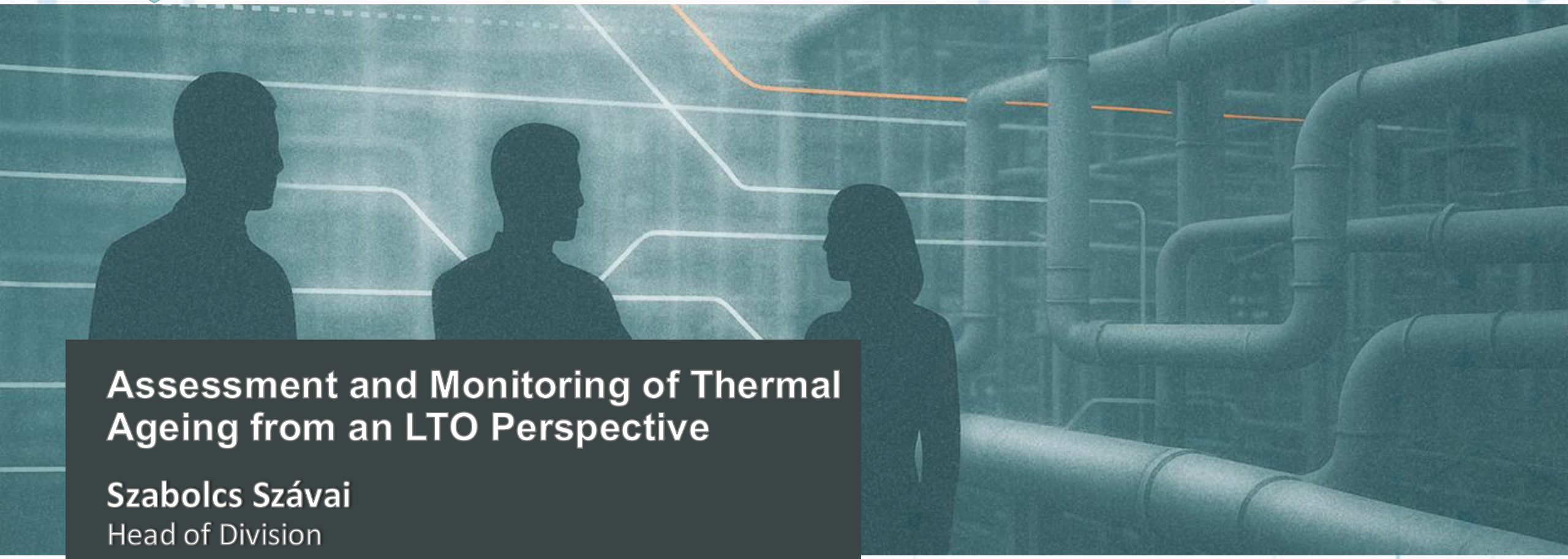
AEMI Atomic Energy Engineering Ltd.



Assessment and Monitoring of Thermal Ageing from an LTO Perspective

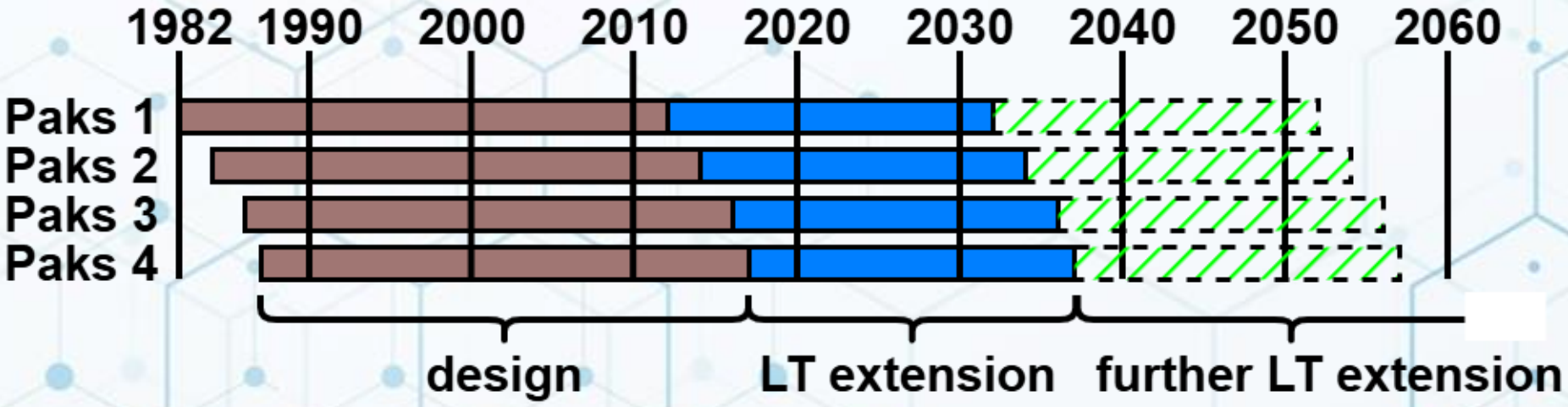
Szabolcs Szávai
Head of Division

AEMI Atomic Energy Engineering Ltd.

Technical Division, Miskolc

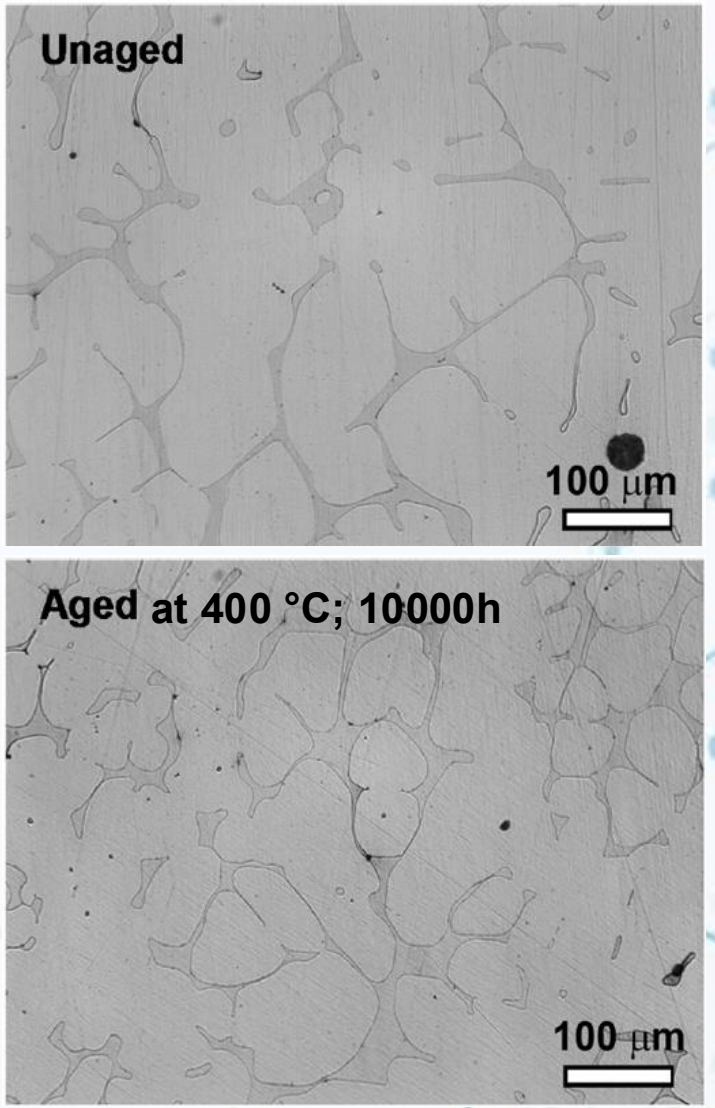
Paks NPP LTO efforts

- **Aim: further LT extension to 70 years**
- **Specific tasks**
  - Characterizing ageing effects
  - Question of susceptibility (materials, components)
- **Investigations, research**
  - TLAA for thermal embrittlement
  - Monitoring of key parameters



Thermal ageing in long-term operation

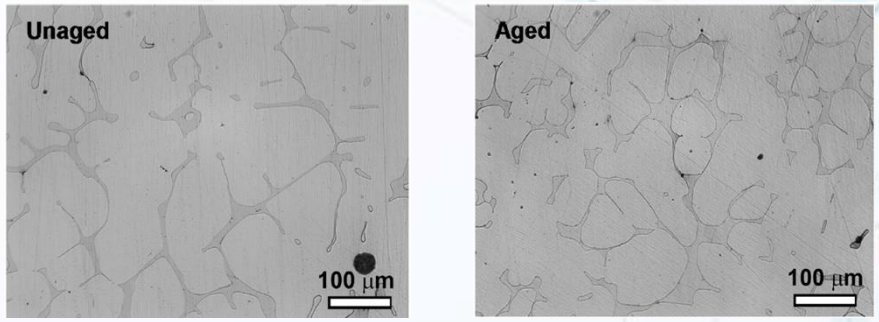
- **Thermal Ageing**
  - Prolonged, irreversible changes
    - LTO!
    - prevention, mitigation
- **IAEA SSG-48 (Specific Safety Guide)**
  - Ageing management for LTO
  - Importance of thermal ageing monitoring
  - Time Limited Ageing Analysis (TLAA)
- **Research projects**
  - DELISA-LTO
  - Light Water Reactor Sustainability (LWRS) Program
  - EPRI Technical Reports



Thermal ageing, lesson learnt

The effect of thermal exposure must be assessed at component level, not only through material strength.

- Long exposure at operating temperature can change microstructure and reduce resistance to crack initiation and growth.
- Yield strength may change only slightly while fracture resistance decreases, particularly in ferrite-containing cast steels.
- The Paks objective is to justify operation from 50 to 70 years and to monitor the assumptions used in that justification.



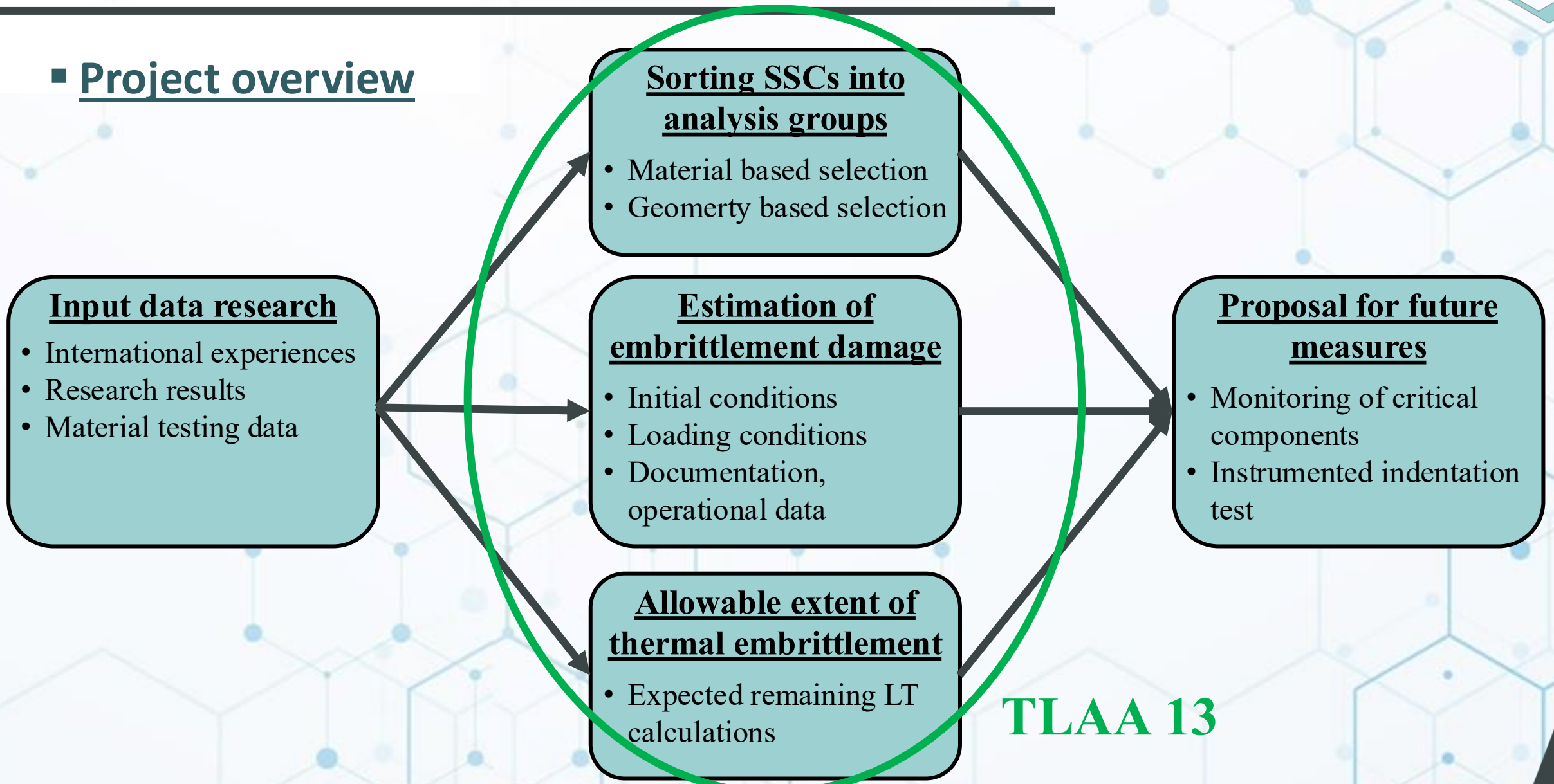
Unaged **Laboratory-aged**

Accelerated ageing: 400 ° C, 10,000 h.
These images do not represent Paks service exposure.

The fracture consequence may be greater than the change in strength.

TLAA No.13 for safety class 1-2 SSCs

- **Project overview**



Paks NPP: how the assessment and monitoring developed

The current work builds on the first assessment and more than a decade of plant measurements.

2009-2010	2011-2024	2014 / 2019-2023	2024-2026	Next step
First thermal-ageing assessment	**Plant measurements**	**C15 review and FSAR**	**70-year revalidation**	**Improved monitoring**
Susceptible materials and components requiring fracture assessment were identified.	Periodic indentation provided hardness and strength-property evidence.	The assessment was reviewed for the fuel-cycle change and maintained in the safety documentation.	Material evidence, methods and component calculations were reviewed for the longer period.	The next objective is to add validated toughness information to the established monitoring programme.

The assessment defines acceptable material assumptions; monitoring checks them against operating evidence.

TLAA No. 13: from material data to component acceptability

The same engineering sequence links the first project to the current 70-year revalidation.

Collect the evidence	Manufacturing records, operating conditions, material tests and the Prometey / Pisarenko experience are combined.
Select the components	Susceptible materials are identified, followed by checks of geometry, loading and the coverage provided by previous calculations.
Evaluate the aged condition	Appropriate ageing allowances or aged J-R curves are used in the component integrity assessment.
Define the follow-up	The conclusion and the material properties requiring continued monitoring are documented.

Investigated materials

- **WWER specific material grades**
- **Thermal ageing effects are highly dependent on material composition and microstructure**
- **Microstructural background of ageing effects**
  - Spinodal decomposition
  - G-phase precipitation
  - Carbide & nitride precipitation
  - Dynamic Strain Ageing
  - Segregation
- **Data for investigations**
  - Prometey measurements
  - Pisarenko measurements
  - Oak Ridge National Lab research data on microstructure
  - US Nuclear Regulatory Commission research on ageing effects

Type of material	Steel grades used in WWER type reactors
Perlitic steels: Carbon steels	SZt3szp5, 10, 15, 15L, 20, 20L, 20K, 22K, 25, 25L, 30, 35, 40, 45
Low alloy steels	29Ch, 30 Ch , 35 Ch, ,40Ch , 45Ch ,12 Ch M, 15ChM, 20ChM, 20ChMA, 20ChML, 20ChMFL, 30ChM, 30ChMA, 35ChM, 35ChMA, 10Ch2M, 12ChM, 30GSZA, 10ChSZND, 10ChN1M 16GNMA, 10GN2MFA,10GN2MFAL
Cr-Mo-V alloy steels	12Ch1MF, 25Ch1MF, 15Ch1M1F, 15Ch1M1FL, 12Ch2MFA, 12Ch2MFAfA, 18Ch2MFA, 15Ch2MFA, 15Ch2MFAA, 25Ch2MFA, 25Ch2M1F, 25Ch3MFA, 10Ch2M1FB, 15Ch2NMFA, 15Ch2NMFAfA, 15Ch3NMFA, 15Ch3NMFAA, 36Ch2N2MFA, 38ChN3MFA, 20Ch1M1F1BR
Si-Mn alloy steels	15GSZ, 16GSZ, 20GSZL, 09G2SZ
High alloy steels: Steels containing high Cr	2 08Ch13, 20Ch13, 20Ch12VNMF, 09Ch17N, 30Ch13, 14Ch17N2, 08Ch14MF, 1Ch12V2MF, 18Ch12VMBFR, 05Ch12N2M, 05Ch12N2MFVI,05Ch12N2MVD, 06Ch13N7D2, 06Ch12N3DL, 06Ch12N3D, 07Ch16N4B
Austenitic, Cr-Ni corrosion resistant steels	09Ch18N9 10Ch18N9, 12Ch18N9, 08Ch18N10T, 12Ch18N10T, 08Ch18N12T, 12Ch18N9T, 12Ch18N12T, 12Ch18N9TL, 03Ch16N9M2, 08Ch16N11M3, 0Ch17N13M2T, 09Ch16N15M3B, 12Ch18N12M3TL,10Ch18N12M3L, 45Ch14N14V2M, Ch 18N22V2T2, 31Ch 19N9MVBT, 10Ch11N20T3R
Iron-Ni alloy steels	03Ch21N32M3B, Ch N35VT, ChN35VTVD, ChN35VTJU, 1Ch16N36MBTJUR, 0Ch20N46B

Material groups require different ageing assessments

Composition, manufacturing condition and microstructure determine which degradation mechanism is relevant.

Material family	Representative grades	Assessment approach
Carbon and low-alloy steels	22K; 15H2MFA	Transition-temperature allowances and available thermal-ageing evidence are reviewed.
Wrought austenitic base metals	08H18N10T / 08H18N12T	Relatively stable base metal is distinguished from ferrite-containing weld metal.
Cast austenitic steels and welds	Ferrite-containing valve castings	Reduced fracture resistance is assessed using aged J-R curves.
Martensitic stainless steels	20H13; 14H17N2	Grade, heat treatment and phase composition are reviewed separately.

Ferritic steels: retain the relevant fracture allowance

For 22K and 15H2MFA, the reviewed evidence generally indicates limited thermal ageing under the relevant Paks conditions.

- Thermal embrittlement is assessed mainly through the possible shift of the ductile-to-brittle transition temperature.
- The existing brittle-fracture calculations are reviewed to check whether their ageing allowance remains bounding.
- For the steam-generator carbon-steel assessment, the report retains the previous 30 °C allowance as a bounding value.
- Indentation measurements support condition trending; stable strength values do not independently prove unchanged toughness.

Ferritic steels: retain the relevant fracture allowance

For 22K and 15H2MFA, the reviewed evidence generally indicates limited thermal ageing under the relevant Paks conditions.

- DBTT shift is not significant
- Strength parameters slight increase → possible strain ageing
- Upper shelf impact energy unchanged (based on Charpy-test)
- No macroscopic property change due to small diffusion speed

- Instrumented indentation based monitoring in Paks
  - **No significant changes detected in strength properties**

- **Thermal ageing is negligible for PAKS → monitoring is advised**

Wrought austenitic steels: distinguish base metal and welds

Favourable evidence for the wrought base metal is not an automatic exemption for every welded region.

- The reviewed VVER experience indicates limited thermal embrittlement of wrought austenitic base metals at the relevant service temperatures.
- Weld metal can contain δ-ferrite, so its susceptibility must be considered separately from the parent material.
- The assessment therefore checks material grade, welding condition and the applicability of previous component calculations.
- Where the existing evidence and calculations remain bounding, a new standalone fracture calculation is not required.

Wrought austenitic steels: distinguish base metal and welds

Favourable evidence for the wrought base metal is not an automatic exemption for every welded region.

- Different thermal ageing properties than CASS
- Homogeneous austenite microstructure → minimal δ-ferrite
- Strength properties slight increase
- No segregation and precipitation
- Improved fatigue crack resistance
- Under 400° C, thermal embrittlement do not cause significant degradation
- **Thermal ageing is negligible for PAKS, but monitoring is strongly advised**

Cast austenitic steels: toughness is the controlling property

The ferrite phase can embrittle at reactor operating temperatures even when the tensile response changes only modestly.

- Decomposition of δ-ferrite into Fe-rich and Cr-rich regions can reduce the fracture resistance of the duplex microstructure.
- The extent and rate of ageing depend on chemistry, ferrite fraction, temperature and exposure time.
- NUREG/CR-4513 Rev. 2 correlations are used to estimate the saturation Charpy energy and the corresponding aged J-R curve.
- The hot-leg main gate valve is the principal component example because its cast body requires an explicit aged-state fracture check.

Assessment quantities

Chemistry + ferrite fraction

Saturation impact energy

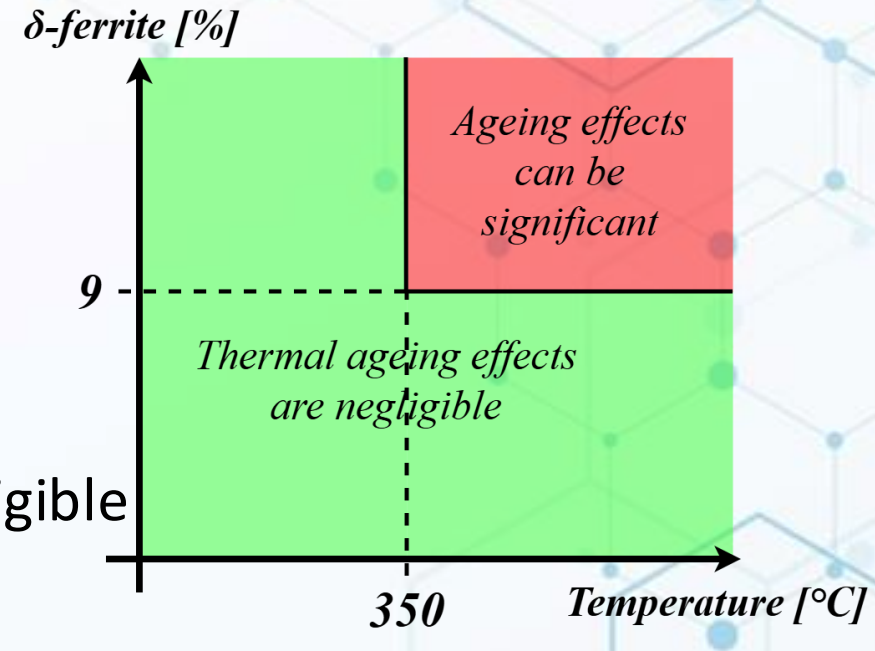
Aged J-R resistance curve

Component crack tolerance

Cast austenitic steels: toughness is the controlling property

The ferrite phase can embrittle at reactor operating temperatures even when the tensile response changes only modestly.

- Critical primary circuit components
  - Main circulation pump, Main gate valve, etc.
- Higher ferrite content + coarser grains
  - High risk of spinodal decomposition degradation
- Threshold values of δ-ferrite < 9%
  - For T < 350° C thermal embrittlement effects are negligible
  - Long incubation time
- Quantitative embrittlement estimation procedure
  - NUREG/CR-4513 rev. 2.
    - Material composition based calculation
    - Estimation of saturation Charpy impact value
    - Parameters for J-R curve reconstruction



Martensitic stainless steels need a separate review

20H13 and 14H17N2 cannot be assessed simply by using the assumptions adopted for 22K or 15H2MFA.

20H13	The assessment considers its tempered-martensitic structure, heat treatment and available service evidence.
14H17N2	Its different alloy content and possible ferrite-containing microstructure require a grade-specific review.
Assessment consequence	Conservative assumptions are retained where long-term data are limited; suitable archived material can support verification when available.

Martensitic stainless steels need a separate review

20H13 and 14H17N2 cannot be assessed simply by using the assumptions adopted for 22K or 15H2MFA.

- Investigation of composition and microstructure is key
  - Ageing mechanisms are highly dependent on alloying elements

20H13
(Cr = 12-14%)

- Mainly tempered martensite + carbides ($M_{23}C_6$)
- Temper embrittlement phenomena → diffusion aided precipitation on grain boundaries
- Segregation induced DBTT shift (in case of LTO)
- Precipitation weakens cohesion → intergranular fracture susceptibility

14H17N2
(Cr = 16-18%; Ni = 1,5-2,5%)

- Corrosion resistant components with high strength demand
- Presence of δ-ferrite in martensitic matrix
- Ni content stabilizes austenite and accelerates spinodal decomposition (G-phase precipitation)
- Lower activation energy → faster ageing mechanisms → stricter monitoring required

Susceptible material grades

- 15H2MFA
- 22K
- 08H18N9TL
- SZv04H19H11M3
- EA400/10T
- SZv10HMFT
- UONI 13655

Material group	Estimated extent of embrittlement (70 years)	Proposed evaluation method
Carbon steels (22K)	**Potentially negligible, future monitoring required**	Advanced instrumented indentation test
Low-alloy steels (15H2MFA)		Advanced instrumented indentation test
Rolled austenitic steels	No	Screening
Cast austenitic steels and welds	**Can be significant**	**NUREG/CR-4513 Rev. 2 (saturation J-R curve) and instrumented indentation test**

Component screening: why not analyse every item again?

Components are selected when relevant thermal exposure, susceptible material and a need for explicit integrity verification coincide.

1. Thermal exposure	The project first identifies components operating continuously above 220 °C; this is a screening threshold, not a universal physical limit.
2. Material and region	Base metal, castings and welds are distinguished using the actual material and manufacturing records.
3. Geometry and previous analyses	Applicable dimensional provisions and the coverage of existing fracture and fatigue calculations are checked.
4. Assessment disposition	Each retained item is assigned to previous bounds, a dedicated calculation, monitoring, or a combination of these.

Exclusion criterias for SSCs

Class 1 components:

- **Materials with a nominal cross-sectional thickness of 16 mm or less, where thicknesses are determined as follows**
  - For pumps, valves and fittings, the maximum nominal wall thickness of the connecting pipes
  - For vessels and tanks, the nominal thickness of the shell or the lid shall be used, as appropriate
  - For stubs or extensions welded to vessels, the lower value between the vessel shell thickness to which the item is welded to or the item's maximum radial thickness is used, for the integrated (internal) shell excluding the buttweld bead
  - For flat lids, tube sheets or flanges, use the maximum shell thickness of the butt-welded section
  - For integral assemblies where pipework is secured to the vessel or a stub, the greater nominal thickness of the pipe connections
- **Bolted joints, including bolts, nuts and studs, with a nominal size ≤ 25 mm**
- **Bars where the nominal cross-sectional area ≤ 645 mm²**
- **The total wall thickness of pipes, pipework, fittings, pumps and valves where the nominal pipe diameter ≤ 152.4 mm**
- **The material of pumps, valves and fittings where all pipe connections have a nominal wall thickness ≤ 16 mm**
- **Non-ferrous metals**

Exclusion criterias for SSCs

Class 2 components:

- **Materials with a nominal cross-sectional thickness of 16 mm or less, where thicknesses are determined as follows**
  - For pumps, valves and fittings, the maximum nominal wall thickness of the connecting pipes
  - For vessels and tanks, the nominal thickness of the shell or the lid shall be used, as appropriate
  - For stubs or extensions welded to vessels, the lower value between the vessel shell thickness to which the item is welded to or the item's maximum radial thickness is used, for the integrated (internal) shell excluding the buttweld bead
  - For flat lids, tube sheets or flanges, use the maximum shell thickness of the butt-welded section
  - For integral assemblies where pipework is secured to the vessel or a stub, the greater nominal thickness of the pipe connections
- **Bolted joints, including bolts, nuts and studs, with a nominal size ≤ 25 mm**
- **Bars where the nominal cross-sectional area ≤ 645 mm²**
- **The total wall thickness of pipes, pipework, fittings, pumps and valves where the nominal pipe diameter ≤ 152.4 mm**
- **The material of pumps, valves and fittings where all pipe connections have a nominal wall thickness ≤ 16 mm**
- **Non-ferrous metals**
- **Materials for components where the lowest operating temperature reaches at least 66°C**

Exclusion criterias for SSCs

Screws:

- Where nominal screw diameter < 25 mm

Brackets:

- Materials where the nominal cross-sectional diameter ≤ 16 mm
- Bolt assemblies, including bolts, nuts and studs, with a nominal size ≤ 25 mm
- Bars where the nominal cross-sectional area ≤ 645 mm^2
- Pipe supports where all pipe connections have a nominal wall thickness ≤ 16 mm
- Non-ferrous metals
- Pipe support components where the maximum tension stress does not exceed 41 MPa, or which are subject to compressive stress
- Rolled structural elements where the flange thickness ≤ 16 mm
- Class 1 and 2 supports listed in table NF-2311(b)-1, where the wall thickness ≤ 64 mm, and the minimum operating temperature is 17°C higher than the temperature specified in the table
- Materials used in Class 2 and MC support structures where the minimum operating temperature reaches 66°C
- Materials used in Class 2 support structures where the minimum operating temperature exceeds the permissible minimum design temperature shown in figure NF-2311(b)-1

Geometrical screening: the dimension must be defined correctly

The project uses component-specific Code provisions; a dimensional exemption is not a statement that the material does not age.

Criterion	Project value	How it is used
Nominal thickness	≤16 mm	For vessels, use the relevant shell or head thickness. For pumps and valves, the connecting-pipe thickness is relevant under the applicable provision.
Nominal pipe size	NPS 6 or less	The project summary quotes 152.4 mm. This is a nominal-size provision, not a measured bore or outside-diameter criterion.
Bolting and bars	≤25 mm ≤645 mm^2	Bolt diameter and bar cross-sectional area are separate criteria and must not be interchanged.
Class 2 and supports	Additional conditions	Temperature and stress provisions apply only with their stated component and clause conditions.

Detailed screening: B1 (Class 1 / Class 2) and B2 (bolting / supports).

Screening results: examples from the component register

The register records why an item is covered by a bounding assessment and what follow-up remains necessary.

Identifier	Component type	ABOS	Material grade	Operating temperature [C°]	Type	Dimension [mmxmm] DN/PN	Conclusion
40YA11S201	COLD LEG MAIN GATE VALVE	1	Cast austenitic stainless 08H18N10TL	<270	849-500 PSZE	500/125	The calculation for the hot-leg FET package characterised by the highest delta-ferrite content can be regarded as an over-estimate.
40YA12S201	HOT LEG MAIN GATE VALVE	1	Cast austenitic stainless 08H18N10TL	<300	849-500 PSZE	500/125	The calculation for the hot-leg FET housing, characterised by the highest delta-ferrite content, can be regarded as an over-estimate. Further monitoring is recommended.
40YA12W001	STEAM GENERATOR	1	Carbon steel housing, austenitic collector and tubes	-	-	-	The primary circuit collector welds and the GF casing bottoms must be assessed. The calculation for the GF casing bottom with the highest T_{ko} value is to be regarded as an over-estimate. Further monitoring is recommended.
40YA21S201	COLD LEG MAIN GATE VALVE	1	Cast austenitic stainless 08H18N10TL	<270	849-500 PSZE	500/125	The calculation for the hot-leg FET housing, characterised by the highest delta-ferrite content, can be regarded as an over-estimate.
40YA22S201	HOT LEG MAIN GATE VALVE	1	Cast austenitic stainless 08H18N10TL	<300	849-500 PSZE	500/125	The calculation for the hot-leg FET housing, characterised by the highest delta-ferrite content, can be regarded as an over-estimate. Further monitoring is recommended.

The register preserves the component identity and the reason for using a previous bound, a new calculation or monitoring.
Highlighted components are selected for further investigation

The retained items

Screening retained 34 review items; the cast hot-leg valve required the dedicated aged J-R assessment.

- Main circulation pump ✓
  - Pumps made from austenite are not subject to evaluation (ASME)
  - δ-ferrite for welds ≈ 4-8% < 9% threshold value
  - Previous studies → brittle fracture resistance verified
  - Component not susceptible for thermal ageing effects
- Hot leg main gate valve 
  - CASS material + thermal embrittlement → increased strength properties
    fatigue curve upward shift
    J-R curve downward shift
  - **J-R curve based investigation is necessary**

The retained items

Screening retained 34 review items; the cast hot-leg valve required the dedicated aged J-R assessment.

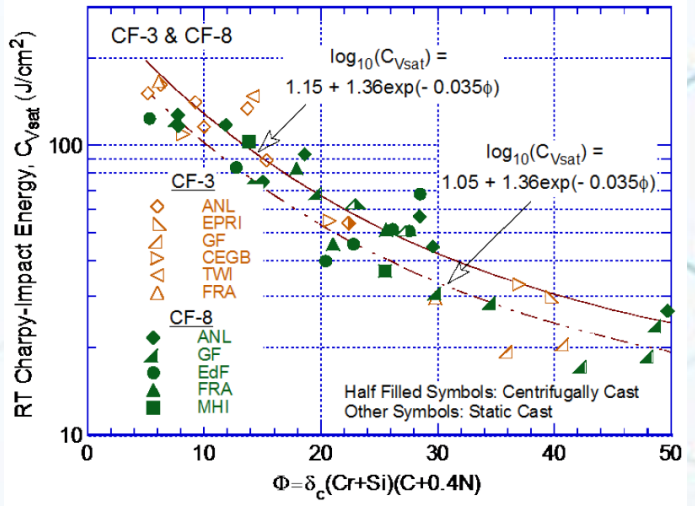
- Primary pipe ✓
  - δ-ferrite for welds ≈ 4-8% < 9% threshold value
  - Component not susceptible for thermal ageing effects
- Steam generator ✓
  - Calculated DBTT shift for 70 years < 30° C
  - Load and geometry based selection criterias are not met
  - Not susceptible for thermal ageing
  - Impact test not advised for austenitic components
- Pressurizer ✓
  - Diffusion speed not enough to induce macroscopic property degradation
  - Scheduled monitoring is advised ⚠
- Feedwater system ✓
  - Operating temperature induces negligible thermal embrittlement

Main gate valve: composition determines the aged input

The two casting records illustrate why the fracture-resistance estimate must be heat-specific.

Chemistry [wt%]	20YA12S201	20YA52S201
C / Si	0.05 / 0.47	0.07 / 0.50
Mn / Cr	1.34 / 17.60	1.35 / 15.02*
Ni / Ti	9.03 / 0.59	9.24 / 0.43
P / S	0.033 / 0.009	0.023 / 0.011
N	0.04 assumed	0.04 assumed

Quantity	12S201	52S201
Reported ferrite [%]	16.55	5.60
Yield / tensile [MPa]	275 / 495	245 / 500
Selected CVsat [J/cm²]	67.85	157.38



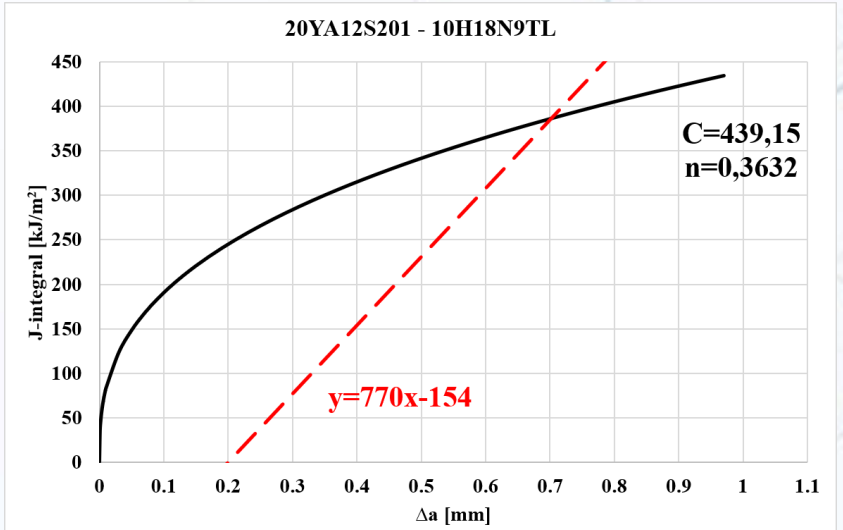
Different casting records produce different aged-state resistance inputs. The CF8-type correlation must be applicable to the actual material.

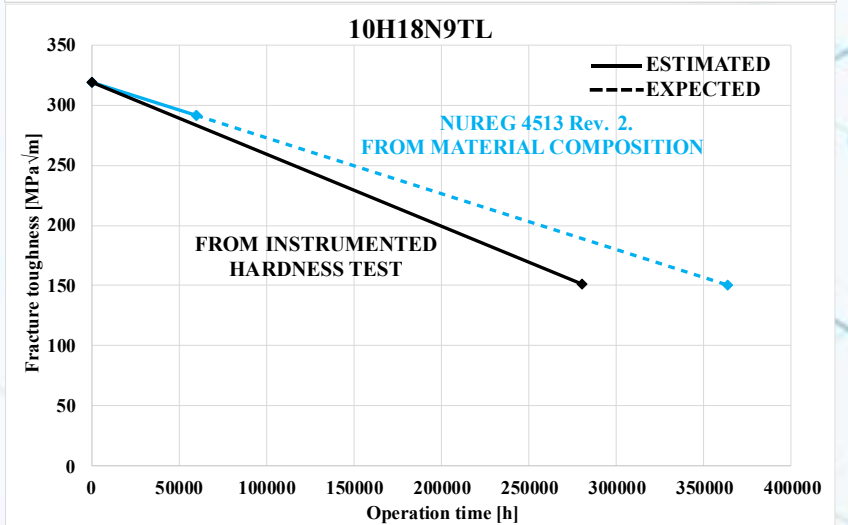
* Source value retained: verify Cr and assumed nitrogen against the material certificates. Ferrite is reported as a phase fraction, not wt%.

From saturation Charpy energy to an aged J-R curve

The material correlation provides the resistance curve used in the component calculation.

- NUREG 4513 Rev. 2. calculations
  - Initial condition → from $C_{V_saturation}$= 200 J/cm²
  - Actual condition → from calculated $C_{V_saturation}$
  - Calculation of J-Δa curve with power-type relation
  - ASTM E18-22 based evaluation of K_{JIc}
- Degradation observed from calculated values
- Both C_V and K_{JIC} tends towards saturation



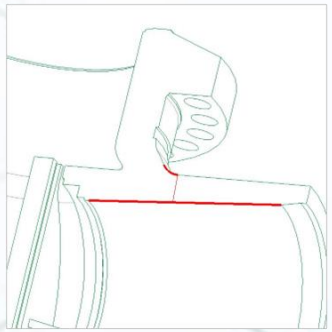


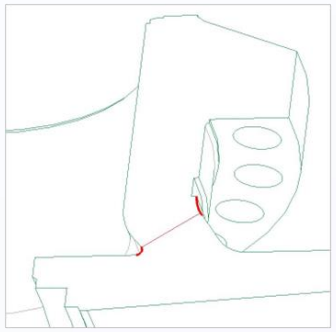
Example: 20YA12S201. J in kJ/m²; Δa in mm.
Black: modelled resistance. Red: 0.2 mm offset line.

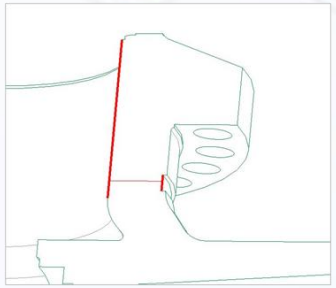
Main gate valve: the assessment uses postulated flaws

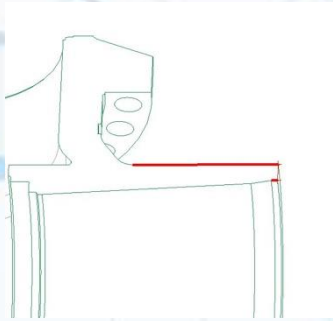
Eight critical locations were examined using the aged material properties and the component loading.

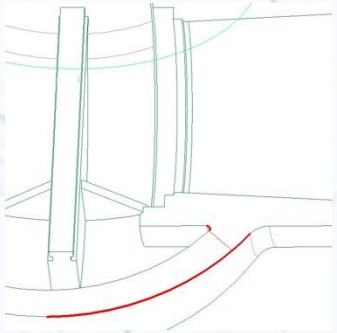
- The assumed initial crack depth is one quarter of the wall thickness: a/t = 1/4.
- The assumed semi-elliptical crack shape is a/c = 1/3.
- The same aged resistance basis is checked against the crack-driving force at the relevant component locations.

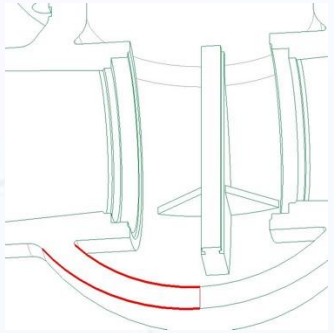

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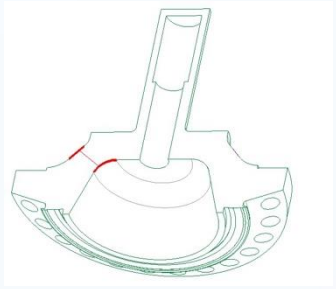

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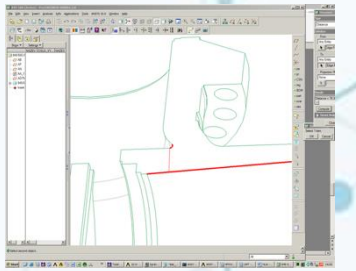

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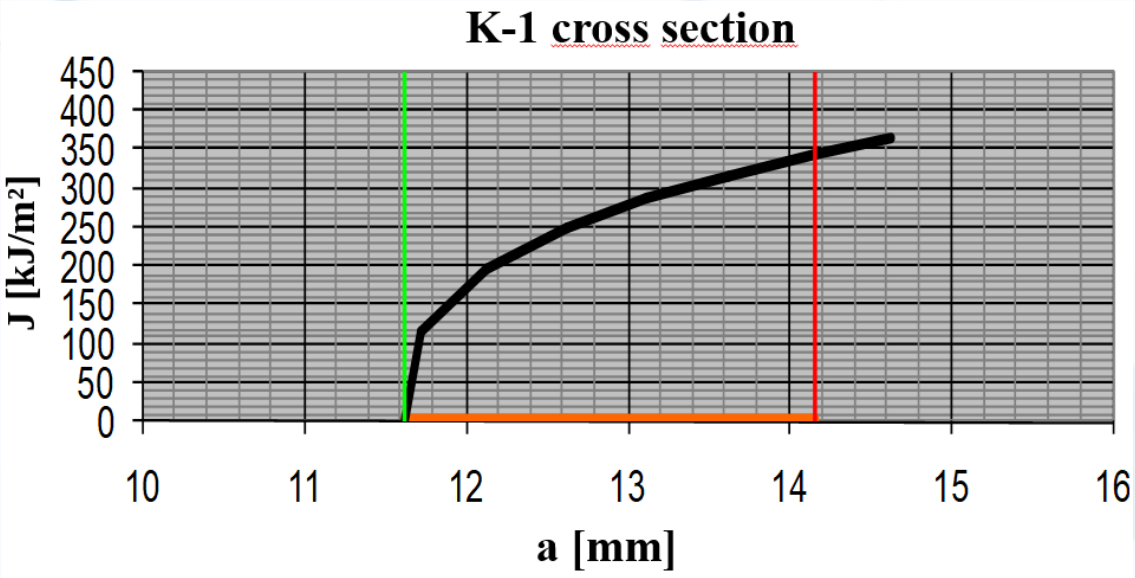

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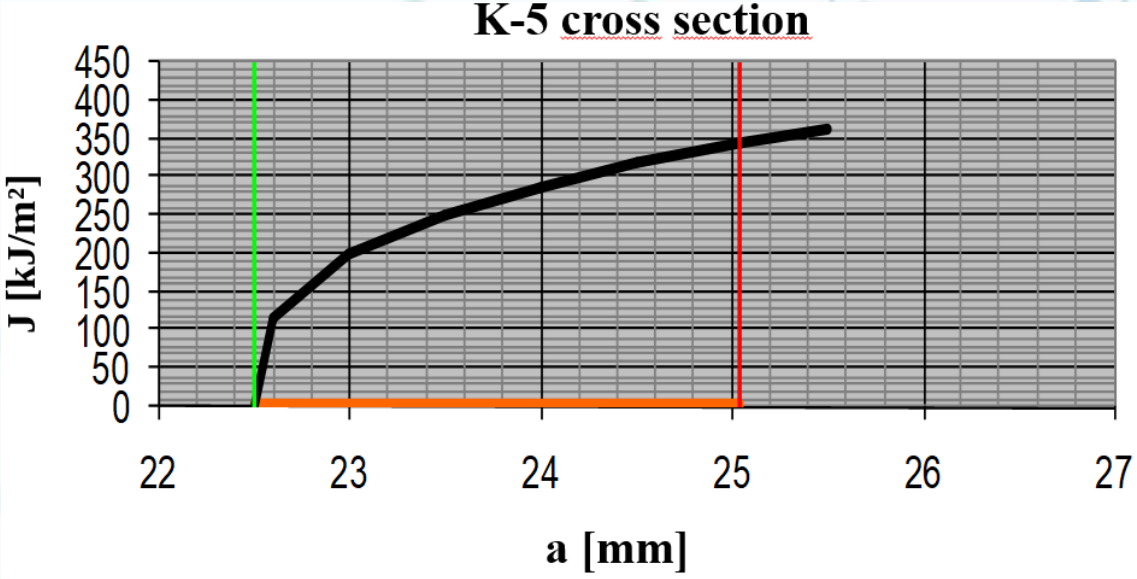

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8

J-R assessment: the applied driving force stays below resistance

The illustrated checks satisfy the source assessment criteria at 1.25 times the design loading.





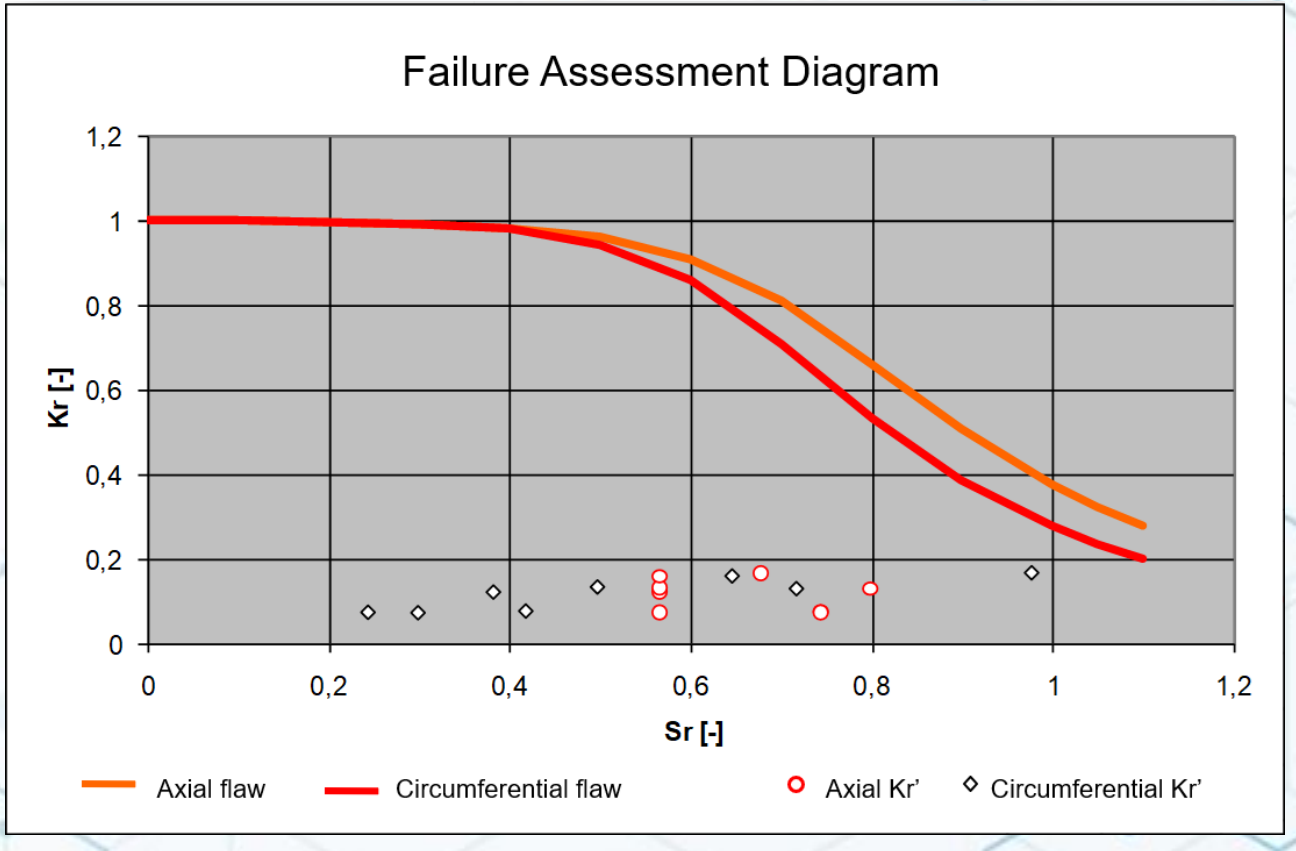
The black curve is the aged material resistance; the orange curve is the applied J from the component calculation.

For the reported cases, the applied driving force remains below the resistance over the evaluated crack extension. The result supports crack stability for the assumed material state, flaw dimensions and loading.

The failure assessment diagram checks two failure modes

The evaluated points remain within the acceptance boundary for fracture and plastic collapse.

- The fracture coordinate compares crack-driving force with material fracture resistance.
- The load coordinate compares the applied load with the plastic limit capacity.
- Both axial and circumferential flaw cases were assessed using the source Appendix K procedure.
- The diagram confirms the reported acceptability for the specified ageing, flaw and loading assumptions.



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KIBE13 conclusion: the assessment supports 70-year operation

Within its defined scope, thermal embrittlement does not introduce a life limit before the evaluated 70-year horizon.

- Existing fracture bounds remain applicable where their inputs and assumptions cover the extended period.
- The dedicated cast-valve calculation satisfies the applied crack-stability and collapse criteria.
- This conclusion does not mean that material properties remain unchanged; it means that the assessed margins remain adequate.
- Periodic monitoring should continue, with results compared against the material assumptions and criteria used in the assessment.

Instrumented indentation: the 2011-2024 plant programme

The measurements established a practical record of hardness and strength properties on operating components.

- The programme covered all four units: 99 measurement series on 48 components at 63 locations.
- Force and indentation depth were recorded to estimate hardness, contact response, yield strength and tensile strength.
- Measurements were repeated at 27 locations; the remaining 36 locations provided a single observation.
- The continuation should revisit identifiable locations and preserve complete raw force-depth records.

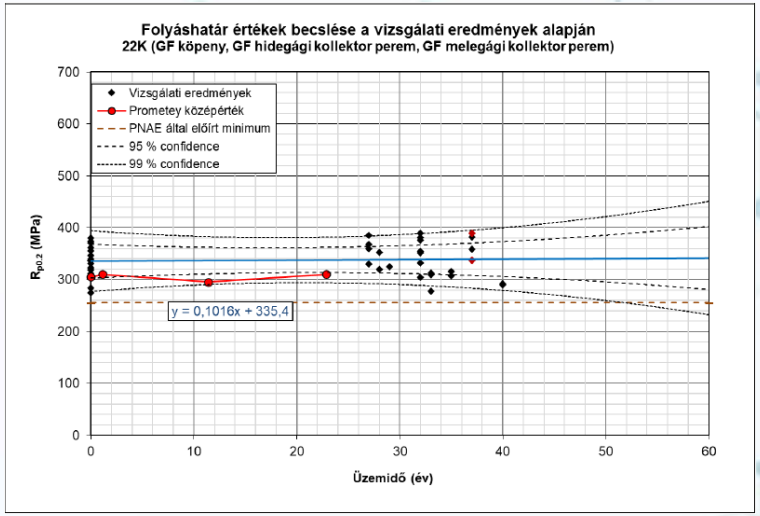


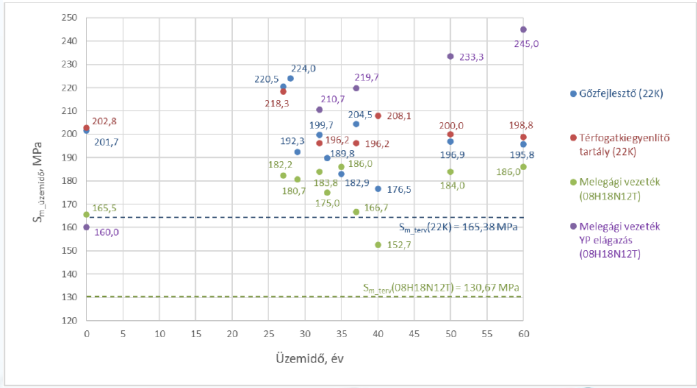
On-site testing during an outage. The small impression is accompanied by a recorded force-depth response.

What did the strength measurements show?

The accepted results were generally stable or moderately higher, but some conservative projections required follow-up.

- Yield and tensile strengths were compared with manufacturing records and projected to 50 and 60 years.
- The studies used 95% and 99% confidence bounds; these are statistical projections, not measurements at those future ages.
- At the 99% level, some steam-generator and cold-leg valve projections required further investigation.
- The derived allowable stress intensity S_m is a design-stress quantity, not the fracture-mechanics parameter K.





The 2025 review: extract more information from the record

Historical results were reorganised, and the force-depth curves were examined for usable fracture-resistance information.

- Measurements were regrouped by component type so that comparable materials and service conditions could be evaluated together.
- Historically excluded results were retained in the record for review rather than treated as proof that degradation was absent.
- Selected archived curves were re-evaluated using a critical indentation energy model to estimate fracture toughness.
- The aim is to continue the existing monitoring programme with a property that is more directly relevant to crack tolerance.

Fracture toughness from indentation: three approaches

Each model requires different information; the legacy measurements constrain which approach can be applied.

Method	What it evaluates	Requirement / limitation
Critical stress-strain	Contact pressure is related to a material fracture-stress criterion.	The cited ferritic-steel application requires fracture-related calibration.
Critical indentation energy	A pressure-depth integral is evaluated up to a model-derived critical depth h*.	The method needs a credible modulus-depth relation and a damage criterion.
Energy release rate	A change in potential energy is related to an equivalent fracture area.	The cited formulation needs unloading information and its equivalent-energy assumptions.

Current application: CIE on selected legacy records. Next calculation: ERR using measured or reconstructed unloading information.

Critical indentation energy: how the estimate is obtained

The unloading response defines a critical depth; the contact-pressure response is then integrated up to that depth.

1. Unloading response

$$E_D = \frac{1-\nu^2}{\frac{2\sqrt{A_c}}{S\sqrt{\pi}} - \frac{1-\nu_i^2}{E_i}}$$

The unloading slope S and contact area Ac determine the apparent modulus ED at the measured depth.

2. Critical depth

$$D = 1 - \frac{E_D}{E}, \qquad E_D(h^*) = E(1 - D^*)$$

ED(h) is fitted and h* is found where it reaches the assumed critical modulus. The adopted ED*/E ratio is 0.5202.

3. Energy conversion

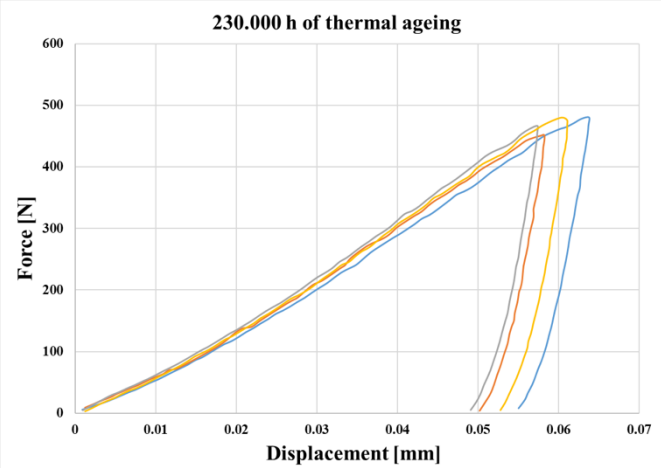
$$K_{\text{ind}} = \left[E \int_0^{h^*} \frac{4P(h)}{\pi d(h)^2}\, dh \right]^{1/2}$$

P/Ac is integrated up to h* and converted into Kind using the source-model convention.

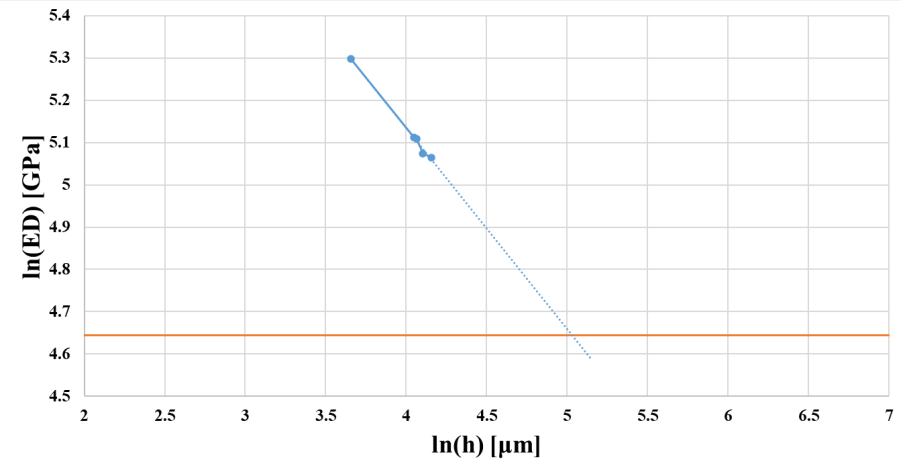
Kind denotes an indentation-derived estimate. The assumed damage threshold and extrapolated h* require validation.

Legacy data: determining the critical indentation depth

The old instrument supplied one final unloading per indent, so nearby measurements were evaluated together.



Recovered force-depth curves



The threshold intersection defines h*

The archived P-h curves were recovered from the reports; complete raw measurement files were not available for this evaluation. For each selected series, the unloading slopes were combined to fit an apparent-modulus-versus-depth relation.

The assumed damage criterion determines where that relation reaches E_D^* and therefore defines h*. For the pressurizer example, h* changed from 0.153 mm in 2013 to 0.126 mm in 2018; the 2023 record was not reliably evaluable.

Indentation-derived toughness: the recovered results

The results demonstrate an evaluation method and identify changes that deserve verification.

Component / record	Year / service	Material	h* [mm]	Kind [MPa√m]
Steam generator: 10YA42W001	2011 / 29 y	22K	0.131	186.44
Pressurizer: 30YP10B001	2013 / 27 y	22K	0.153	213.68
Same pressurizer	2018 / 32 y	22K	0.126	188.55
Reactor head: 30YA00W001	2013 / 27 y	15H2MFA	0.0747	161.05
Hot-leg valve: unit 2, loop 1	2016 / 32 y	CASS*	0.0793	151.27

Same pressurizer: 213.68 → 188.55 MPa√m, about 11.8% lower. This is a two-date comparison, not a calibrated ageing law.

* The source records use different casting-grade designations; confirm the material identity before model-to-model comparison.

Hot-leg valve: the lower estimate deserves attention

The approximately 150 MPa√m result may indicate advanced ageing, but it is not yet a replacement for the assessment input.

- The estimate comes from the 2016 indentation record for the unit 2, loop 1 hot-leg valve after about 32 years of service.
- Its magnitude is a relevant warning signal, consistent with the concern raised in the 2025 review.
- Before quantitative comparison, material state, test temperature, toughness definition and uncertainty must be reconciled.
- The next step is repeat measurement and reference fracture testing; the result alone does not establish component non-conformity.

2016 record

151.27

MPa√m

Unit 2 / loop 1
Hot-leg main gate valve
32 years of service

Indentation-derived estimate

Continue the plant measurements with a toughness objective

The proposed continuation combines improved measurement, method comparison and validation against reference tests.

Measure	Repeat at traceable locations and record complete force-depth data with partial unloadings.
Evaluate	Retain strength trending, calculate toughness estimates and quantify sensitivity to the measurement and model assumptions.
Validate	Compare CIE, ERR and suitable conventional fracture tests on representative materials and ageing states.
Use the result	Compare verified material information with the KIBE13 inputs; review the component assessment if the evidence warrants it.

Conclusions: assessment and monitoring address the same issue

The next step is to improve the material evidence used to verify the assumptions behind long-term component integrity.

- The first thermal-ageing project established the susceptible-component scope and the need for plant monitoring.
- The current KIBE13 review supports the evaluated 70-year period, including the dedicated aged-state assessment of the cast valve.
- The historical indentation programme provides useful strength data; re-evaluation gives toughness estimates that deserve further verification.
- Improved indentation measurements, numerical evaluation and reference tests can support the next stage of toughness-oriented monitoring.

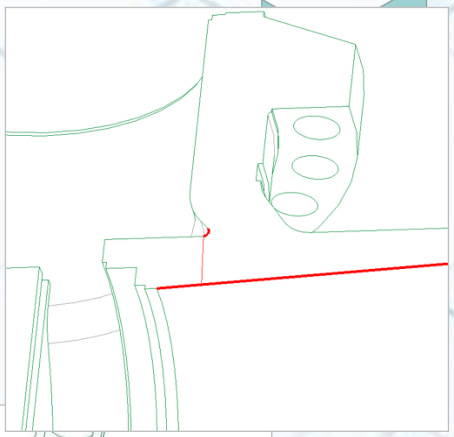
AEMI Atomic Energy Engineering Ltd.

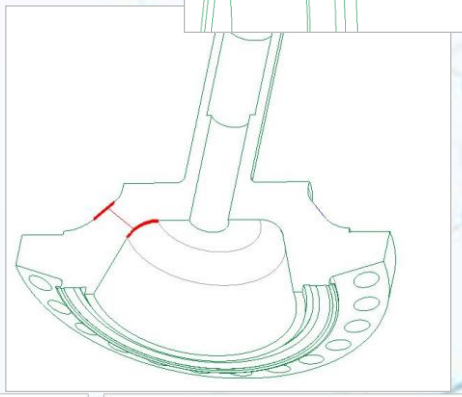
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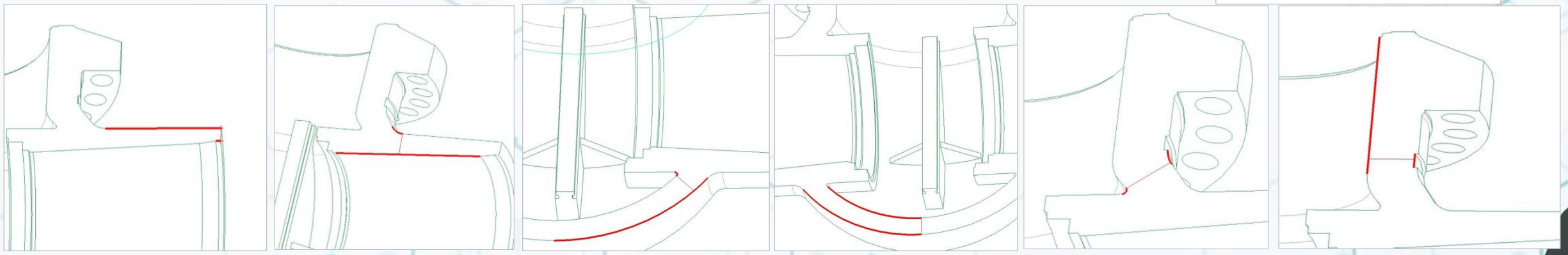
Aemi Atomic Energy Engineering Ltd. – Technical Division
H-3525 Miskolc, Kazinczy Ferenc str. 13. 1/3., Hungary
www.aemi.hu/technical-division/
info.tech@aemi.hu

Failure assessment diagram based evaluation

- **Preliminary data**
  - LT limiting effect of fatigue crack propagation not observed
  - Flattening of J-R curve → reduced critical flaw size
- **ASME BPCV XI: Appendix K → J-R curve based evaluation**
- **8 analysed cross section**

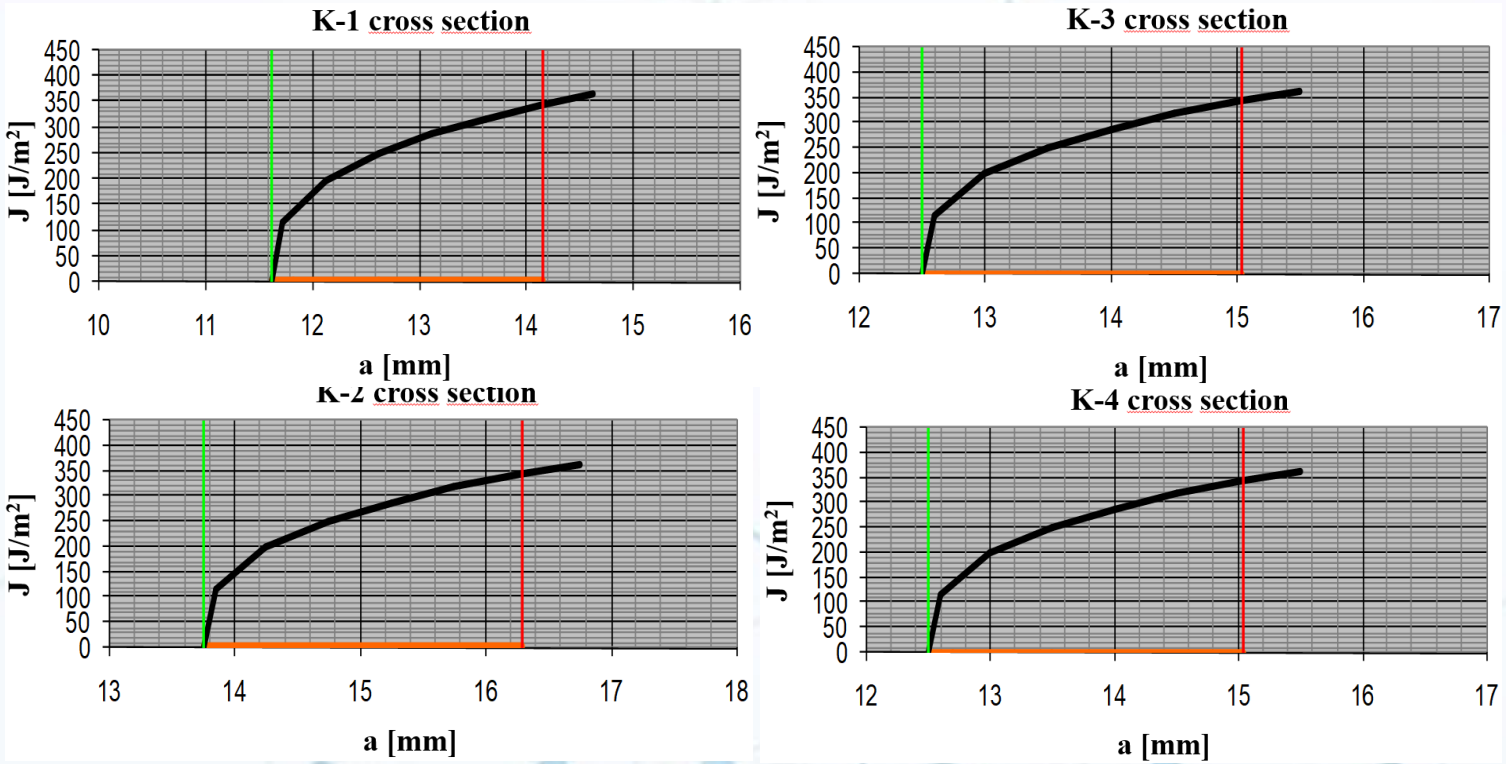


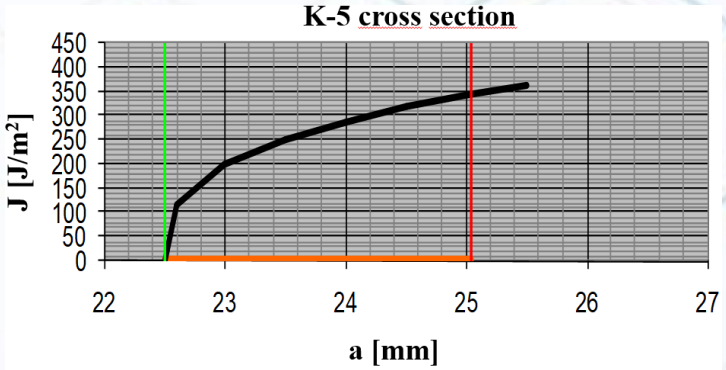


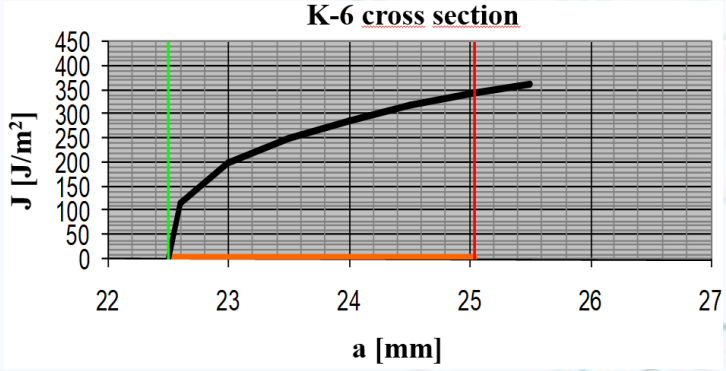


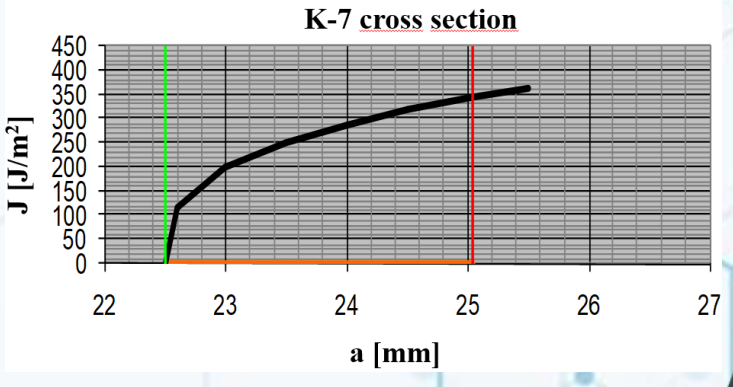
Failure assessment diagram based evaluation

- **Satisfactory results**
  - MGV conformity for crack stability
    - J-R criteria → a/t=1/4 wall thickness
      a/c=1/3 shape factor
    - J → 1,25 * design load



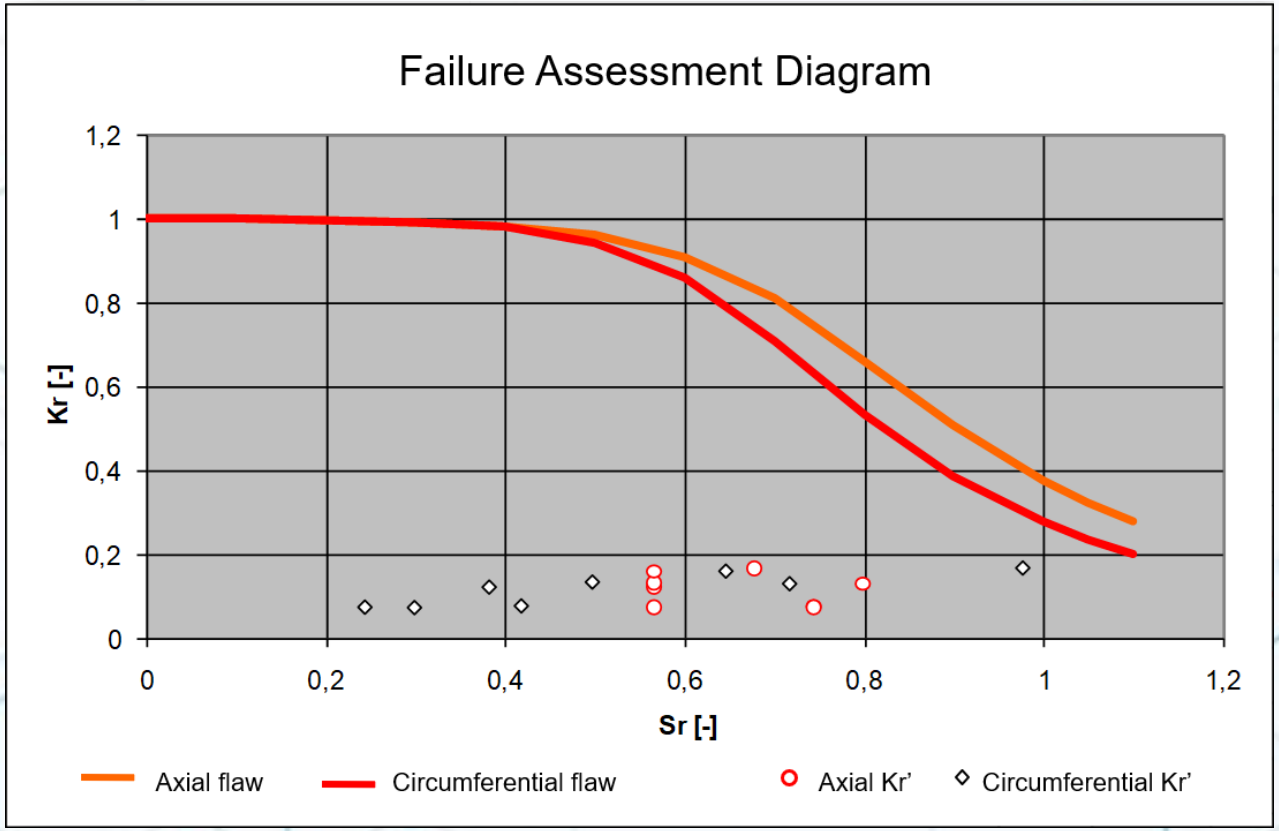






Failure assessment diagram based evaluation

- **Satisfactory results**
- **ASME BPVC XI K-4320**
  - Two parameter failure assessment diagram
    - Axial flaw case
    - Circumferential flaw case



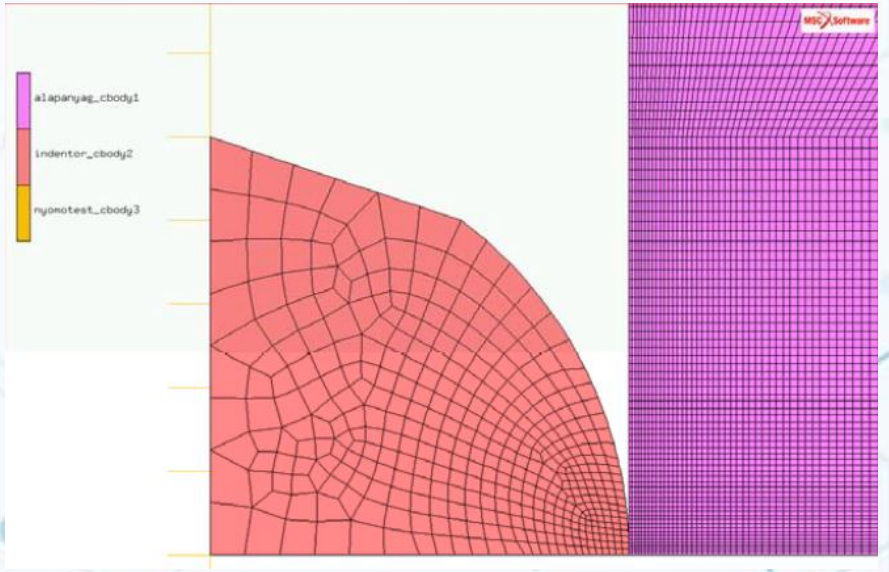
Key findings of TLAA No.13

- **Susceptible material types for thermal embrittlement**
  - Cast austenitic steels
    - DBTT upward shift indicates thermal embrittlement → for Paks not experienced
  - Ferritic steels
    - Investigation of incubation time is necessary
    - Flattening of J-R curve can cause smaller allowable crack size
- **For both material groups**
  - Monitoring is advised!
  - Quasi-destructive testing methods are favourable → **instrumented indentation test**
  - Fatigue crack propagation calculations are advised in the future

IIT for monitoring

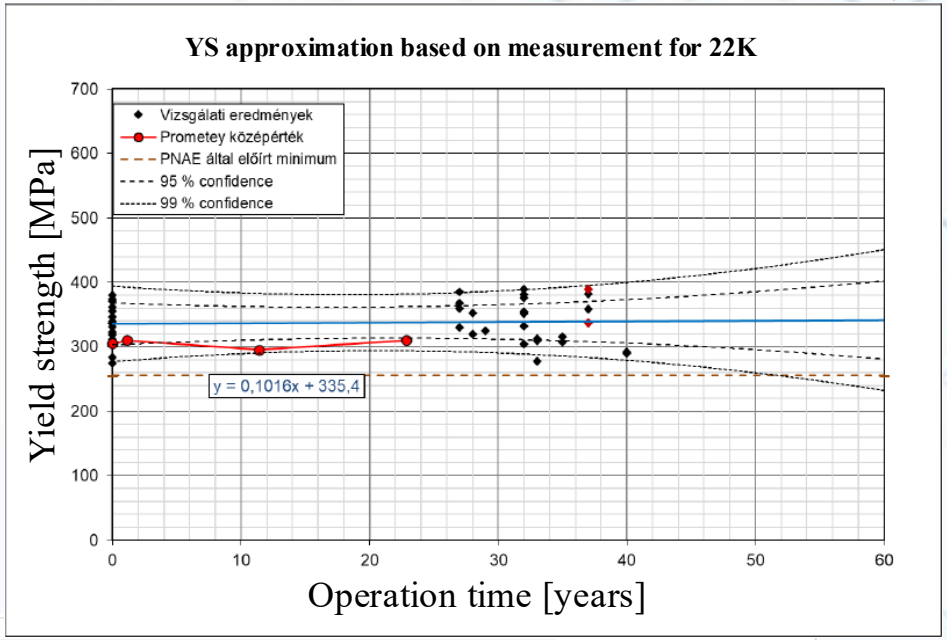
- **Monitoring for more than a decade**
  - Use of instrumented indentation test (IIT)
  - Material property evaluation
    - Hardness
    - Contact modulus
    - Strength properties
  - ~100 measurements (14 years)
- **Preparatory research work**
  - Identification of SSC for investigation
    - Primary circuit
    - Multiple material grade
  - Calibration of evaluation methods
  - Literature overview

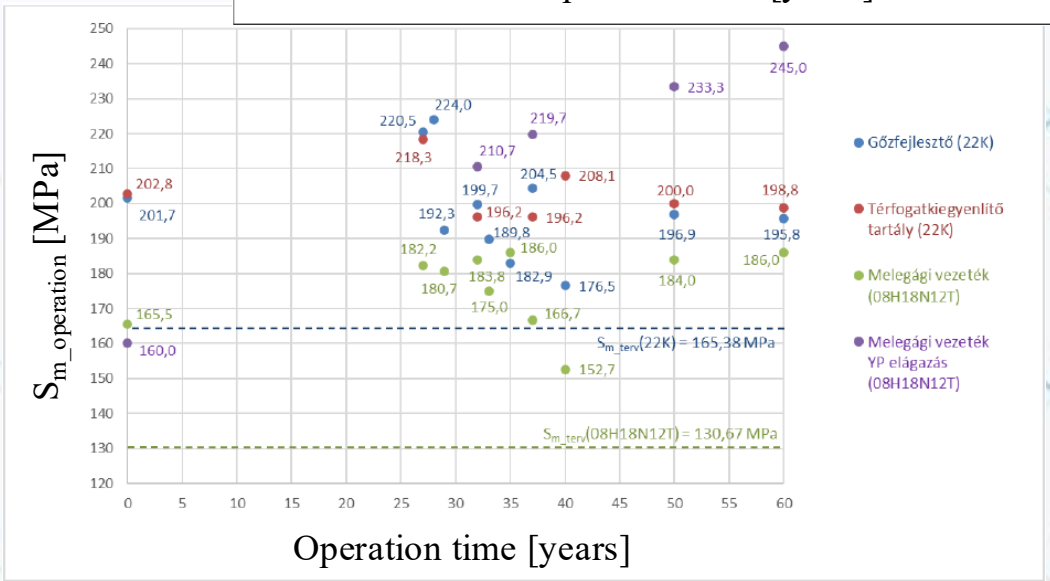




IIT for monitoring

- **Periodic measurements on components**
- **Calculation of indentation stress-strain curve**
- **Results**
  - Provisional change in strength properties
    - Using confidence intervals of 95% and 99%
  - Allowable stress intensity estimation
    - Using national regulatory methods (ASME)
  - Comparison with design values
    - All component groups
    - Satisfactory results (with few exceptions)
- **<u>Fitness for service</u>**





IIT for monitoring

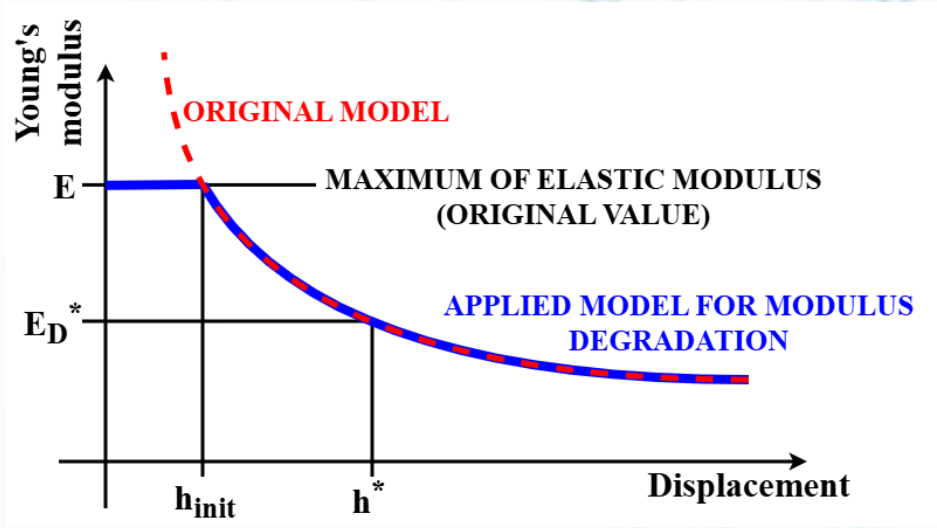
- **Summary of results**
  - Grouping results by component types
    - Similar loads
  - Review of excluded measurements
- **Possible use of existing results**
  - Re-evaluation with current standards
  - Extraction of unavailable measurement curve data points
  - Fracture property evaluation
  - Use of AI driven methods for complex
- **Recommendations**
  - Cyclic tests
  - Detailed logging and documentation of result data

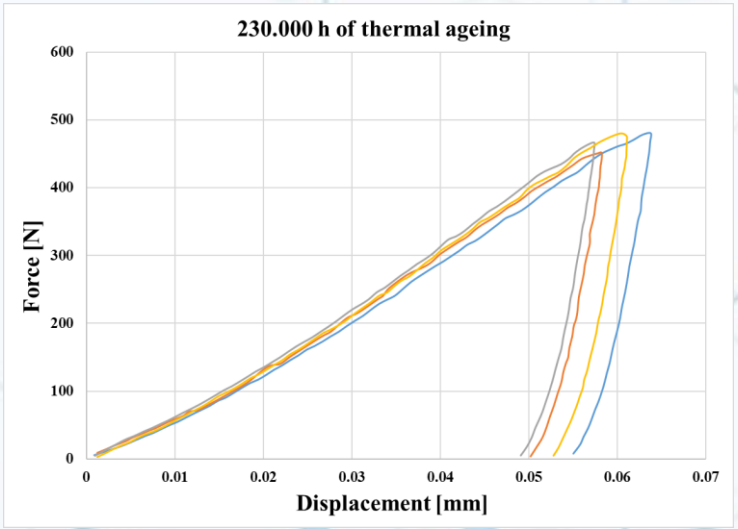
Enhancement of IIT

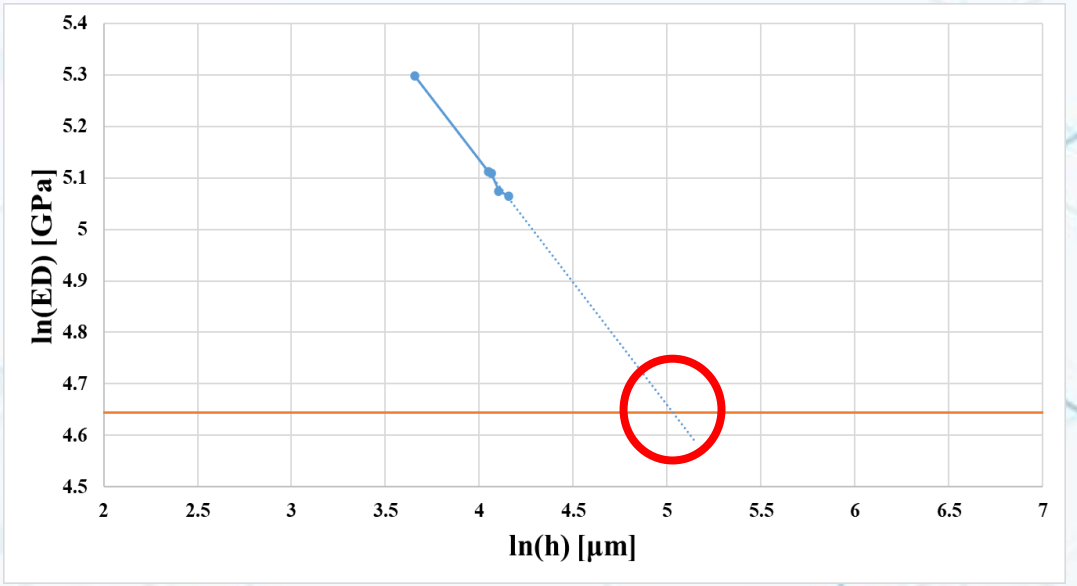
- **Investigation of strength properties do not show significant changes**
- **Evaluation of fracture toughness**
  - Investigation of embrittlement
  - Easier characterization of degradation
- **Multiple evaluation methods**
  - Critical indentation energy model (CIE)[2]
  - Critical stress strain model (CSS)[3]
  - Energy release rate method (ERR)[4]
- **Requirements**
  - Cyclic indentation test result
- **Use of existing results**
  - CIE evaluation

Critical indentation enegy model

- **Work of indenter ≈ fracture toughness**
- **Critical indentation depth (h*)**
  - Determination through **degradation of materials contact modulus** due to indentation
- **1 location – multiple measurements**
  - Single unloading cycle
  - Unified E_D degradation trend for sample

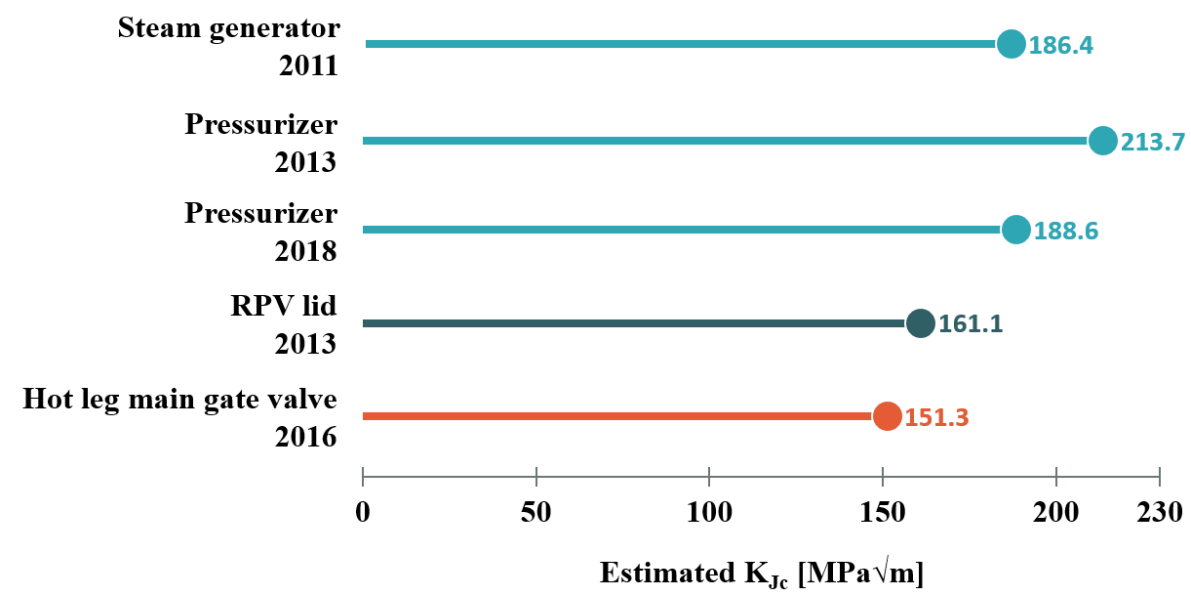


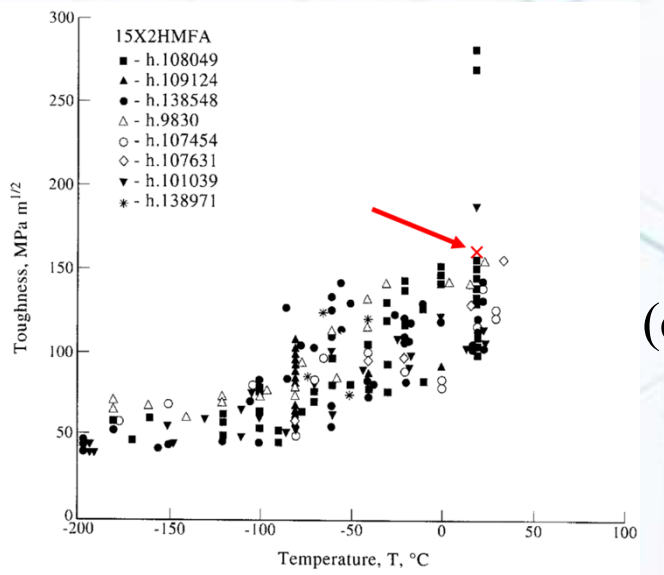




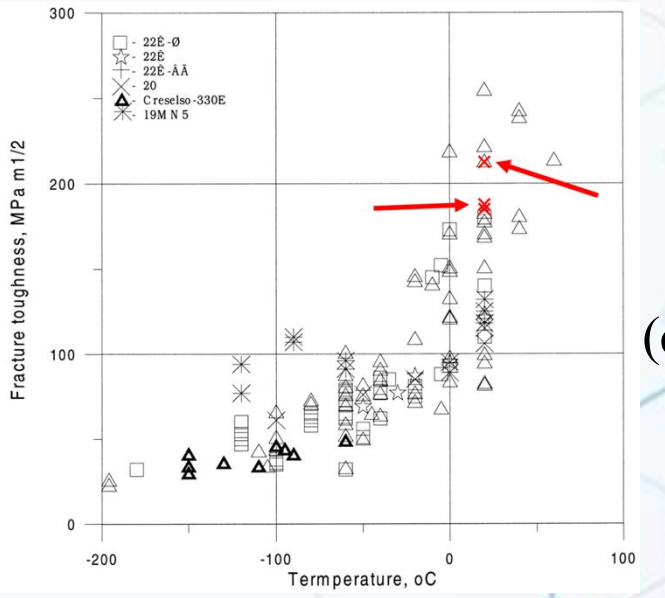
Critical indentation enegy model

- **Result from averaging measurements**
- **Successful application of evaluation method**
- **Goals**
  - Comparison of different calculation methods
  - Comparison of estimated values with conventional fracture test results





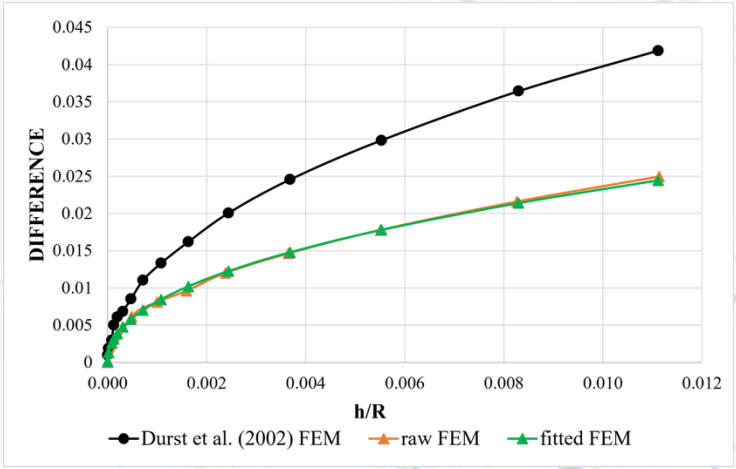
15H2MFA
(carbon steel)

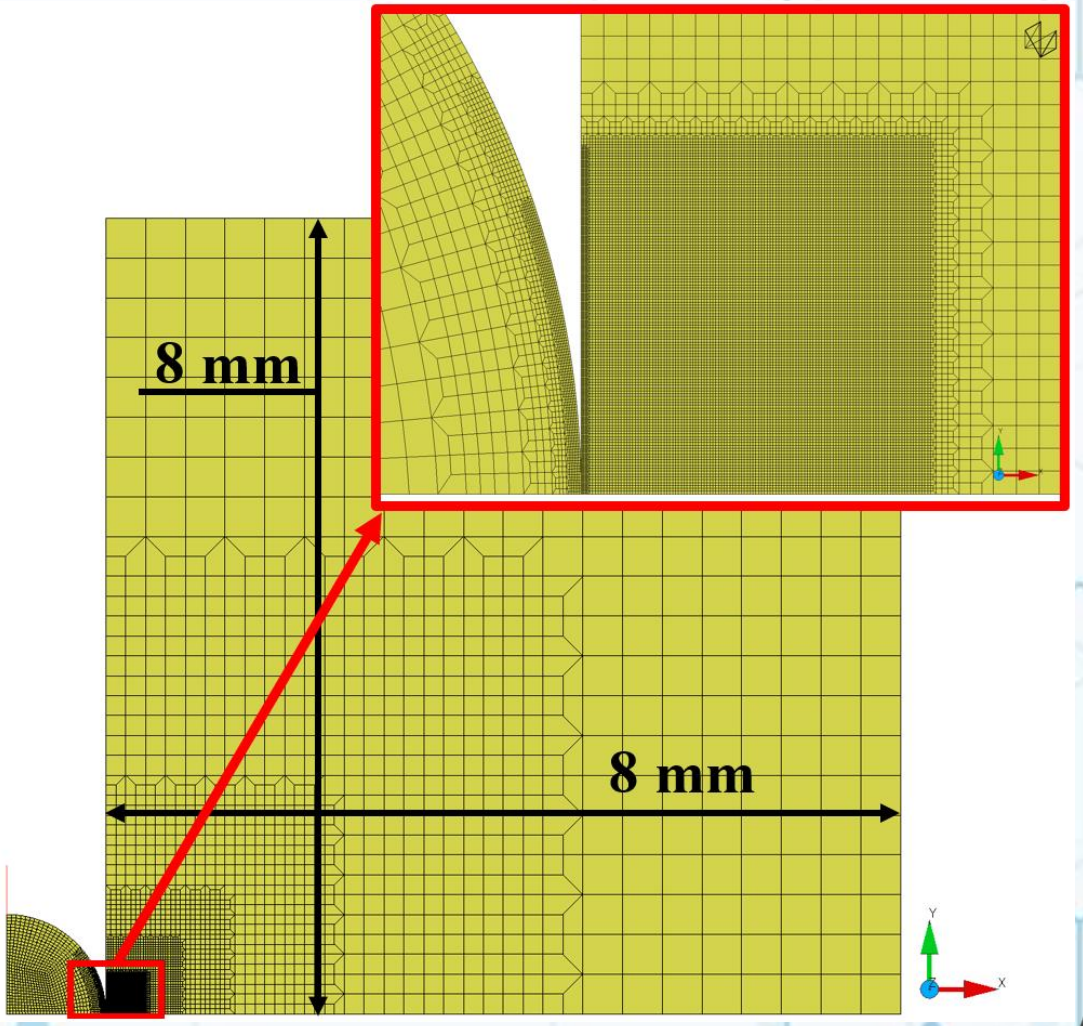


22K
(carbon steel)

Enhancement of IIT

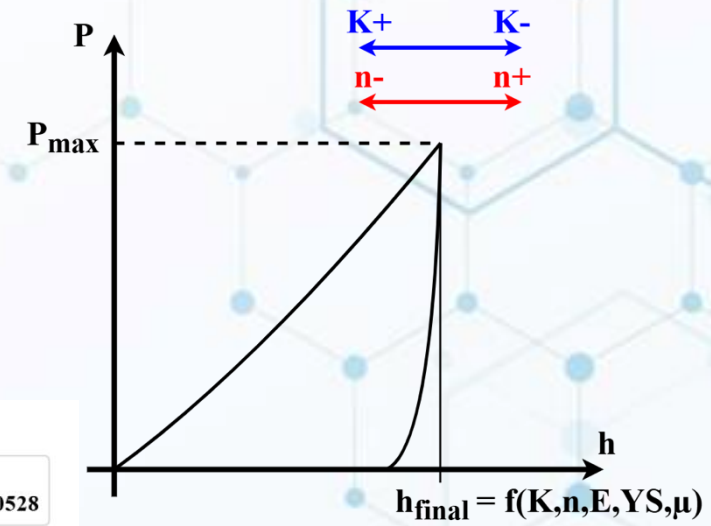
- **FEM for supplement of measurement curves**
  - Multiple cycle results
  - Untested scenarios
- **FEM model**
  - Axisymmetric model
  - Elastic-plastic constitutive equation
  - Meshed ball indenter
  - Fine mesh (1.56 μm at contact)

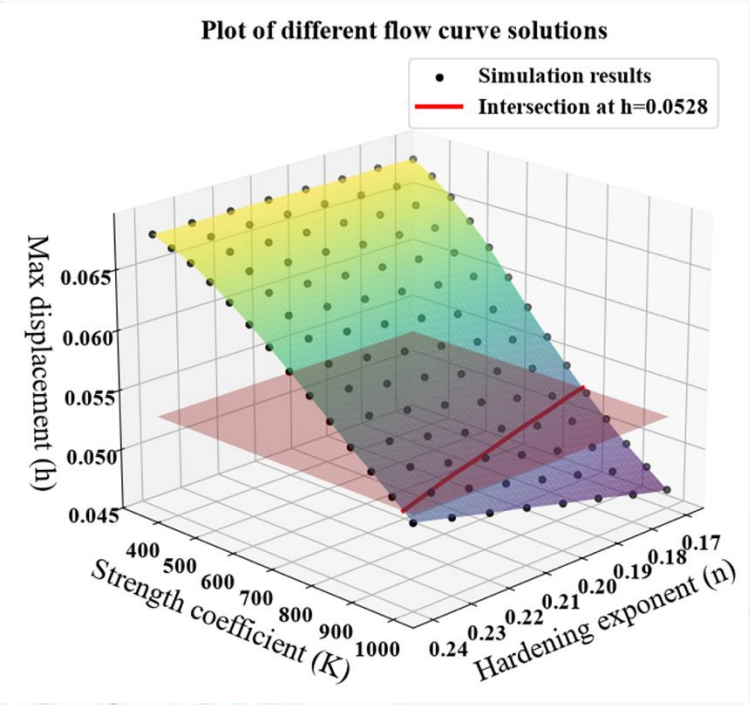




Enhancement of IIT

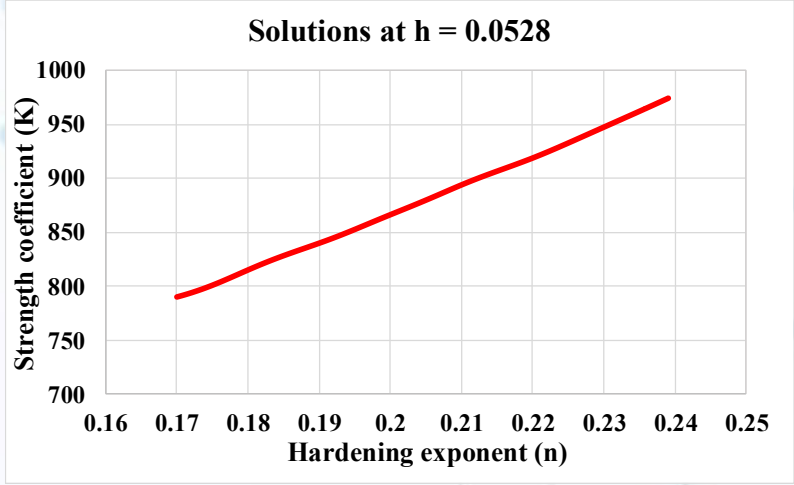
- **Inverse parameter extraction**
  - Approximately 100 simulation for 1 measurement
- **Fixed values**
  - Young's modulus, Poisson's ratio
  - Yield strength
  - Maximum force of indentation
- **Obtained values**
  - Flow curve parameters
    - 350 < **K** < 1000
    - 0.17 < **n** < 0.24
- **Multiple results**
  - Intersection at h_{final} final depth

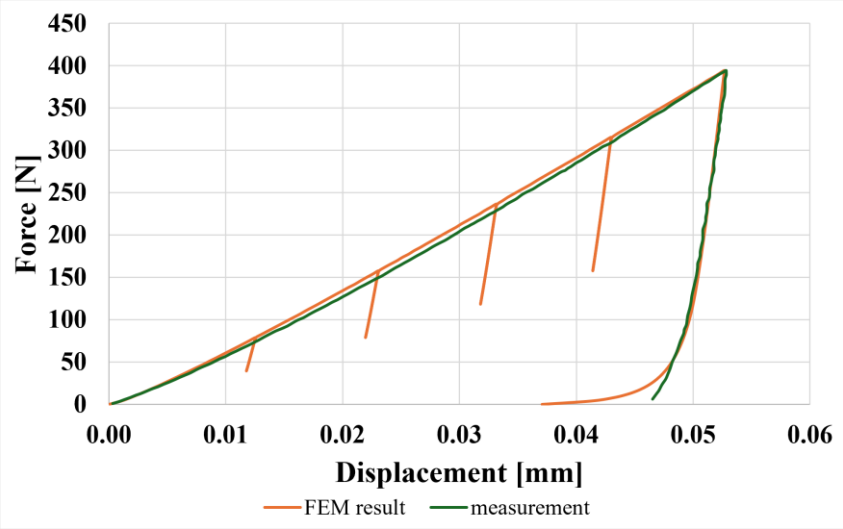


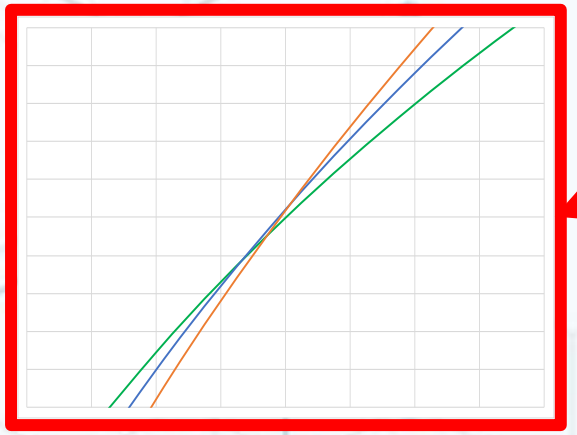


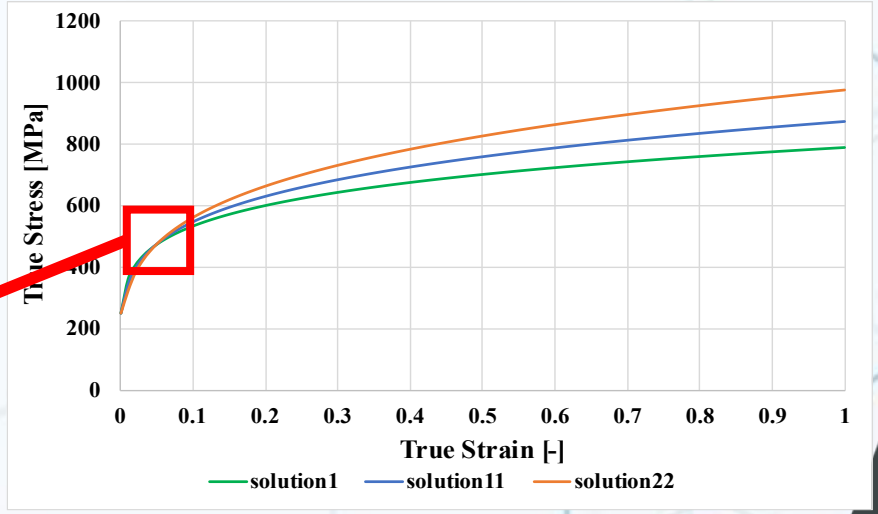
Enhancement of IIT

- **Observed intersection of flow curves**
  - ε_r = 0.049
  - Best fit with Normalized Mean Absolute Error method
- **Good fit with original measurement**
- **Future use of FEM results for ERR calculation**
- **Aim to use fracture toughness as a degradation marker**









Conclusion

- **Thermal ageing effects have high influence on allowable LT**
- **Prevention and mitigation is key**
- **Paks NPP LTO program**
  - TLAA for thermal embrittlement
  - Identification of susceptible components
- **Monitoring of thermal embrittlement indicators**
  - Strength properties, fracture properties
  - Use of IIT
  - FEM integration for existing measurements
- **Research needed**
  - Extent of thermal ageing
  - Evaluation methods for fracture toughness from IIT

Citations

[1] Chen, Y., Xu, C., Zhang, X., Chen, W-Y., Park, J.-S., Almer, J., Li, M., Li, Z., Yang, Y., Rao, A. S., Alexandreanu, B., Natesan, K. „Microstructure and deformation behavior of thermally aged cast austenitic stainless steels” (2017), 18th International Conference on environmental degradation of materials in nuclear power systems

[2] Lee, J.-S., Jang, J.-I., Lee, B.-W., Choi, Y., Lee, S. G., Kwon, D. „An instrumented indentation technique for estimating fracture toughness of ductile materials: A critical indentation energy model based on continuum damage mechanics” (2006), Acta Materialia, 54, 1101–1109.

[3] Byun, T. S., Kim, J. W., Hong, J. H. „A theoretical model for determination of fracture toughness of reactor pressure vessel steels in the transition region from automated ball indentation test” (1998), Journal of Nuclear Materials, 252, 187-194.

[4] Zhang, T., Wang, S., Wang, W. „A unified energy release rate based model to determine the fracture toughness of ductile metals from unnotched specimens” (2019), International Journal of Mechanical Sciences, 150, 35-50.