Joint ICTP/IAEA Workshop on Irradiation-induced Embrittlement of Pressure Vessel Steels

23 - 27 November 2009

Comparison of PWR and WWER RPV integrity and lifetime approaches

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Rez
COMPARISON OF PWR AND WWER RPV INTEGRITY AND LIFETIME APPROACHES

Milan Brumovský

Joint ICTP/IAEA Workshop on Effects of Mechanical Properties and Mechanisms Governing the Irradiation-induced Embrittlement of Pressure Vessel Steels
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INTRODUCTION

- INTEGRITY EVALUATION OF RPVs ARE USUALLY FULLY LEAD BY PTS ANALYSES
- THIS PRESENTATION WILL DEAL ONLY WITH A DETERMINISTIC APPROACH
- PWR ANALYSES ARE BASED MOSTLY ONY ASME/RSE-M/KTA CODES
- VVER ANALYSES ARE PERFORMED ACCORDING TO RUSSIAN MRKR-SKhR-2004 AND VERLIFE
Standards Currently Applicable for RPV Integrity Assessment for WWER

- Unified Procedure for Lifetime Assessment of Components and Piping in VVER NPPs, VERLIFE, ver. 2008 (prepared within the frame of VERLIFE project of the 5th Framework Programme of the EU) – in what follows, VERLIFE approach is mostly presented
- Guidelines on Pressurized Thermal Shock Analysis for WWER Nuclear Power Plants, Revision 1, IAEA-EBP-WWER-08 (Rev. 1), IAEA, Vienna, 2006
- Standards for Strength Evaluation of Component and Piping of Nuclear Power Plants, PNAE G-7 002-86 (in Russian)
- Methodology of Determination of the Residual Lifetime of the Reactor Pressure Vessels of WWER Reactors During Operation, MRK-SChR-2004” (in Russian)
INTRODUCTION

- ALL APPROACHES ARE BASED ON APPLICATION OF FRACTURE MECHANICS APPROACH
- DIFFERENCES CAN BE FOUND IN:
  - DEFINITION OF CHARPY TRANSITION TEMPERATURE
  - DESIGN FRACTURE TOUGHNESS CURVES
  - USE OF TRANSITION TEMPERATURES
  - EVALUATION OF RADIATION DAMAGE
  - POSTULATED DEFECTS AND GROUNDS FOR THEIR SIZE, TYPE, SHAPE
DEFINITION OF CHARPY TRANSITION TEMPERATURE

PWR ACCORDING TO ASME:

\( \text{RT}_{\text{NDT}} \) BASED ON DWT AND CHARPY TESTS

VVER ACCORDING TO PNAEG:

*critical temperature of brittleness* is a basis for an assessment of resistance against brittle failure. This critical temperature of brittleness, \( T_k \), is determined using notch toughness testing of Charpy-V type specimens, only. In principle, this temperature is defined as a temperature, at which the mean value from 3 notch toughness tests is equal to a criterial value \((\text{KCV})_c\) which is dependent on the yield strength \((R_{\text{p0.2}})\) of the material:

<table>
<thead>
<tr>
<th>( R_{\text{p0.2}} ) [MPa]</th>
<th>( (\text{KCV})_c ) [J.cm(^{-2})]</th>
<th>( (\text{KV})_c ) [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>less than 300</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td>300–400</td>
<td>40</td>
<td>32</td>
</tr>
<tr>
<td>400–550</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>550–700</td>
<td>60</td>
<td>48</td>
</tr>
</tbody>
</table>

At the same time, at a temperature equal to \( T_k + 30^\circ \mathrm{C} \) the following supplementary requirements must be fulfilled:

\[
\begin{align*}
\text{KCV} & \geq 1.5 \ (\text{KCV})_c \\
(\text{KCV})_{\text{min}} & \geq 0.7 \times 1.5 \ (\text{KCV})_c = 1.05 \ (\text{KCV})_c \\
(\text{fracture appearance})_{\text{min}} & \geq 50\% \ (\text{fibrous fracture}, \%)
\end{align*}
\]
DEFINITION OF CHARPY TRANSITION TEMPERATURE

Differences between these critical temperatures, as determined experimentally for Types 15Kh2MFA and 15Kh2NMFA steel and ASTM A 533-B steel are:

\[ \delta T = R T_{NDT} - T_k = \pm 10^\circ C \] (11)

The brittle to ductile transition temperature (critical temperature of brittleness) of the WWER pressure vessel materials is time or use dependent, since many damaging mechanisms can affect it, and can be expressed in the form:

\[ T_k = T_{k0} + \Delta T_F + \Delta T_T + \Delta T_N \] (12)

where

- \( T_K \) is the instant critical temperature of brittleness
- \( T_{k0} \) is the initial critical temperature of brittleness
- \( \Delta T_F \) is the shift of critical temperature due to radiation embrittlement
- \( \Delta T_T \) is the shift of critical temperature due to thermal ageing
- \( \Delta T_N \) is the shift of critical temperature due to cyclic damage
DEFINITION OF CHARPY TRANSITION TEMPERATURE

The transition temperature shift due to radiation embrittlement ($\Delta T_F$) can be expressed as

$$\Delta T_F = A_F \times (F \times 10^{-22})^{1/3}$$

(13)

where

$A_F$ is the radiation embrittlement coefficient

$F$ is the neutron fluence with energies greater than 0.5 MeV.

The shift $\Delta T_N$ represents the changes in the material properties caused by low-cycle fatigue damage. All transients are considered, including heatup and cooldown, pressure testing, scram, etc. For WWER pressure vessel materials, the Code provides the following formula to be used in the calculations:

$$\Delta T_N = 20 \times A \ [^\circ C]$$

(16)

where $A$ is the usage factor from the fatigue calculations, which means that the maximum shift due to cyclic damage is equal to $+20^\circ$C. This shift is, of course, only taken into account in locations with high stress concentrators, where a high usage factor is obtained - i.e. mostly for nozzles.
DESIGN FRACTURE TOUGHNESS CURVES

**PWR and BWR:**

\[ K_{IC} (T-RT_{NDT}) = \min \{36.5+3.1 \exp[0.036(T-RT_{NDT}+55.5)]; 220 \text{ MPa.m}^{0.5}\} \]

**WWER (generalised curve):**

\[ [K_{IC} (T-T_k)] = \min \{26 + 36 \exp [0.020 (T-T_k)]; 200 \text{ MPa.m}^{0.5}\} \]
DESIGN FRACTURE TOUGHNESS CURVES

Comparison of ASME and VVER design curves

- KIC - ASME
- KIR - ASME
- [KIC] - VVER-generc

KIC, KCJ, MPa.m^0.5

T-RTNDT, T-Tk, °C
DESIGN FRACTURE TOUGHNESS CURVES

Original design fracture toughness curve applicable to base metals (PNAEG, VERLIFE):

\[ [K_{IC}]_3 = 26 + 36 \cdot \exp \left[ \frac{(0.02 (T - T_k))}{g_{62}} \right] \]

has been modified (RD-EO-0353-02, RD EO 0606 - 2005) as:

\[ [K_{IC}]_3 = 23 + 48 \cdot \exp \left[ \frac{(0.019 (T - T_k))}{g_{62}} \right] \]
DESIGN FRACTURE TOUGHNESS CURVES

![Graph showing design fracture toughness curves.](image)

- KCJ, MPa.m\(^{0.5}\)
- T - Tk0, °C

- B=10
- B=16
- B=25
- B=30
- B=37.5/40
- B=50
- B=75
- B=100
- B=125
- B=150

- [KIC]3-G
- [KIC]3-WM
DESIGN FRACTURE TOUGHNESS CURVES

WWER (generalised curve):

\[ K_{IC} (T-T_k) = \min \{ 26 + 36 \exp [0.020 (T-T_k)]; 200 \} \]

MASTER CURVE:

\[
\begin{align*}
K_{JC(\text{med})} &= 30 + 70 \cdot \exp [0.019 (T - T_0)] \\
K_{JC(0.05)} &= 25.2 + 36.6 \exp [0.019(T-T_0)] \\
K_{JC(0.95)} &= 34.5 + 101.3 \exp [0.019(T-T_0)]
\end{align*}
\]
DESIGN FRACTURE TOUGHNESS CURVES

![Graph showing fracture toughness curves with various symbols and lines indicating different B values and confidence levels.](image-url)
DESIGN FRACTURE TOUGHNESS CURVES

![Graph showing Kic, MPa.m^0.5 vs. T-Tk, T-T0, °C]

- Red line: ASME
- Blue line: [KIC]3-G
- Green line: MC(0.05)
Temperature dependence of WWER-440 RPV static fracture toughness of surveillance materials
1 year = approx. 6x10^{23}m^{-2} (E>0.5 MeV)
USE OF „MASTER CURVE”

ACCORDING TO VERLIFE PROCEDURE:

Reference temperature $T_0$
Reference temperature $T_0$, increasing during operation, is determined experimentally from surveillance specimens irradiated to required neutron fluence. End-of-life design fluence should be taken as a basis for initial evaluations. Possible thermal and fatigue aging should be also taken into account.
USE OF „MASTER CURVE“

- Determination of reference temperature $T_0$ is performed using “Master curve” approach using multi-temperature approach preferably to the single-temperature one.
- Reference temperature $T_0$ is defined from experimentally determined values of static fracture toughness, $K_{JC}$, adjusted to the thickness of 25 mm. Margin $\sigma$ is added to cover the uncertainty in $T_0$ in accordance with Appendix III and for the assessment the value $RT_0 = T_0 + \sigma$ is used.
Reference temperature, $T_0$, as determined in accordance with the standard ASTM E 1921-02 is increased by a margin, equal to a standard deviation $\Delta \sigma$ only for the tested condition, i.e. either initial or for a given degradation state. Reference temperature $T_0$ is defined from experimentally determined values of static fracture toughness, $K_{JC}$, adjusted to the thickness of 25 mm. Margin is added to cover the uncertainty in $T_0$ associated with using of only a few specimens to establish $T_0$. The standard deviation $\sigma$ of the estimate of $T_0$ is given by:

$$\sigma_1 = \beta / N^{0.5}, ^{\circ}C$$

where $N$ = total number of specimens used to establish the value of $T_0$,

$\beta = + 18 ^{\circ}C$. 
USE OF „MASTER CURVE“

To consider the scatter in the materials, another margin denoted in what follows $\delta T_M$ should be applied. If this value is not available the application of the following values is suggested

$\delta T_M = 10^\circ C$ for the base material,

$\delta T_M = 16^\circ C$ for weld metals
The resulting margin is:

$$\sigma = (\sigma_1^2 + T_M^2)^{1/2}$$

Thus, reference temperature when used in integrity evaluation, \(RT_0\), is defined as:

$$RT_0 = T_0 + \sigma$$
If the experimentally determined values of the initial critical temperature of brittleness $T_{ko}$ from component Acceptance Tests are known (based on component Passport), they can be used only in the case that the following temperature margin $\delta T_M$ will be added; the margin has to take into account the scatter of the values of mechanical properties in the semi-product; $\delta T_M$
USE OF „MASTER CURVE“

- $\delta T_M$ is the mean quadratic deviation of $T_{ko}$ determined for the given semi-product in the frame of Qualification Tests or in the frame of a set of identical semi-products established during production of the component by the identical technology. If this value is not available the application of the following values is suggested

  $\delta T_M = 10^\circ C$ for the base material,
  $\delta T_M = 16^\circ C$ for weld metals.
Shift of the critical temperature of brittleness is determined from the formula

$$\Delta T_F = T_{kF} - T_{ki}$$  \hspace{1cm} (5)

where $T_{kF}$ is a value of transition temperature for a fluence $F$,

$T_{ki}$ is a value of transition temperature for initial conditions (unirradiated).
In both cases, these temperatures are determined from similar sets of specimens (minimum 12) using similar test equipment and procedure. The difference in fluence between specimens of one set should be smaller than ±15% of the mean value, and the difference in irradiation temperatures of individual specimens should be within a ±10°C. Finally, the mean value of irradiation temperature should be no higher than +10°C above the inner wall temperature of the reactor pressure vessel.
EVALUATION OF RADIATION DAMAGE

 Obtained experimental values of KV (impact notch energy) are evaluated using the following equation

$$KV = A + B \text{th} \left[ \frac{(T-T_0)}{C} \right]$$

(6)

where A, B, C and T0 are constants derived by statistical evaluation. It is strongly recommended to set lower shelf energy at 3 J to avoid incorrect fitting when a small number of specimens are tested in the lower shelf energy temperature region.
Shift of the transition temperature is determined for the criterion \( KV = 41 \, \text{J} \) (7)

This procedure results in valid values of \( \Delta T_F \) only when the upper shelf energy, derived from the formula (6) - i.e., sum of \( (A+B) \), - is greater than 68 J.
The results of determinations of the shift in the critical temperature of brittleness obtained at least for three different neutron fluences (the difference between the fluences has not be smaller than the value of the lowest fluence) are to be evaluated by the least squares method using the relationship:

$$\Delta T_F = A_F^{\text{exp}} \cdot (F \cdot 10^{-22})^n$$  \hspace{1cm} (8)

where $F$ is the fluence of fast neutrons with the energy higher than 0.5 MeV, $A_F^{\text{exp}}$ and $n$ are empirical constants obtained by statistical evaluation.
Then, the mean trend curve should be vertically shifted upward by the value of $\delta T_M$. If any experimental point exceeds this adjusted trend curve, the curve should be shifted further until it bounds all data. This upper boundary of the shifts is to be used in assessment of RPV resistance against fast fracture.
It is not allowed to extrapolate shifts of the transient temperatures for the fluences higher than 20% of the maximum fluence used for the experiment.
EVALUATION OF RADIATION DAMAGE

EXAMPLE OF DATA FITTING-1

![Graph showing transition temperature vs. fluence]

- Transition temp [°C]
- Fluence [10E18 n/m²]

- Best fit
- Best fit + margin
- Surveillance data
If there are insufficient surveillance test results:

In a such a case, the coefficients of irradiation embrittlement have to be used in the following relationship for the pressurised reactor vessel materials in accordance to the formula (10):

\[ \Delta T_F = A_F^{\text{exp}} \cdot (F \cdot 10^{-22})^{1/3} \]  \hspace{1cm} (10)
CRACK POSTULATION

VERLIFE PROCEDURE:

- Crack postulation is based on qualification of NDE for the RPV.
- **Orientation**: both axial and circumferential cracks.
- **Shape**: semi-elliptical underclad or surface cracks.
- **Depth**: in the case when *qualified* non-destructive testing (NDT) is used, the depth is defined on the basis of the qualification criteria:
  - recommended value $a_{calc} = s/10$, \( s \) is wall thickness
  - i.e. 15 mm for WWER 440
  - 20 mm for WWER 1000.
  - without qualification of NDT: $a_{calc} = s/4$
- **Aspect ratio**: $a/c = 0.3$ and $a/c = 0.7$.
- Assessed points on the crack front: at least near interface points and the deepest point (the whole crack front assessment is recommended).
CRACK POSTULATION

Underclad crack

Surface breaking crack
CRACK POSTULATION

- Undreclad crack may be postulated for cladded RPV, provided that integrity of cladding is assured by qualified non-destructive inspections.
- Assessment of effect of cladding is based on the use of its J-R curve (in the case of multi-layer cladding, J-R curve for the 1st layer).
- The postulated underclad crack is conservatively defined as partially penetrating 1 mm into the cladding.
CRACK POSTULATION

- In this case, the integrity of cladding above the postulated defect during the whole PTS regime has to be verified.

- J-values for all time steps of the regime shall be calculated (it is sufficient to calculate J-values only for the middle point of crack front in cladding).

- These J-values have to be (for all assessed time steps) smaller than the end-of-life values of J-R curve corresponding to 1 mm crack extension (i.e. J_{1mm} values).

- The J_{1mm} values are specified as follows:
  a) If no RPV specific data are available, generic values of J_{1mm} are:
     - 100 kJ/m² for WWER 440 RPV
     - 150 kJ/m² for WWER 1000 RPV.
  b) If component specific data are available, then experimentally determined J_{1mm} divided by safety factor 2 shall be used.
CRACK POSTULATION

RUSSIA PROCEDURE MRKR:

- Methodology of Determination of the Residual Lifetime of the Reactor Pressure Vessels of WWER Reactors During Operation, MRKR-SChR-2004” (in Russian)
- Crack postulation is based on results from NDE for the RPV during manufacturing, only
- **Shape:** semi-elliptical underclad or surface cracks.
- **Depth:** no requirements for **qualified** non-destructive testing (NDT)
  - recommended value $a_{calc} = 0.07 \, s$ (s is wall thickness)
  - i.e. 10 mm for WWER 440
  - 14 mm for WWER 1000.
- **Aspect ratio:** $a/c = 0.3$ and $a/c = 0.7$. 
## COMPARISON OF APPROACHES

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>China</th>
<th>Czech Rep.</th>
<th>Finland</th>
<th>France</th>
<th>Germany</th>
<th>Hungary</th>
<th>Korea</th>
<th>Slovakia</th>
<th>Russia</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR</td>
<td>VVER¹</td>
<td>VVER</td>
<td>VVER and PWR</td>
<td>PWR</td>
<td>PWR</td>
<td>VVER</td>
<td>PWR</td>
<td>VVER</td>
<td>VVER</td>
</tr>
<tr>
<td>Codes/Approaches</td>
<td>ASME XI</td>
<td>PNAE G-7-002-86/VERLIFE</td>
<td>VERLIFE</td>
<td>ASME III, XI, VERLIFE</td>
<td>RSE-M</td>
<td>KTA</td>
<td>VERLIFE</td>
<td>ASME XI</td>
<td>VERLIFE</td>
</tr>
</tbody>
</table>

¹ Chinese VVER: calculations were performed for design stage in 1998-1999
### COMPARISON OF APPROACHES

<table>
<thead>
<tr>
<th>Transients</th>
<th>China</th>
<th>Czech Rep.</th>
<th>Finland</th>
<th>France</th>
<th>Germany</th>
<th>Hungary</th>
<th>Korea</th>
<th>Slovakia</th>
<th>Russia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Transients</td>
<td>SB-LOCA</td>
<td>SB-LOCA</td>
<td>Large LOCA</td>
<td>LB-LOCA &amp; SB-LOCA</td>
<td>LB LOCA SLB</td>
<td>SGTR SBLOCA</td>
<td>Case to case, mainly transients with pressurization under low temperature as Small LOCA, Primary to secondary leakage</td>
<td>VVER-1000: Primary Small LOCA, Primary to Secondary Leakage</td>
<td>VVER-440: Primary Small LOCA, Secondary Leakage</td>
</tr>
<tr>
<td></td>
<td>Overcooling with repressurization based on PRA</td>
<td>LS-LOCA</td>
<td>Safety valve opening and reclosure</td>
<td>SLB-SSLB</td>
<td>SLB</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
## COMPARISON OF APPROACHES

<table>
<thead>
<tr>
<th>Thermo-Hydraulic Computation</th>
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<th>France</th>
<th>Germany</th>
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<th>Korea</th>
<th>Slovakia</th>
<th>Russia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tools for global system</td>
<td>RELAP 5</td>
<td>TRAP</td>
<td>RELAP 5</td>
<td>APROS, RELAP5</td>
<td>Cathare</td>
<td>S-RELAP5 Version V311 PTS</td>
<td>RELAP5 ATHLET</td>
<td>TRAP</td>
<td>RELAP4</td>
</tr>
<tr>
<td>Plumes and mixing (Y/N)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Tools for mixing analysis</td>
<td>No</td>
<td>Engineering approach based on experimental results</td>
<td>REMIX/NE WMIX, CATHARE</td>
<td>REMIX</td>
<td>SATURNE SYRHES</td>
<td>KWU-MIX</td>
<td>REMIX</td>
<td>PHOENICS</td>
<td>EBOMIX</td>
</tr>
</tbody>
</table>

26.11.2009
## COMPARISON OF APPROACHES

<table>
<thead>
<tr>
<th></th>
<th>China</th>
<th>Czech Rep.</th>
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<tbody>
<tr>
<td><strong>Fluence</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurement via monitoring</td>
<td>Yes</td>
<td>Y,</td>
<td>Y</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes (surveillance capsules)</td>
<td>Yes</td>
</tr>
<tr>
<td>(Y(position)/N)</td>
<td></td>
<td>surveillance capsules, outer surface</td>
<td>(samples outside RPV, max fluence)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Y 3D</td>
<td>Yes</td>
<td>Yes</td>
<td>recalculation based on measured values</td>
<td>Yes</td>
</tr>
<tr>
<td>Attenuation through the</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>thickness (Y/N)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

- **Yes** indicates that the approach is used.
- **No** indicates that the approach is not used.
- **Y** indicates that the approach is considered for future implementation.

**Fluence** via monitoring includes Y, surveillance capsules, and outer surface for China. For other countries, the approach includes Y samples outside RPV, max fluence. Calculation methods vary, with 3D being used in some cases. Attenuation through the thickness is considered for China, Czech Republic, and Slovakia, with Russia not explicitly stated.
# COMPARISON OF APPROACHES

<table>
<thead>
<tr>
<th>Vessel Temperature and Stress Evaluation</th>
<th>China</th>
<th>Czech Rep.</th>
<th>Finland</th>
<th>France</th>
<th>Germany</th>
<th>Hungary</th>
<th>Korea</th>
<th>Slovakia</th>
<th>Russia</th>
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</thead>
<tbody>
<tr>
<td>FE (tools) or analytical</td>
<td>MSC.MARC</td>
<td>MSC.MARC</td>
<td>FE, SYSTUS</td>
<td>FE (FLUENT, ABAQUS)</td>
<td>FE (ASTER, CUVE1D, CASTEM, SYSTUS analytical)</td>
<td>FE</td>
<td>MSC.MARC</td>
<td>FE (ABAQUS, ANSYS)</td>
<td>FE - ADINA</td>
</tr>
<tr>
<td>Safety factor on loading</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Level A Service limits 2 (primary), 1 (secondary)</td>
<td>Level A: 2 Level C: 1.6 Level D: 1.2</td>
<td>1</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Weld residual stress (Y/N)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>In clad: Yes In weld: No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
## COMPARISON OF APPROACHES

<table>
<thead>
<tr>
<th>Crack Driving Force</th>
<th>China</th>
<th>Czech Rep.</th>
<th>Finland</th>
<th>France</th>
<th>Germany</th>
<th>Hungary</th>
<th>Korea</th>
<th>Slovakia</th>
<th>Russia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Postulated surface defects (depth and aspect ratio, shape 1 or 2)</td>
<td>Shape 2 Depth=0.1t or based on NDE a/c=1/3</td>
<td>Depth up to 0.25t a/c=2/3 Surface semi elliptical crack in the base or weld metal</td>
<td>Shape 1 15 mm, aspect ratio 1 (Loviisa)</td>
<td>No</td>
<td>design: a= 20 mm a/c=0.3</td>
<td>No</td>
<td>Depth up to 0.1t; a/c=1/3 Shape 1 Inelastic</td>
<td>0.1t or based on NDE a/c=1/3 shape 2</td>
<td>a=0.1, a/c=0.3, 0.7, shape 2</td>
</tr>
<tr>
<td>Postulated subsurface defects (depth and aspect ratio)</td>
<td>Depth=1.5 mm or based on NDE a/c=1/3</td>
<td>No</td>
<td>a = 0.1*s, a/c = 0.3 and 0.7</td>
<td>No</td>
<td>Operation: a = 6 mm, 2c=60 mm</td>
<td>Depth=NDE x2 (10 mm) Ratio a/2c=1/6</td>
<td>Depth up to 0.1t; a/c=1/3 Shape 1 Inelastic</td>
<td>N0</td>
<td>a=0.1, a/c=0.3, 0.7, shape 2</td>
</tr>
<tr>
<td>Cladding considered (Y/N)</td>
<td>Yes</td>
<td>Cladding considered only in temperatures and stresses calculations</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Safety factor on ( K_1 )</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No (on load)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

---

1. Russian approach: postulated defect is selected according to the size of a realistic manufacturing defect i.e. which could probably exist (with appropriate margins)
# COMPARISON OF APPROACHES

<table>
<thead>
<tr>
<th>Material Fracture Resistance</th>
<th>China</th>
<th>Czech Rep.</th>
<th>Finland</th>
<th>France</th>
<th>Germany</th>
<th>Hungary</th>
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<th>Russia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack initiation parameter ((RT_{NDT}, T_k, T_0))</td>
<td>(RT_{NDT})</td>
<td>(T_k)</td>
<td>(T_0 ) or (T_k)</td>
<td>(RT_{NDT})</td>
<td>(RT_{NDT})</td>
<td>(T_0 ) or (T_k)</td>
<td>(RT_{NDT}, T_0)</td>
<td>(T_k)</td>
<td>(T_k)</td>
</tr>
<tr>
<td>Crack Arrest ((Y/N))</td>
<td>If required</td>
<td>No</td>
<td>Not until now</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Not utilised</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Shift formula for radiation embrittlement ((\text{code, surveillance}))</td>
<td>R.G 1.99 and surveillance test</td>
<td>Code (PNAE G-7-002-86)</td>
<td>Design – code operation – surveillance results</td>
<td>Direct measurement on toughness of irradiated specimens and Russian code</td>
<td>(- CVN) shift - from all the surveillance programs of 58 plants</td>
<td>Surveillance</td>
<td>Surveillance results</td>
<td>RG1.99, surveillance</td>
<td>surveillance</td>
</tr>
<tr>
<td>Safety factors</td>
<td>(2^{0.5})</td>
<td>No</td>
<td>On predicted (T_0 ) or (T_k)</td>
<td>10°C lower bound</td>
<td>1</td>
<td>On predicted (T_k) or (T_0)</td>
<td>(2^{0.5})</td>
<td>according to VERLIFE</td>
<td>Yes</td>
</tr>
</tbody>
</table>
# COMPARISON OF APPROACHES

<table>
<thead>
<tr>
<th>Integrity Evaluation Criteria</th>
<th>China</th>
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<th>Finland</th>
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<th>Russia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleavage (Y/N)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Yes + ductile with thermal ageing considering surface content</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

26.11.2009
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<tbody>
<tr>
<td>Cleavage (Y/N)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Ductile in cladding (Y/N)</td>
<td>No</td>
<td>No</td>
<td>Not up to now (yes in future)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Not up to now (yes in future)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Crack arrest (Y/N)</td>
<td>Yes</td>
<td>No</td>
<td>Not until now</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Not until now</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Crack length correction (Y/N)</td>
<td>No</td>
<td>No</td>
<td>Y for T0 approach only</td>
<td>Yes</td>
<td>Yes, reference toughness curve length = 100 mm</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Fatigue crack growth correction (Y/N)</td>
<td>Yes</td>
<td>No</td>
<td>N for postulated defect</td>
<td>No</td>
<td>Yes (but negligible in vessel wall)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>WPS (Y/N)</td>
<td>No</td>
<td>No</td>
<td>Yes (monotonical unloading only)</td>
<td>Yes (Large LOCA, external)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Shallow crack effect loss (Y/N)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Biaxial Effects (Y/N)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
## COMPARISON OF APPROACHES

<table>
<thead>
<tr>
<th>Nozzles</th>
<th>China</th>
<th>Czech Rep.</th>
<th>Finland</th>
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<th>Russia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Considered (Y/N)</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Postulated crack, size, shape</td>
<td>Depth=(0.025-0.1)t Elliptical Only performed during design</td>
<td>Depth up to 0.25t (a/c=2/3) Surface semi-elliptical crack in the base or weld metal</td>
<td>Based on NDE; sub-surface (10x18 mm)</td>
<td>- circular - 20 mm depth</td>
<td>Inlet: nozzle corner, 6 o’clock, straight crack front, size: NDEx2 (10mm)</td>
<td>Outlet nozzle: cylindrical part, 6 o’clock, semi-elliptical, (a/2c=1/6), size NDEx2 (10mm)</td>
<td>Surface and underclad flaws in lower nozzle, (a=0.1-0.25), (a/c=1)</td>
<td></td>
<td>Surface and underclad cracks in radius, (a=0.1), (a/c=1/3)</td>
</tr>
</tbody>
</table>
CONCLUSIONS

- PWR and VVER evaluation procedures for RPV integrity are based on similar principles but they differ in many aspects.
- Differences are mostly connected with the use of different materials and design codes.
- VERLIFE procedure for VVER integrity and lifetime evaluation tries to harmonize old VVER approach with PWR one.
- VERLIFE procedure is now being upgraded, updating and extended (with participation of experts from all VVER countries as well as other PWRs) as an IAEA guidelines.
Pressurised Thermal Shock in Nuclear Power Plants: Good Practices for Assessment

Handbook on Deterministic Evaluation for the Integrity of Reactor Pressure Vessel

Report prepared within the framework of the IAEA programme on engineering support for design, operation, maintenance, and plant life management for safe long term operation
Thank you for your attention

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