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

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Surveillance Programs for Monitoring the Integrity of the Reactor Pressure Vessel (RPV)

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Outline

- Generalities
- US surveillance programs
  - Design of a surveillance program for LWR pressure vessels (ASTM E185-02, E900-02)
  - Performing, analyzing and interpreting surveillance results (ASTM E2215-02, E636-02)
- Other types of surveillance programs
  - Germany
  - France
  - Japan
  - WWER reactors (Eastern European countries)
Generalities
The Reactor Pressure Vessel (RPV)

- Limiting component: primary circuit barrier, considered as non-replaceable
- Cylindrical shell + hemispherical top & bottom
- Vessel dimensions are larger for BWR than for PWR
- Structure: plate or forging, welds
- Material: low alloy steel, with traces of alloying elements (Cu, Ni, Cr, P, V, Mn)
- Typical operating conditions:
  - PWR: 300°C, 150 bar
  - BWR: 265°C, 75 bar
Generalities

Monitoring the integrity of RPV’s

- Irradiation induces degradation of the mechanical properties of the RPV material
  - increase of yield strength $\Rightarrow$ HARDENING
  - increase of DBTT $\Rightarrow$ EMBRITTLEMENT
- Fracture toughness will accordingly be affected
- Irradiation and therefore degradation is less severe for BWR than for PWR, nevertheless it must be monitored
- At the conditions of operation as well as accidental ones, fracture should be avoided
- Available technology at the time legislation was written:
  - (Pellini) Drop Weight Test
  - Charpy Impact Test
  - Plane Strain Fracture Toughness Test ($K_{IC}$)
Generalities - Evolution of fracture toughness according to the US legislation

- Fracture toughness ($K_{lc}$) measurements previously required large samples ⇒ prohibitive for irradiated materials
- Legislation (ASME code) assumes a lower bound fracture toughness curve indexed by $RT_{NDT}$
- $RT_{NDT}$ is based on a combination of Pellini drop weight test (NDT) and Charpy impact test results
- Upon irradiation, the following assumption is made:

$$\Delta RT_{NDT} = \Delta T_{41J}$$
Design of surveillance programs for LWR pressure vessels - ASTM E185-02 -

- **Scope**: “designing a surveillance program for monitoring the radiation-induced changes in the mechanical properties of ferritic materials in the beltline of LWR vessels”

- **Applicability**: “all LWR vessels for which the predicted maximum fast neutron fluence \((E > 1 \text{ MeV})\) at the end of the design lifetime (EOL) exceeds \(1 \times 10^{17} \text{ n/cm}^2\) at the inside surface of the vessel”
The surveillance program must be planned and implemented in order to ensure that:

a) capsule exposures (fluences) can be related to beltline exposures

b) surveillance materials are representative of those materials most likely to limit the operation of the vessel (i.e. most irradiation-sensitive)

c) tests yield results useful for the evaluation of radiation effects on the reactor vessel
Materials Selection

- Actual materials used for fabricating the beltline of the RPV or from weldments matching the RPV weld(s)
- Minimum: one heat of base metal + one weld (only required if there is a weld in the beltline)
- Most limiting base and weld materials have to be included in the surveillance program
  → choice to be made on the basis of the highest EOL adjusted reference temperature (ART), calculated in accordance with ASTM E900-02
- Heat-Affected Zone (HAZ) material no longer needs to be included (but should be kept in the archives)
Chemical Analysis Requirements

- Available chemical composition information for the surveillance materials should at least include: P, S, Cu, V, Si, Mn, Ni

Archive materials

- Full-thickness sections of the original materials (plates, forgings and welds) should be retained
- Enough material to fill up six additional capsules should be available
- HAZ associated with archive weld material should also be retained
- ASTM E185-02 – Test Specimens

- Type of specimens
  - Charpy: ASTM E23 type A
  - Tension: ASTM E8
  - Fracture toughness: E1820 and E1921

- Specimen location
  - Base metal: quarter-thickness (¼T); ½T not allowed
  - Weld: any location throughout the thickness except within 12.7 mm from root or surfaces of the weld

- Specimen orientation
  - Base metal: T-L (Charpy/toughness); T (tension)
- ASTM E185-02 –
  Minimum number of specimens

- Unirradiated baseline specimens
  - 15 Charpy specimens for each material
  - 6 tension specimens for both materials (at least 2 tests at room temperature and 2 at RPV operating temperature)
  - 8 fracture toughness specimens

- Irradiated specimens

<table>
<thead>
<tr>
<th>Material</th>
<th>Charpy</th>
<th>Tension</th>
<th>Fracture Toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Each Base Metal</td>
<td>15</td>
<td>3</td>
<td>(8^A)</td>
</tr>
<tr>
<td>Each Weld Metal (if required)</td>
<td>15</td>
<td>3</td>
<td>(8^A)</td>
</tr>
</tbody>
</table>

\(^A\) Only fracture toughness specimens from the limiting material are required.
- ASTM E185-02 – Irradiation requirements (I)

- Encapsulation of specimens
  - Main requirements for capsule, holder and means of attachment: inert atmosphere; corrosion-resistant; representative temperature history; sufficiently rigid; allow insertion of replacement capsules

- Location of capsules
  - Vessel wall capsules (required)
    - Principle: neutron spectrum, temperature history and maximum neutron fluence for the specimens must match as closely as possible those of the vessel
    - Lead factor: $1 < LF \leq 3$
Location of capsules (cont)

- **Accelerated irradiation capsules (optional)**
  - Positioning all capsules in low lead factor locations might not be possible due to physical constraints
  - Additional capsules may be positioned closer to the core (higher lead factor locations)
  - Data with LF > 5 have to be validated (e.g. using a reference material)

Neutron dosimeters

- Information required about fast and thermal neutron fluence, fluence rate, spectrum, dpa and dpa rate in iron
- Dosimeters to be located inside each vessel wall capsule and accelerated capsule
Use of a reference material is optional

Aim: providing an independent check for deviations from expected surveillance conditions (e.g. temperature, fluence rate, spectrum)

Examples: HSST plates; JRQ

Temperature of reactor coolant should be monitored and recorded

Optionally, temperature monitors can be included in the capsules (low melting point elements or eutectic alloys)
- ASTM E185-02 –
Number of Capsules and Withdrawal Schedule

- Basis: predicted transition temperature shift
- Minimum: 4 capsules + 1 standby

**TABLE 1  Suggested Withdrawal Schedule**

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Target Fluence</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>$5 \times 10^{18}$ n/cm$^2 (5 \times 10^{22}$ n/m$^2$) for PWRs: $E &gt; 1$ MeV</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(Required if EOL $\Delta R_{NTD} &gt; 56^\circ$C [100°F])</td>
<td></td>
</tr>
<tr>
<td>Second</td>
<td>EOL 1/4-T</td>
<td>1</td>
</tr>
<tr>
<td>Third</td>
<td>EOL ID</td>
<td>1</td>
</tr>
<tr>
<td>Fourth</td>
<td>(EOL 1/4-T - 1st Capsule)/2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>(Required if EOL $\Delta R_{NTD} &gt; 111^\circ$C [200°F])</td>
<td></td>
</tr>
<tr>
<td>Subsequent</td>
<td>Supplemental Evaluations</td>
<td>Not Required</td>
</tr>
</tbody>
</table>

“A lower target fluence is appropriate for BWR’s”
Most significant changes to E185 since its original issuance

- Original release: 1961
- 1973 revision
  - Orientation changed from L-T to T-L for Charpy specimens
- 1993 revision
  - Allowance for LF > 3
  - Elimination of requirement for testing HAZ specimens
- 2002 revision
  - Practice split into E185 (design of a new surveillance program) and E2215 (testing and evaluation of surveillance capsules)
Examples of surveillance capsule layout
Example of angular position of surveillance capsules
Prediction of radiation-induced transition temperature shift  
- ASTM E900-02 -

➢ Applicability requirements

• A533B Cl.1 & 2, A302 Gr. B & B (modified), A508 Cl.2 & 3
• Copper contents between 0 and 0.50 wt%
• Nickel contents between 0 and 1.3 wt%
• Phosphorous contents between 0 and 0.0025 wt%
• Irradiation temperatures between 260 and 299 ºC
• Neutron fluence between $1 \times 10^{16}$ and $8 \times 10^{19}$ n/cm²  
  (E $>$ 1 MeV)
• Neutron fluence rate between $2 \times 10^{8}$ and $1 \times 10^{12}$ n/cm²/s (E $>$ 1 MeV)

➢ Source: statistical analysis of irradiated material database  
(May 2000)
Mean transition temperature shift (TTS) in °F:

\[ \text{TTS} = \text{SMD} + \text{CRP} \]

where SMD (stable matrix damage) and CRP (copper rich precipitate) are given by:

\[
\begin{align*}
\text{SMD} &= A \exp\left[\frac{20730}{(T_c + 460)}\right](\Phi)^{0.5076} \\
\text{CRP} &= B\left[1 + 2.106Ni^{1.173}\right]F(Cu)G(\Phi)
\end{align*}
\]

\[ A = 6.70 \times 10^{-18} \]

\[ B = \begin{pmatrix}
234, \text{welds;} \\
128, \text{forges;} \\
208, \text{Combustion Engineering plates;} \\
156, \text{other plates}
\end{pmatrix} \]

\[ F(Cu) = \begin{cases} 0, & \text{Cu} \leq 0.072 \text{ wt } \% \\ (Cu - 0.072)^{0.377}, & \text{Cu} > 0.072 \text{ wt } \% \end{cases} \]

\[ G(\Phi) = \frac{1}{2} + \frac{1}{2} \tanh\left[\frac{\log(\Phi) - 18.24}{1.052}\right] \]

(saturation of Cu effects accounted for)
To calculate TTS at some location within the RPV wall (e.g. \(\frac{1}{4}T\)), fluence attenuation and spectrum change have to be accounted for.

The preferred exposure parameter is \(dpa\) (displacements per atom):

\[
\phi_x = \phi_{IS} \left[ \frac{dpa_x}{dpa_{IS}} \right]
\]

\((x = \text{distance into the vessel wall from IS - inside surface})\)

Alternatively:

\[
\phi_x = \phi_{IS} \exp (-0.24 \, x)
\]
- ASTM E900-02 – Uncertainty-related issues

- Standard error of the correlation:
  
  \[ 22.0°F = 12.2°C \]

- Role of phosphorous:
  
  - identified as a potential embrittling agent in RPV steels; however:
  
  - P effect cannot be unambiguously identified in the database
  
  - a simple uncertainty analysis for the effect of P provided an overall effect of 1 to 2°F on the global uncertainty

- Within the database, a neutron fluence rate (flux) effect could not be unambiguously identified
Evaluation of surveillance capsules from LWR reactor vessels - ASTM E2215-02 -

➢ Determination of Capsule Condition
  • Visual examination (identification marks; signs of damage)
  • Capsule content (comparison with capsule fabrication records; corrosion or damage to the specimens; condition of thermal monitors, evidence of melting)
  • Irradiation temperature history (PWR: coolant inlet temperature; BWR: recirculation temperature)

➢ Measurement of Irradiation Exposure
  • Power history of the reactor prior to capsule removal
  • Determination of neutron fluence rate, energy spectrum, neutron fluence, dpa rate and dpa in accordance with ASTM E853 and E560
Tension tests

- **Methods**: E8 and E21
- **Test temperatures**: RT, service temperature and one intermediate temperature
- **Measurements**: $R_y$, $R_m$, $R_u$, $\varepsilon_u$, $\varepsilon_t$, RA

Charpy tests

- **Methods**: A370 and E23; instrumented tests are recommended (E636)
- **Test temperatures**: selected in order to define the full energy transition curve (emphasis on $T_{41J}$ and upper shelf energy)
- **Measurements**: impact energy, lateral expansion and percent shear fracture appearance
Hardness tests *(optional)*
- *Methods*: A370
- To be performed on irradiated Charpy specimens

Fracture toughness tests *(optional)*
- Supplemental fracture toughness tests according to E636
- *Upper shelf*: E1820 *(J-integral method)*
- *Ductile-to-brittle transition*: E1921 *(reference temperature)*

Broken Charpy specimens may be reconstituted for supplemental Charpy and/or fracture toughness testing in accordance with E1253
- ASTM E2215-02 – Evaluation of Test Data (I)

**Tension tests**
- *Aim*: determining the amount of radiation strengthening by comparison with unirradiated tensile data
- Data can be supplemented by hardness measurements

**Charpy tests**
- *Curve fitting*: average curves for impact energy, lateral expansion and SFA determined by statistical fitting to a hyperbolic tangent function (preferred method)
- *Index temperatures*: 41 J and 0.89 mm
- *Upper Shelf Energy*: average for specimens having nominally 100% shear (SFA ≥ 95%)
- *Radiation-induced changes*: by comparison with unirradiated Charpy data
Reference material

- Measured irradiation response should fall within the scatter band of the pre-existing database
- In case of excessive scatter, the cause should be investigated

Hardness tests (*optional*)

- Data may be correlated to the yield strength of the material

Fracture toughness tests (*optional*)

- *Upper shelf fracture toughness*: resistance to crack initiation and extension (J-integral, E1820)
- *Transition fracture toughness*: reference temperature $T_o$ according to E1921 can be used to define an alternative reference temperature ($RT_{To}$, ASME Code Case N-629)
Scope

- Acquiring additional information on radiation-induced changes in fracture toughness, notch ductility and tensile strength of RPV steels

Supplemental Mechanical Property Tests

- Fracture toughness test (static/dynamic)
- Precracked Charpy impact test (dynamic toughness)
- Instrumented Charpy V-notch test (ISO 14556)
- Other mechanical property tests (e.g. miniature testing techniques)
Several countries in the world follow the US regulations

- Belgium
- Spain
- The Netherlands
- Sweden
- Mexico

Other national surveillance programs addressed:

- Germany
- France
- Japan
- WWER countries
Surveillance programs in Germany (1)

- Reference standard: KTA Safety Standard 3203
- Surveillance programs consist of three sets:
  - first set: unirradiated material data
  - second set: ~ ½ of design fluence (PWR: $5 \times 10^{18} \text{n/cm}^2$ for 32 EFPY)
  - third set: design life fluence or above
- Materials to be included:
  - Design fluence < $1 \times 10^{19} \text{n/cm}^2$: one base metal, one weld metal
  - Design fluence > $1 \times 10^{19} \text{n/cm}^2$: two base metals, one weld metal
- Specimen types:
  - Charpy V (12 per material/set)
  - Tensile (3 per material/set)
Lead factor: 1.5 – 12 (mostly around 5)
Surveillance programs in France

- Reference standard: RSE-M Code
- Surveillance programs are similar to US programs
  - capsules removed from reactor
  - specimens subjected to Charpy testing
  - measured shifts compared with predicted values (different correlation used)
- Specified limit for the lead factor: less than 3
- Archive material stored for future use
- Some changes under study to support life extension from 40 to 60 years
Surveillance programs in Japan

- Reference standard: JEAC 4201 (similar to ASTM E185)
- Six capsules inserted into PWR vessels
- Specimens: CVN, tensile and 12.7 mm-thick C(T)
- Materials: base (1 or 2), weld and HAZ
- Fracture toughness tests:
  - ductile-to-brittle transition region
  - upper shelf (unloading compliance method)
Surveillance programs in WWER reactors

- Oldest design (WWER-440/230) has no surveillance program
- Newer designs (WWER-440/213 and WWER-1000) have surveillance programs
- Specimens are placed in 10-20 containers connected in chain; two chains constitute a set
- Six sets are located in each unit
- Planned withdrawal interval: 1, 3, 5, 10 years
- High lead factors: 6 to 18
- Specimens for thermal ageing monitoring are also included (removed after 5 and 10 years)
Surveillance programs in WWER reactors (2)

Location of surveillance capsules in a WWER-1000

Disadvantages:
- different neutron spectrum
- much higher fluence rate (flux)
- irradiation temperature 10-20°C higher
Surveillance programs in WWER reactors (3)

Removal of “boat” samples from older WWER-440/230 reactors (no surveillance program inside the RPV)

Base metal

Weld metal
The ASME Lower Bound fracture toughness curve

\[ K_{IC}^{ASME} = 36.48 + 22.78 \exp\left[0.036 \left(T - R T_{NDT}\right)\right] \]
Equivalence between NDT and $T_{41J}$ irradiation shifts

(Pellini) Drop Weight Test

Charpy Impact Test

$\Delta NDT$ vs $\Delta T_{41J}$

- $\Delta NDT = 130$ mm
- $\Delta T_{41J} = 55$ mm
- 10x10 sample size
- 50x19 test dimensions
- 130 mm length
Fracture toughness is indexed by the Charpy surveillance results

**REFERENCE CONDITION**
- Drop Weight (ASTM E208)
- Charpy criteria
- ASME code
- fracture toughness

**AFTER IRRADIATION**
- Charpy tests
- \( \Delta T_{41J} = \Delta R_{T_{NDT}} \)
- \( R_{T_{NDT}} \text{ IRRAD} \)

\[ \Delta T_{41J} = \Delta R_{T_{NDT}} \]