 + \tanh[(T-130)/105])$, MPa√m

$K_{Jc,\,shelf}$ = 26 MPa√m; Ω = factor for a given state of a material which takes into account thermal ageing, C_T, and irradiation embrittlemment, C_F as given in below equation (7):

(7) $\Omega = \Omega_o \exp[-(C_T + C_F(F/F_o)^n)]$, MPa√m

Ω_0= a value of Ω for unirradiated condition, $C_T=(2/105)\Delta T_t$. $C_F=(2/105)A_F$.

In the following the elaborated K_{Jc} curve for the upper core weld (weld 4) of Balakovo 2 RPV after 40 years of operation is given as an example (8):

(8) $K_{Jc} = 22 + 142[1 + \tanh[(T-130)/105]]$, MPa√m

K_{Jc} = the fracture toughness corresponding the fracture probability 5% and reference thickness $\overline{B}$=150 mm, T= temperature, °C.

The critical fracture toughness curve for RPV core region material was elaborated in a similar way for all selected NPPs for the PTS studies under Task 5. On the basis of the fracture toughness curve, K_{Jc}, allowable value of stress intensity factor, $[K_C]$, is determined by using equation (9).

(9) $$[K_C] = K_{min} + (K_C - K_{min}) \cdot \left(\frac{\overline{B}}{B}\right)^{1/4}$$

where $[K_C]$ is the value of K_C corrected to length of the crack front B. K_C is a value of the fracture toughness with regarding for the shallow crack effect and biaxial loading. K_C is calculated by special procedure [6, 10-12] on the basis of K_{Jc} (8). $\overline{B}$=150 mm, K_{min}=20 MPa√m. According to [6, 10-12] the brittle strength conditions for RPV with a postulated crack are considered in two variants. According to simple conservative approach the strength condition for the crack front located in base/weld metal is represented in the following form:

(10) $n_i K_I \leq [K_C]$,

where K_I= stress intensity factor, n_i= safety factor.

According to the less conservative approach (integral approach) the brittle strength condition is fulfilled if for each time moment for the front of the postulated crack the following condition is fulfilled /10-12/:

(11) $$\frac{1}{\overline{B}} \int_0^B Z dL < 1 \cdot$$

In the condition (11) the parameter Z is equal to the maximum value α for the whole loading period from 0 to the considered time moment τ:

(12) $$Z = \max_{(0,\tau)} \{\alpha\}, \quad \text{where } \alpha = \left(\frac{n_i K_I(L) - K_{min}}{K_C(L) - K_{min}}\right)^4,$$

where $K_I(L)$ is the distribution of SIF along crack front L.

In eqs (10)-(12) for calculating the K_I for the postulated flaw the internal pressure, the thermal stresses as well as the residual stresses of weld seams and cladding were taken into account. It is assumed, that the residual stresses of the cladding is at yield limit in room temperature. In the more detailed stress intensity factor calculations the J-integral is first calculated using elastic-plastic FEM calculations using the MARC code. The stress intensity factor K_I is then determined by using equation (13).

(13) $K_I = \sqrt{JE/(1-v^2)}$, J = J-integral, E= Youngs modulus and v = Poisons factor.

As an example the brittle fracture analysis relating to the MBLOCA transient at Balakovo 2 is shown (Fig 2). This analysis was performed by using a conservative approach for the brittle strength condition.

The postulated sub-surface crack is assumed 14,2 mm deep and 85,2 mm long, having a half-elliptic shape (see Fig 1). The postulated crack is placed in the upper core weld under one primary nozzle in the so called "cold plum" sector. In Fig 2 the temperature dependence of allowable fracture toughness, $[K_C]$, after 40 years of operation and a series of calculated stress intensity curves, n_iK_I (where n_i=1,1- safety factor for accident conditions), are shown for different points along the elliptic crack front. Point 13 shows the stress intensity at the deepest point of the crack and point 1 the vessel/cladding border.

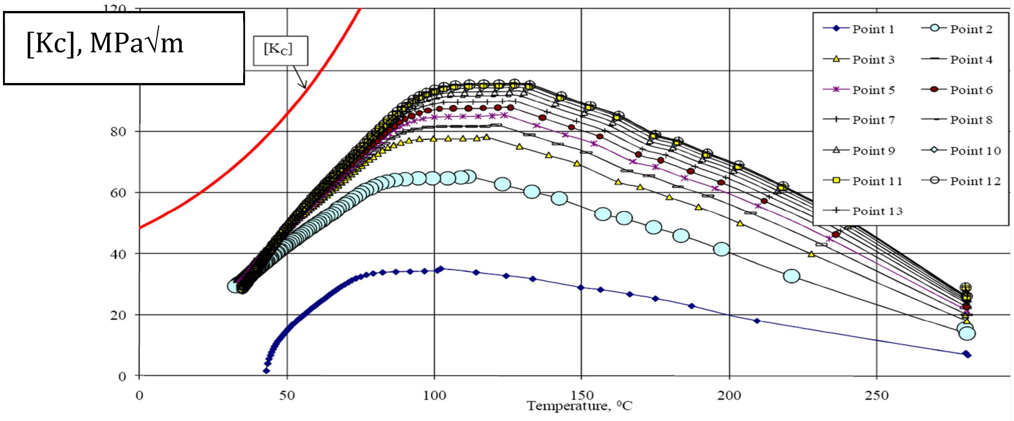

Fig 2. Results of RPV brittle fracture analyses for a MBLOCA at Balakovo 2, core weld 4.

Since the allowable $[K_C]$ curve and the series of calculated stress intensity curves K_I do not meet at any point, the crack is stable and situation accepted. That's why a calculation by using a less conservative integral approach for the brittle strength condition is not performed. The margin between the curves is in this case about 40 °C. This margin can be converted to remaining years of safe operation by using equation (1) and taking also into account the contribution of thermal ageing (ΔT_t). The stress intensity factor and the critical fracture toughness curve were determined in a similar way for all above mentioned VVER 1000 and 440/213 NPPs. The results showed that there is a large margin against brittle fracture initiation in all analysed cases.

As mentioned already the new Russian standard [6] allows for analysing only sub-surface cracks when cladding integrity is proved by ISI and tough enough. Many other standards and guidelines e.g. VERLIFE, RCCM, ASME etc. has the same approach today regarding postulation of crack mode. This has been described in more detail in the IAEA Tecdoc 1627, published in Vienna in 2010 [13], where a large sensitivity study regarding crack mode has been made on an international level. It is clear, that studying a sub-surface crack as compared to a surface crack through the cladding is very beneficial. For a through cladding crack the temperature stresses evolving in the cladding during a PTS, when the inner wall of the RPV is cooling down, creates a strong loading contribution on the crack tip [14]. This would increase the calculated stress intensity factor and reduce the safety margin and accordingly lower the highest allowable transition temperature T_{ka}. This detail is very important when evaluating integrity and safe lifetime of the RPV.

3. Conclusion

In this TAREG project new trend curves for neutron irradiation embrittlement were developed based on the results of neutron fluence upgrading and fracture toughness test results of the surveillance specimens under Tasks 3 and 4. The new test results and the upgraded trend curves were used for RPV integrity assessment for selected VVER 1000 and 440/213 NPPs in Russia and Ukraine in Task 5. The brittle fracture analyses confirmed RPV integrity in all selected NPPs and safe operation could be ensured to the end of design life of 40 years for each reactor.

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