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

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

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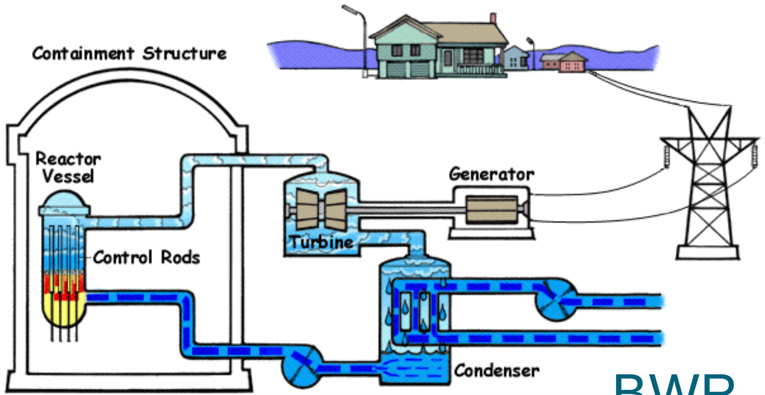
Outline

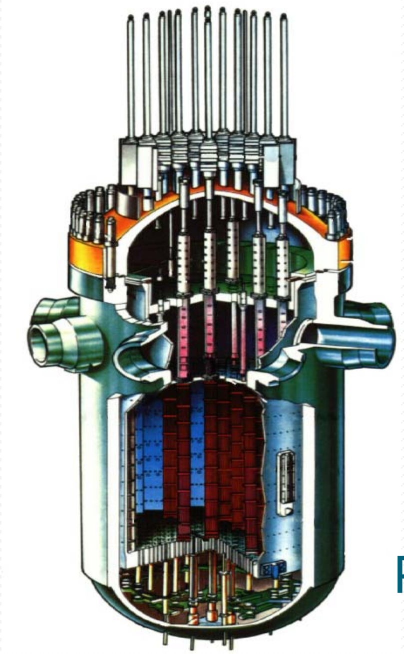
- Generalities
- US surveillance programs
  - Design of a surveillance program for LWR pressure vessels (ASTM E185-02, E900-02)
  - Performing, analyzing and interpreting surveillance results (ASTM E2215-02, E636-02)
- Other types of surveillance programs
  - Germany
  - France
  - Japan
  - WWER reactors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



BWR



PWR

Generalities
Monitoring the integrity of RPV's

- Irradiation induces degradation of the mechanical properties of the RPV material
  - increase of yield strength ⇨ **HARDENING**
  - increase of DBTT ⇨ **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_{Ic}) 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 ($E > 1$ MeV) at the end of the design lifetime (EOL) exceeds 1×10^{17} n/cm² at the inside surface of the vessel"*

- ASTM E185-02 –
Criteria for implementing surveillance programs

- 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

- ASTM E185-02 – Test Materials (I)

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)

- ASTM E185-02 – Test Materials (II)

- 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

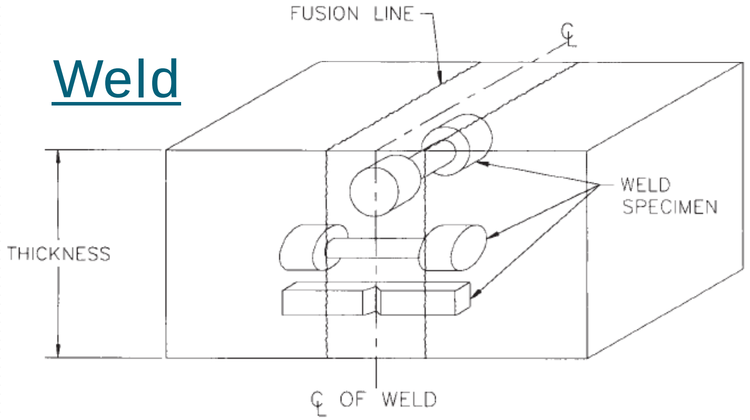
Specimen location

- 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)

Weld



- 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

Material	Charpy	Tension	Fracture Toughness
Each Base Metal	15	3	8[A]
Each Weld Metal (if required)	15	3	8[A]

[A] Only fracture toughness specimens from the limiting material are required.

- ASTM E185-02 – Irradiation requirements (I)

- <u>Encapsulation of specimens</u>
  - *Main requirements for capsule, holder and means of attachment*: inert athmosphere; corrosion-resistant; representative temperature history; sufficiently rigid; allow insertion of replacement capsules
- <u>Location of capsules</u>
  - *Vessel wall capsules (required)*
    - → <u>Principle</u>: neutron spectrum, temperature history and maximum neutron fluence for the specimens must match as closely as possible those of the vessel
    - → Lead factor: $1 < LF \leq 3$

- ASTM E185-02 –
Irradiation requirements (II)

- 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

- ASTM E185-02 –
Reference Materials & Temperature Monitoring

- 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

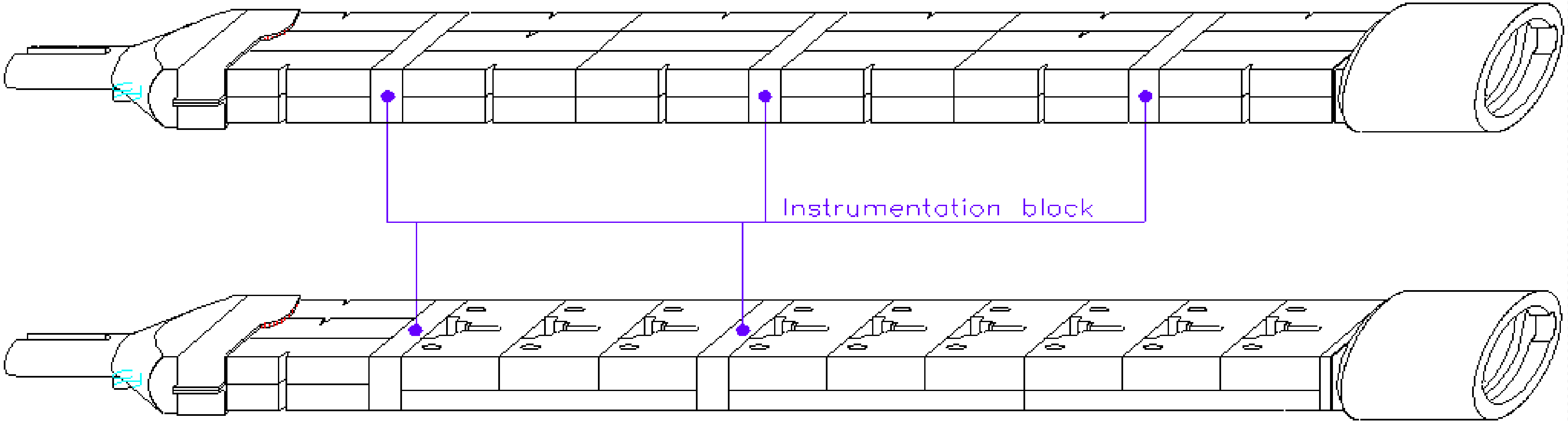
Sequence	Target Fluence	Priority
First	5×10^{18} n/cm^2(5×10^{22} n/m^2) for PWRs; E > 1 MeV	2 (Required if EOL ΔRT_{NDT}> 56°C [100°F])
Second	EOL ¼-T	1 (Required for all materials)
Third	EOL ID	1 (Required for all materials)
Fourth	(EOL ¼-T - 1st Capsule)/2	3 (Required if EOL ΔRT_{NDT}> 111°C [200°F])
Subsequent	Supplemental Evaluations	Not Required

"A lower target fluence is appropriate for BWR's"

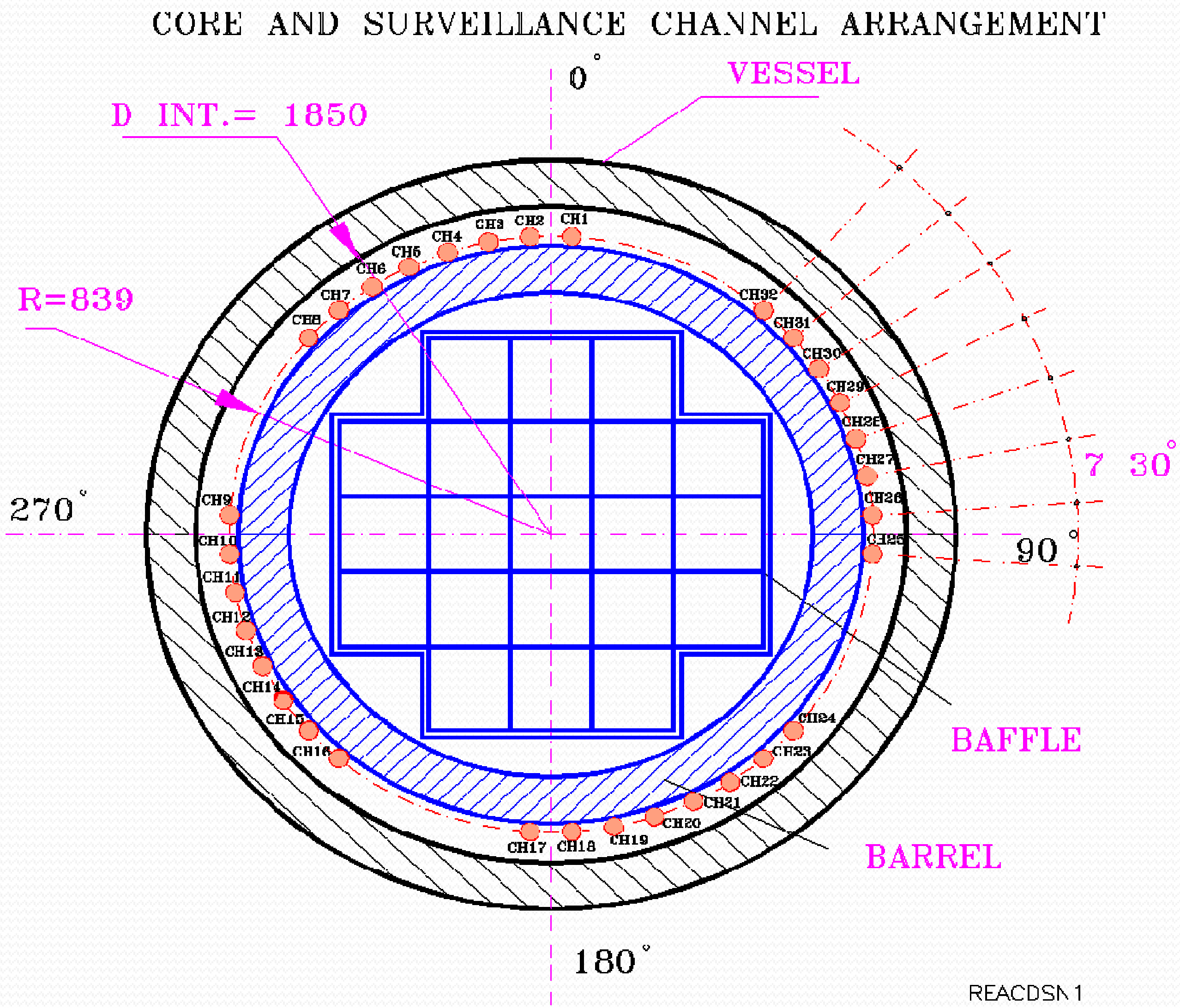
Most significant changes to E185 since its original issuance

- 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 °C
  - Neutron fluence between 1×10^{16} and 8×10^{19} n/cm^2 (E > 1 MeV)
  - Neutron fluence rate between 2×10^{8} and 1×10^{12} n/cm^{2}s (E > 1 MeV)
- Source: statistical analysis of irradiated material database (May 2000)

- ASTM E900-02 – Calculative procedure

- Mean transition temperature shift (TTS) in °F:

TTS = SMD + CRP

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

$$SMD = A \exp[20730/(T_c + 460)](\Phi)^{0.5076}$$

$$CRP = B[1 + 2.106Ni^{1.173}]F(Cu)G(\Phi)$$

$$A = 6.70 \times 10^{-18}$$

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

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

$$F(Cu) = \begin{pmatrix} 0, \ Cu \le 0.072 \text{ wt \%} \\ (Cu - 0.072)^{0.577}, \ Cu > 0.072 \text{ wt \%} \end{pmatrix}$$

(saturation of Cu effects accounted for)

- ASTM E900-02 –
Attenuation through the vessel wall

- To calculate TTS at some location within the RPV wall (e.g. ¼T), fluence attenuation and spectrum change have to be accounted for
- The preferred exposure parameter is *dpa* (displacements per atom):

$$Ø_x = Ø_{IS}\ [dpa_x/dpa_{IS}]$$

(x = distance into the vessel wall from IS - inside surface)

- Alternatively:

$$Ø_x = Ø_{IS} \exp\ (-0.24\ x)$$

- 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

- ASTM E2215-02 –
Measurement of Mechanical Properties (I)

Tension tests

- *Methods*: E8 and E21
- *Test temperatures*: RT, service temperature and one intermediate temperature
- *Measurements*: R_y, R_m, R_u, ε_u, ε_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

- ASTM E2215-02 –
Measurement of Mechanical Properties (II)

- 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

- ASTM E2215-02 –
Evaluation of Test Data (II)

- 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)

Supplemental surveillance tests
- ASTM E636-02 -

- <u>Scope</u>
  - *Acquiring additional information on radiation-induced changes in fracture toughness, notch ductility and tensile strength of RPV steels*
- <u>Supplemental Mechanical Property Tests</u>
  - 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

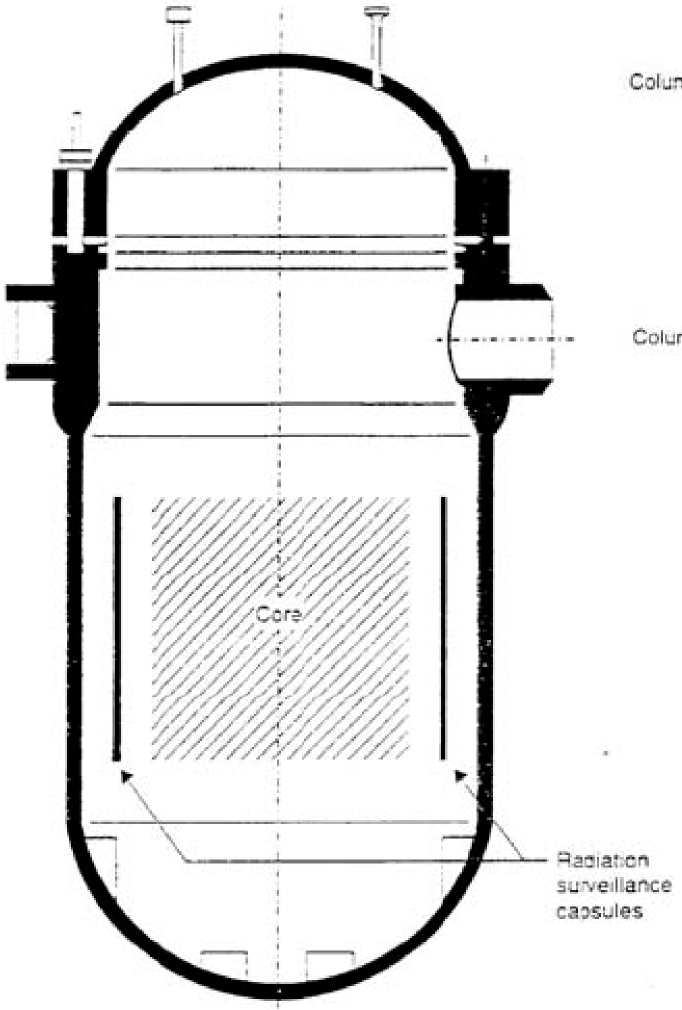
- Belgium
- Spain
- The Netherlands
- Sweden
- Mexico

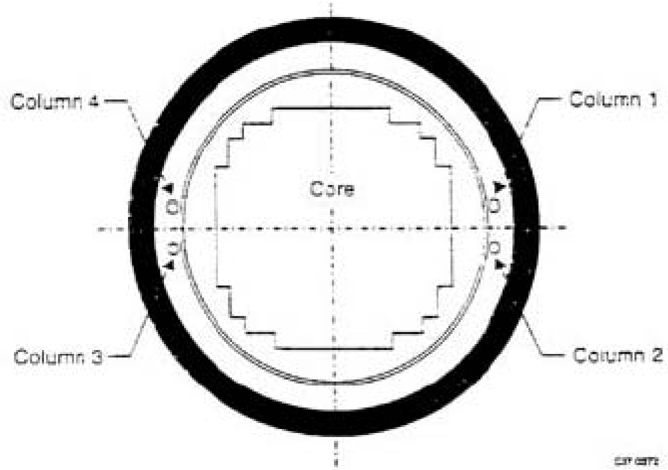
➢ Other national surveillance programs addressed:
  - Germany
  - France
  - Japan
  - WWER countries

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: 5×10^{18} n/cm² for 32 EFPY)
  - third set: design life fluence or above
- Materials to be included:
  - Design fluence < 1×10^{19} n/cm²: one base metal, one weld metal
  - Design fluence > 1×10^{19} n/cm²: two base metals, one weld metal
- Specimen types:
  - Charpy V (12 per material/set)
  - Tensile (3 per material/set)

Surveillance programs in Germany (2)





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

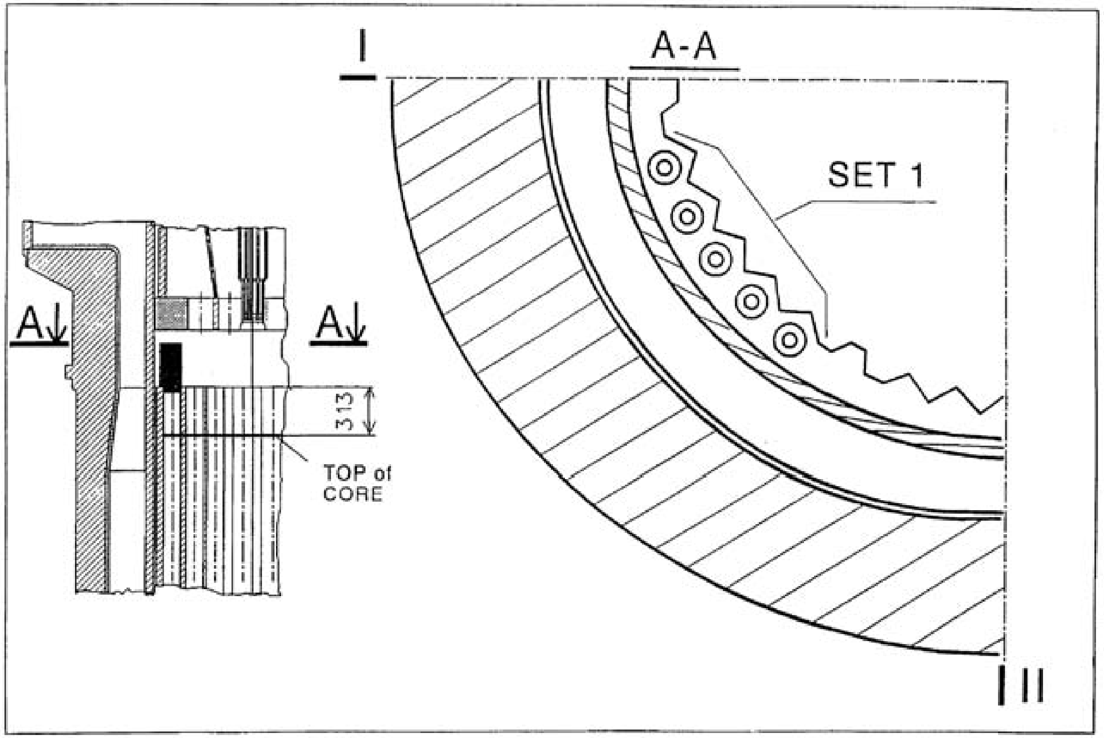
- Reference standard: JEAC 4201 (similar to ASTM E185)
- Six capsules inserted into PWR vessels
- Specimens: CVN, tensile and 12.7 mm-thick C(T)
- Materials: base (1 or 2), weld and HAZ
- Fracture toughness tests:
  - ductile-to-brittle transition region
  - upper shelf (unloading compliance method)

Surveillance programs in WWER reactors (1)

- 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

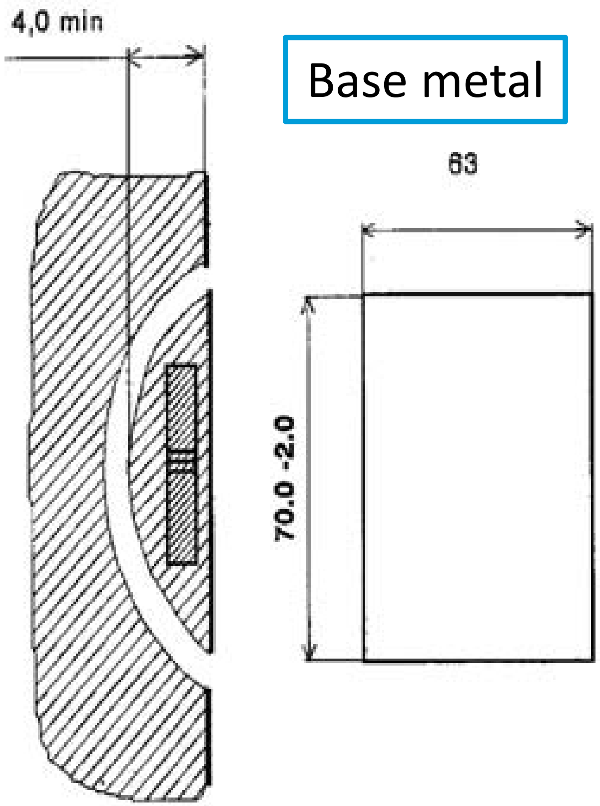


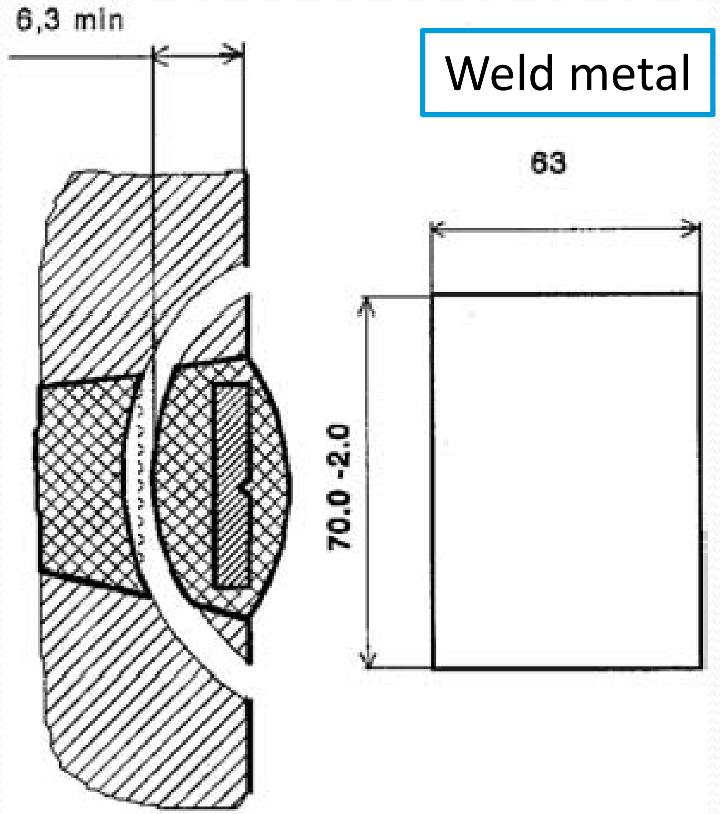
Disadvantages:

- different neutron spectrum
- much higher fluence rate (flux)
- irradiation temperature 10-20°C higher

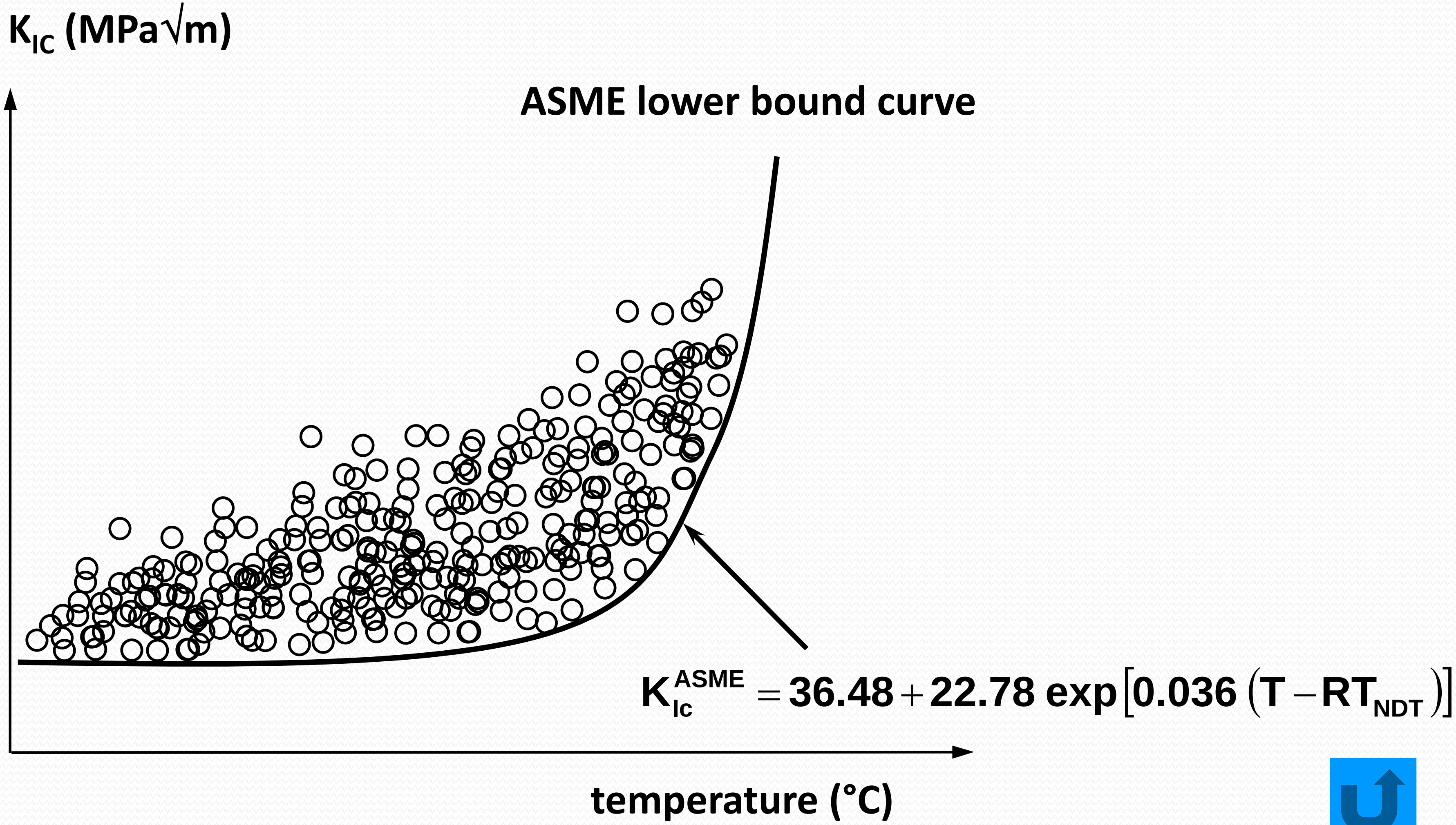
Surveillance programs in WWER reactors (3)

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

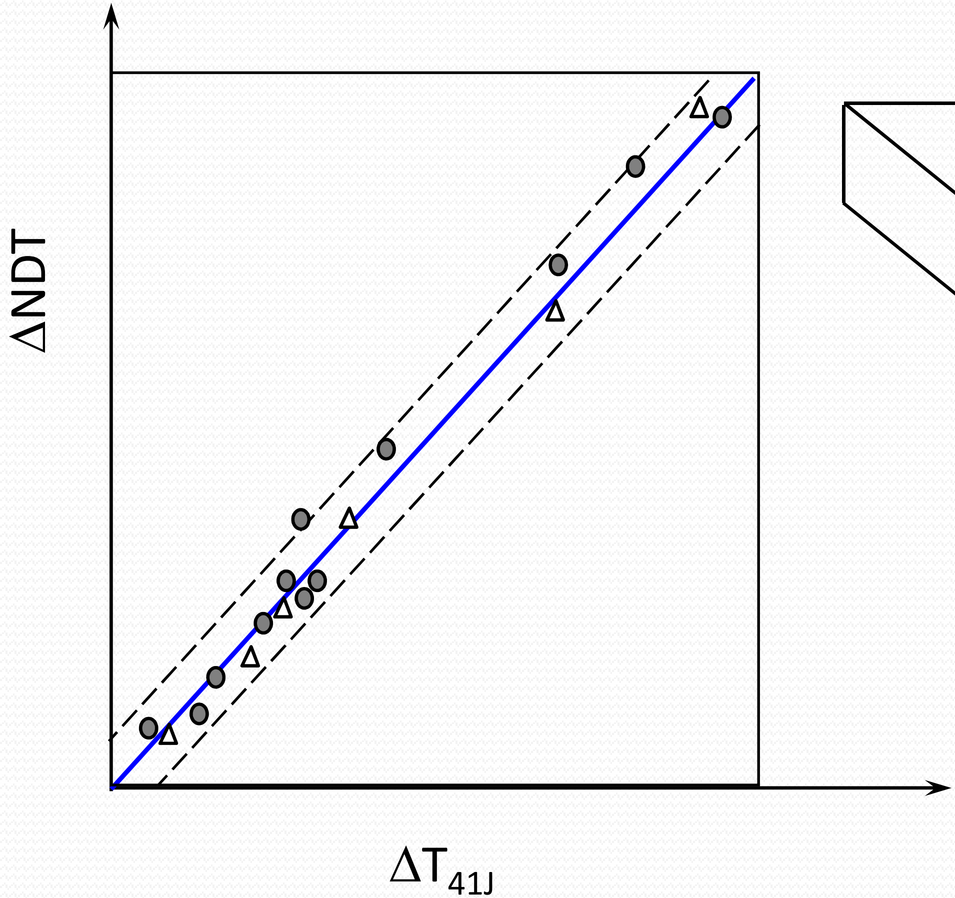




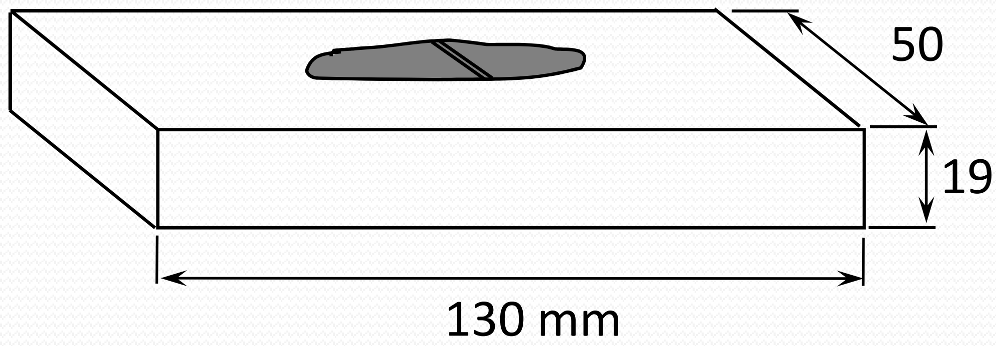
The ASME Lower Bound fracture toughness curve



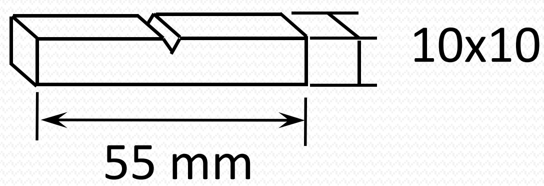
Equivalence between NDT and T_{41J} irradiation shifts



(Pellini) Drop Weight Test



Charpy Impact Test



Fracture toughness is indexed by the Charpy surveillance results

REFERENCE CONDITION

Drop Weight (ASTM E208) → T_{NDT}

Charpy criteria ↓

RT_{NDT}

ASME code ↓

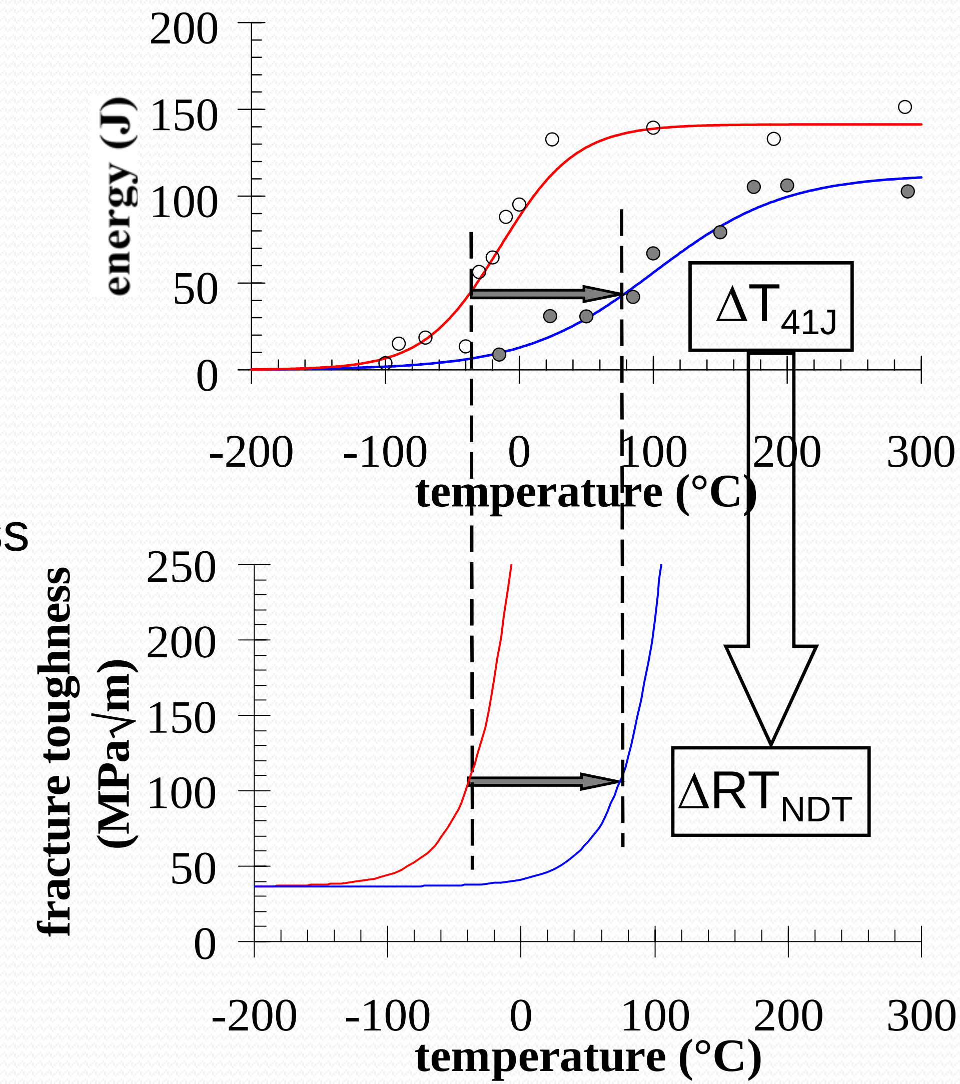
fracture toughness

AFTER IRRADIATION

Charpy tests → $\mathbf{\Delta T_{41J}} = \Delta RT_{NDT}$

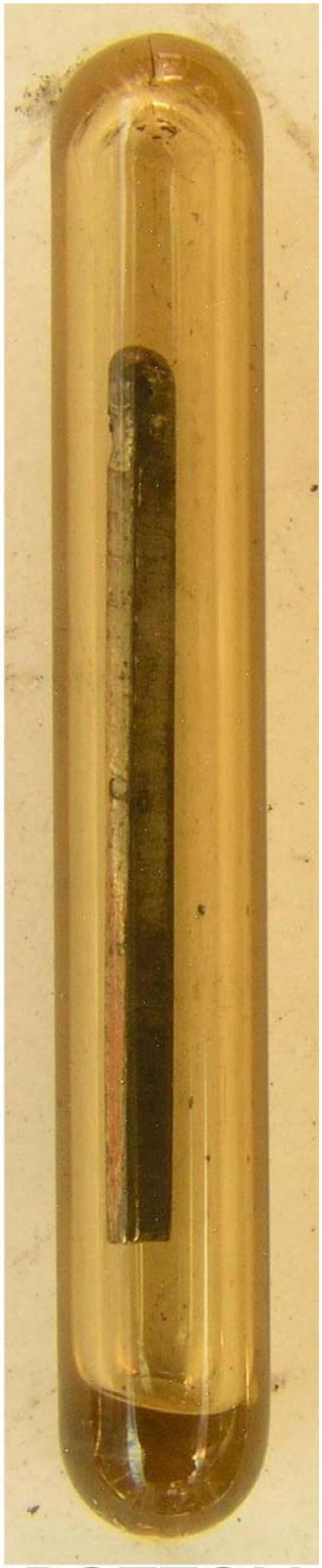
↓

$RT_{NDT\ IRRAD}$



TOP
304 °C

MIDDLE
310 °C



BOTTOM
304 °C