OAK RIDGE National Laboratory

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Miniaturized Fracture Toughness Testing Technology for Irradiated Materials

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Oak Ridge National Laboratory

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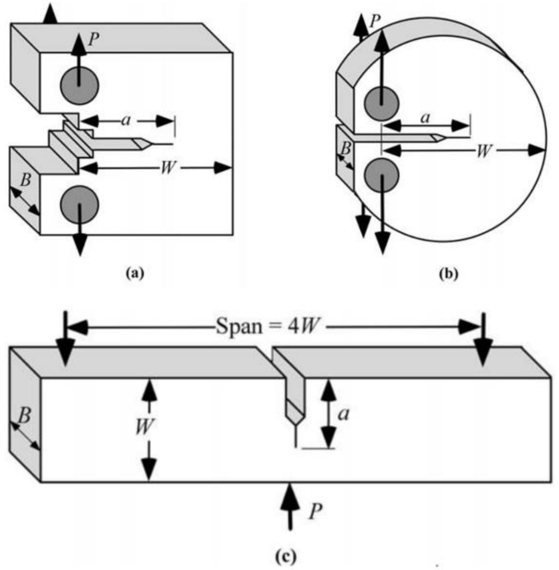
U.S. DEPARTMENT OF ENERGY

Introduction/Background

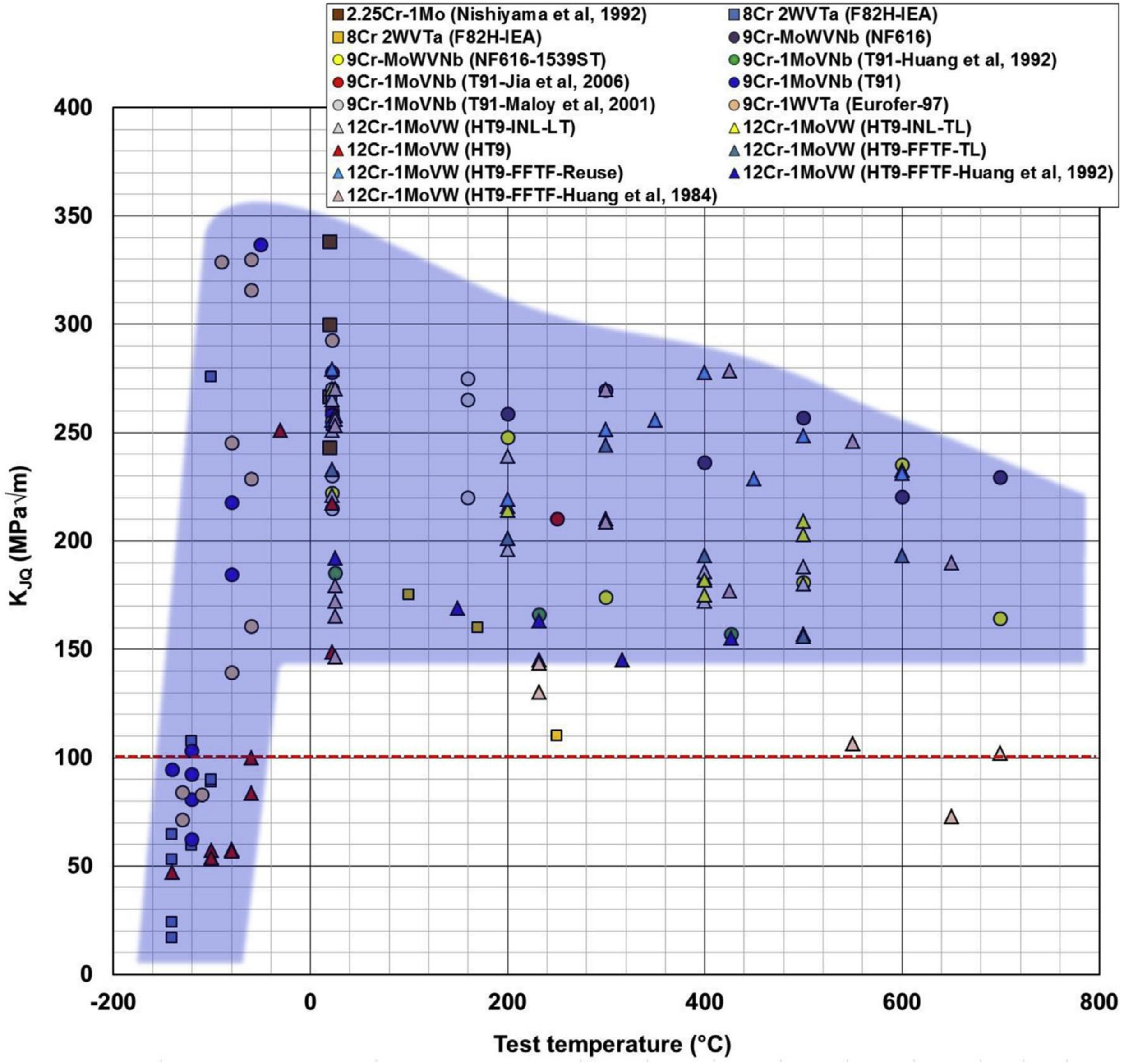
- ❑ Structural materials for advanced reactors, designed for high thermal and economic efficiencies, will be exposed **to high temperatures (300–700°C) and high-dose (>10 dpa) neutron radiation damage.** This exposure leads to significant degradation of their mechanical, corrosion, and physical properties.
- ❑ The design of the core structure and selection of materials for a high-performance reactor will require the **development of comprehensive evaluation techniques and a robust materials property database.**
- ❑ Ensuring the prevention of failure in critical reactor components during operation is a fundamental requirement for assessing nuclear energy system safety. Therefore, **accurately evaluating the fracture resistance of structural materials under service conditions is one of the pivotal steps in the safety assessment process.**
- ❑ While information regarding the high-temperature fracture resistance (J-R) curve of key materials will be essential for successful component design, **very limited data on high-temperature fracture toughness have been generated for the new or advanced structural materials.**
- ❑ ***Aimed to assess the fracture testing and calculation method using 3-mm thick miniature bend bar specimen, the MBS-1 design which was standardized for HFIR irradiation, to characterize the fracture resistance of high-temperature reactor materials before and after irradiation.***



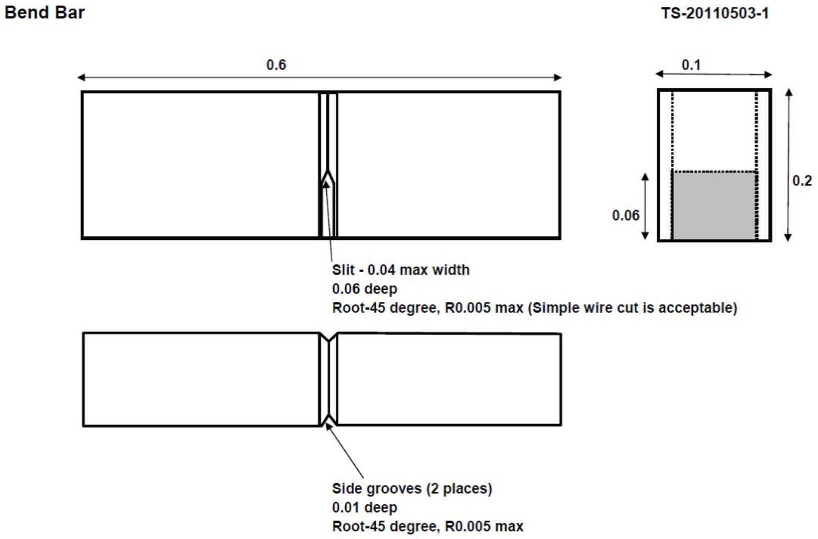
CT, DCT, TPB (SEB) Fracture Specimens

Background: Fracture Toughness from Miniature SEB Specimens

(Byun et al. ASTM-STP 2014, JNM 2016)



Miniature SEB Specimens: 4–5 mm W x 2.5–3 mm B x 12–15 mm L



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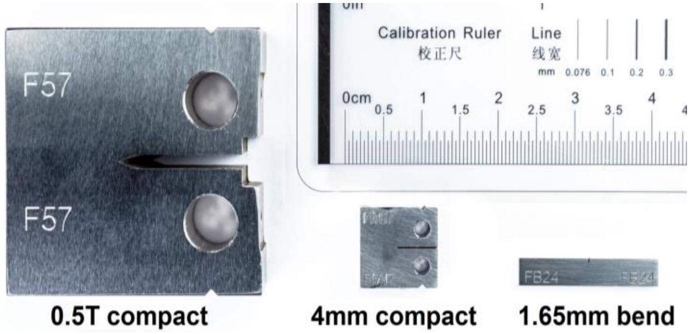
Introduction/Issues & Resolutions

- ❑ Qualification of advanced (high-temperature) reactor materials requires high-temperature fracture testing after high-dose irradiation.
- ❑ Fundamental issues: fracture testing in higher-ductility region may be harder to comply with the strain constraint (size) requirement of valid fracture toughness testing, and miniaturization may be limited.



- ❑ Fracture toughness testing in high-temperature, high-dose condition requires signification simplification in testing practices:
  - **Miniaturization of testing and specimen**
  - **Removal of clip (displacement) gage attachment**
  - **Testing in monotonic load-displacement mode**
  - **Simplest grip design for hotcell manipulator.**

- ❑ Irradiation capsule design has been **standardized** for the routine use of miniaturized bend-bar specimens in **HFIR irradiation** experiments to qualify advanced nuclear materials.

Miniature Bend-bar Specimen (14.8 x 4.5 x 3 mm & 2 DGs)

__MBS-1__ three-point bend fracture specimen design (top) and HFIR Rabbit Capsule __GENBEN-2__
Champlin et al. ORNL/TM-2023/3037

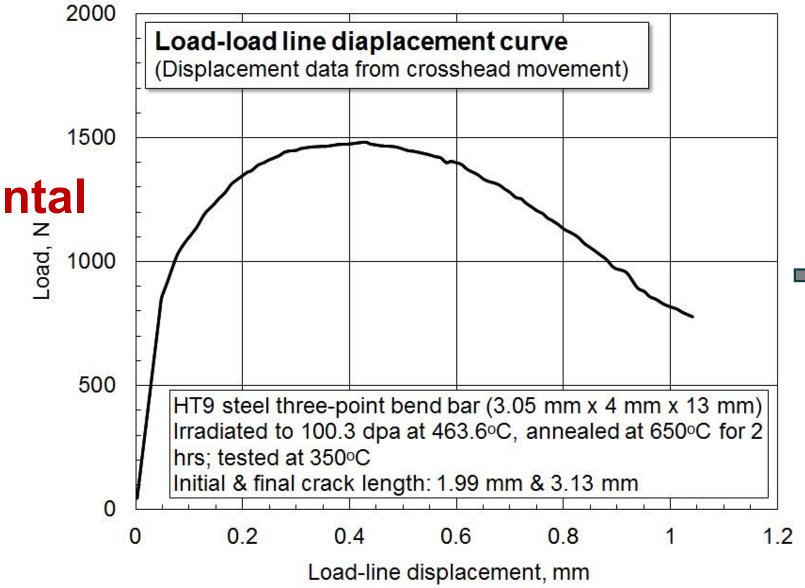
Objective: Fracture Testing & Evaluation Method using MBS Design

With Long History but Lately Simplified for Hotcell and High-T Testing

Method and procedure of fracture testing and analysis have been developed based on:

- **Specimen reuse technique used in high radiation area**
- **A newly developed simple precracking technique in blinded or inaccessible place like hotcell**
- **Simplification of test procedure (no clip-gage attachment) for testing in high-temperature vacuum furnace and high-radiation area**
- **Modification of data analysis procedure in accordance with the change in data acquisition method (without clip gage).**

Experimental Dataset:



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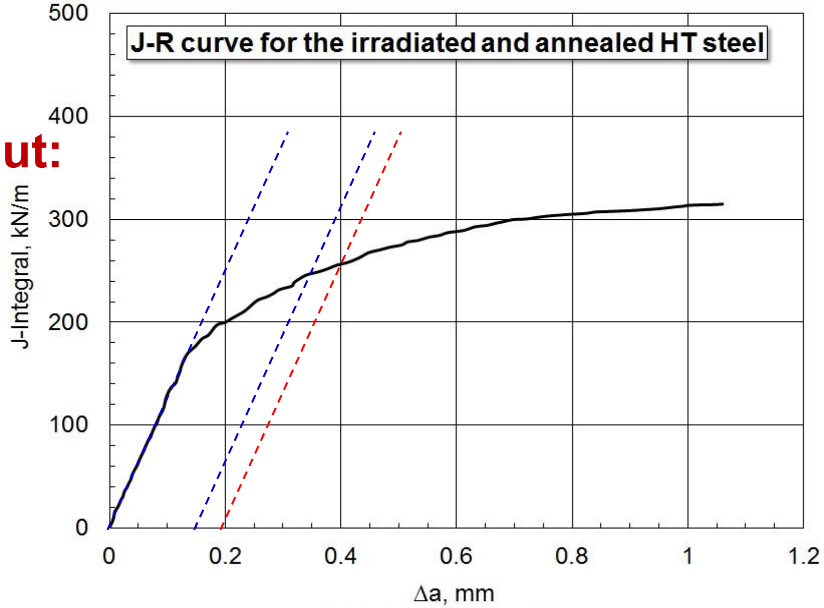
Optical measurement of Initial & Final Crack Length Data

Final Output:



Example: HT9 steel irradiated to 100 dpa at 463 °C and annealed at 650 °C for 2h. Tested at 350 °C.

Curve Normalization Method: J&K Calculation Process

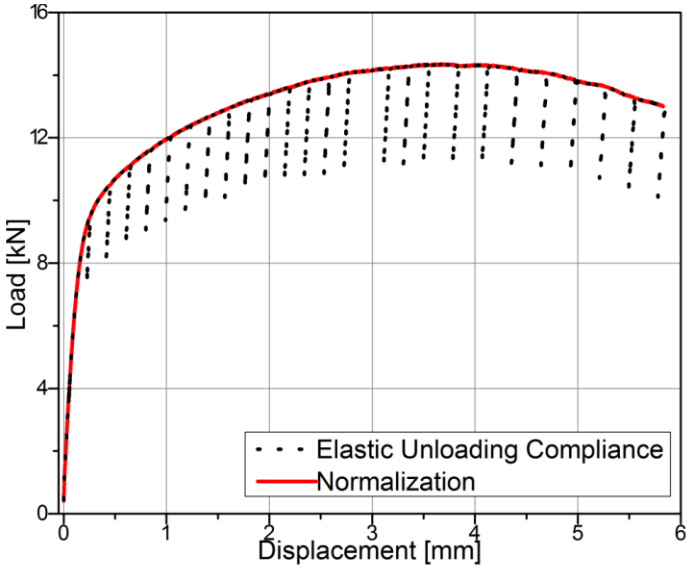
$$J_{(i)} = J_{e(i)} + J_{p(i)} = \frac{K_{(i)}^2(1-\nu^2)}{E} + J_{p(i)}$$

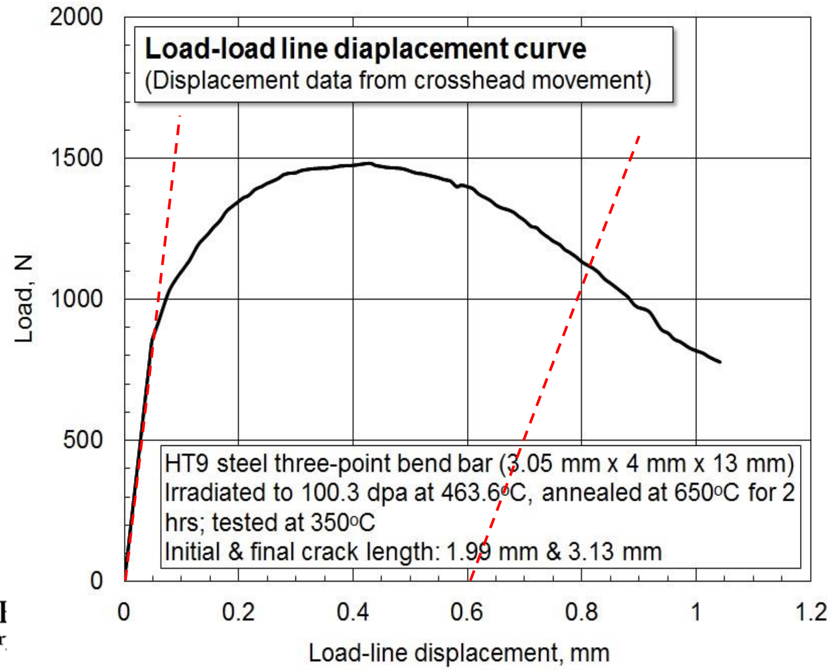
$$J_{p(i)} = \frac{2A_p}{B_N b} \qquad J_{p(i)} = \left[J_{p(i-1)} + \frac{2(A_{p(i)}-A_{p(i-1)})}{B_N}\right]\left[1 - \frac{a_{(i)}-a_{(i-1)}}{b_{(i-1)}}\right]$$

$$A_{p(i)} - A_{p(i-1)} = \frac{[P_{(i)}+P_{(i-1)}][v_{p(i)}-v_{p(i-1)}]}{2}$$

$$K_{(i)} = \frac{P_{(i)}S}{(EB_N)^{\frac{1}{2}}(W)^{\frac{3}{2}}} \frac{3(a_{(i)}/W)^{\frac{1}{2}}\{1.99 - (a_{(i)}/W)(1-(a_{(i)}/W)[2.15 - 3.93(a_{(i)}/W) + 2.7(a_{(i)}/W)^2]\}}{2(1+a_{(i)}/W)(1-a_{(i)}/W)^{\frac{3}{2}}}$$

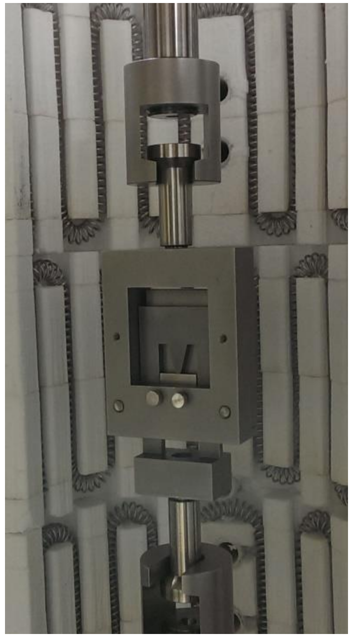
$$C_{LL(i)} = \frac{(1-\nu^2)}{EB_e}\left(\frac{S}{W-a_{(i)}}\right)^2\left[1.193 - 1.98\left(\frac{a_{(i)}}{W}\right) + 4.478\left(\frac{a_{(i)}}{W}\right)^2 - 4.443\left(\frac{a_{(i)}}{W}\right)^3 + 1.739\left(\frac{a_{(i)}}{W}\right)^4\right]$$





$$v_{p(i)} = v_{(i)} - (C_{LL(i)} + C_A)P_{(i)}$$

- *The plastic displacement $v_{pl(i)}$ was updated by replacing the crack length of i-th step with that of previous step (i-1): $a_{(i)} \leftarrow a_{(i-1)}$.*

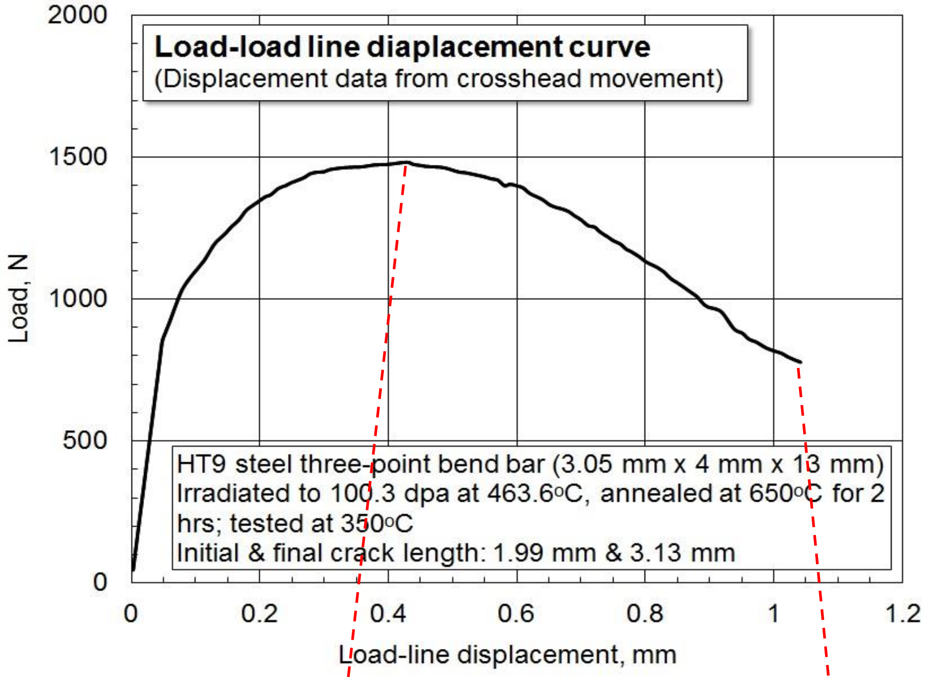


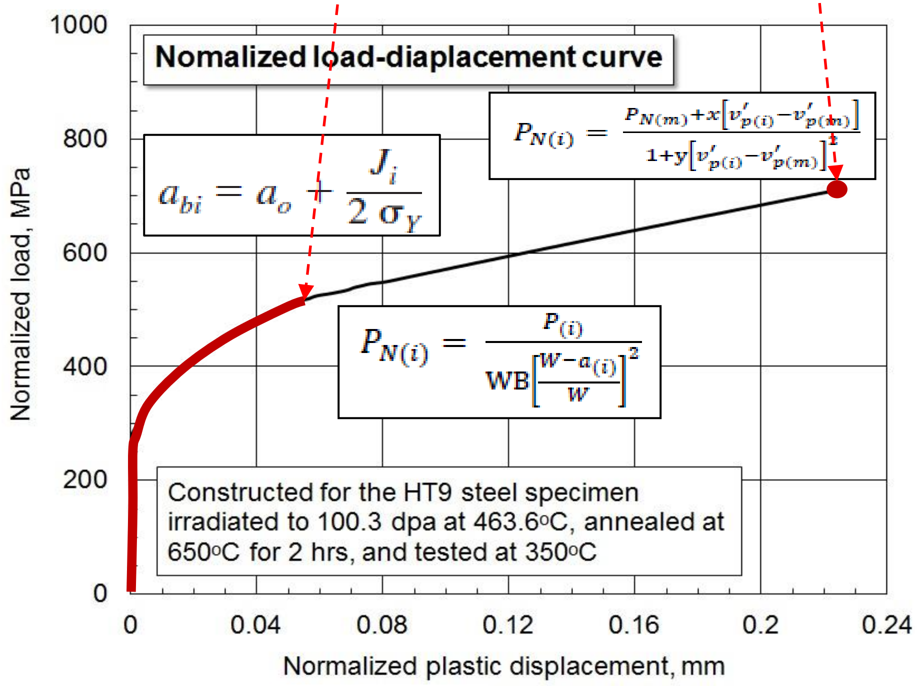
Curve Normalization Method for J-R Curve Construction

- Miniature DCT (10-13 mm dia) or TPB (12-15 mm length, B < 5mm)
- Described in ASTM E1820 Annex
- Requires initial and final crack length measurements and simple P-v record.
- Use theoretical blunting line ($J=2s_Y\Delta a$) and final J. Crack lengths intermediate are calculated using a normalized curve.
- Useful where high rate of loading, high temperature, aggressive environment, or small specimen are used. (for ductile fracture)

- **Iterative calculation is preformed for each point between max load point and final crack length using the normalized curve (function) as criteria.**

$$a_{(i)} = W\left\{1 - \left[\left(\frac{P_{(i)}}{P_{N(i)}}\right)\left(\frac{1}{WB}\right)\right]^{1/2}\right\}$$

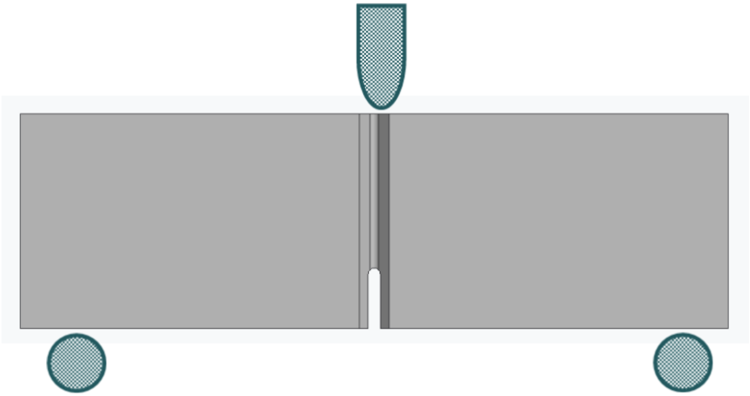


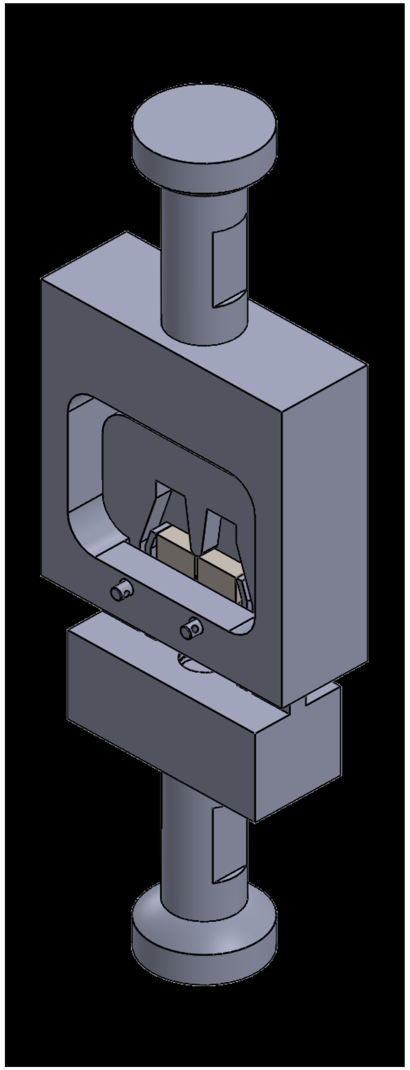


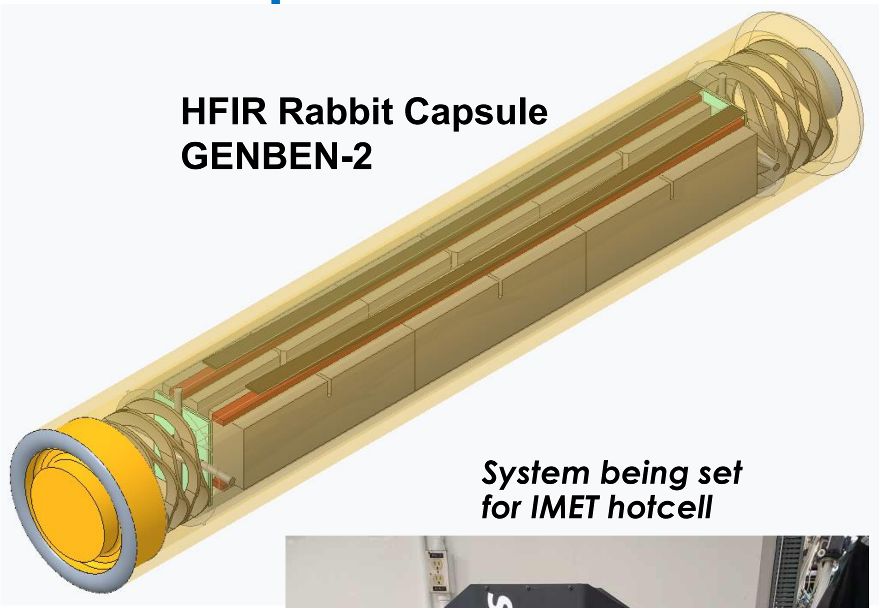
$$v'_{p(i)} = \frac{v_{p(i)}}{W} = \frac{v_{(i)} - C_{(i)}P_{(i)}}{W}$$

TEST SET UP for MBS-1 Sample & Standardized HFIR Rabbit Capsule GENBEN-2

- Three-point or single-edge bend (TPB or SEB) loading mode
- 14.8 mm L x 4.5 mm W x 3 mm B with 2 x 15%B side groove (MBS-1 design)
- 6 specimens in a rabbit capsule
- Simplified testing method and J-R curve calculation procedure were established.
- All specialized for high dose irradiation, handling in hotcell, and testing at high and low temperatures.
- Out of cell setup lately done and being used.



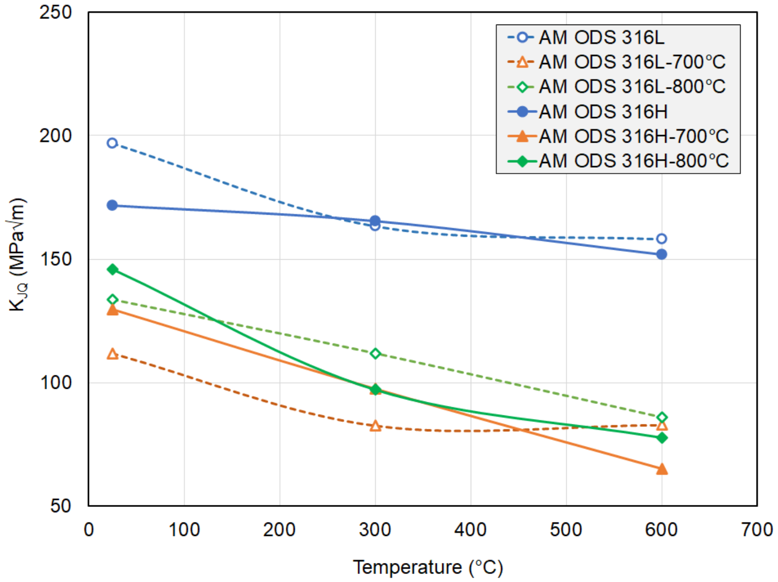


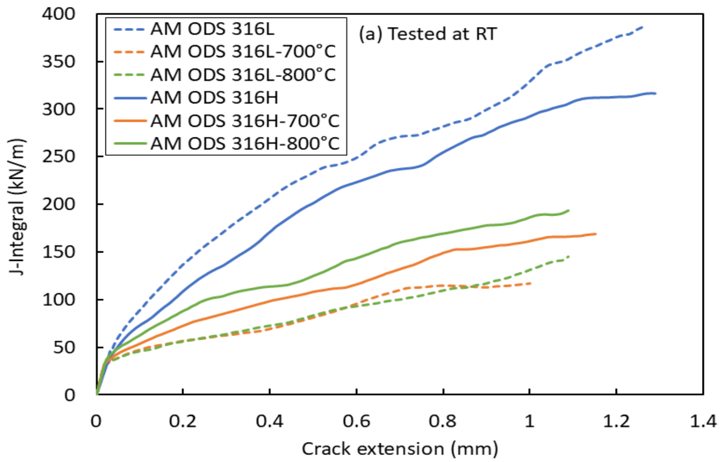


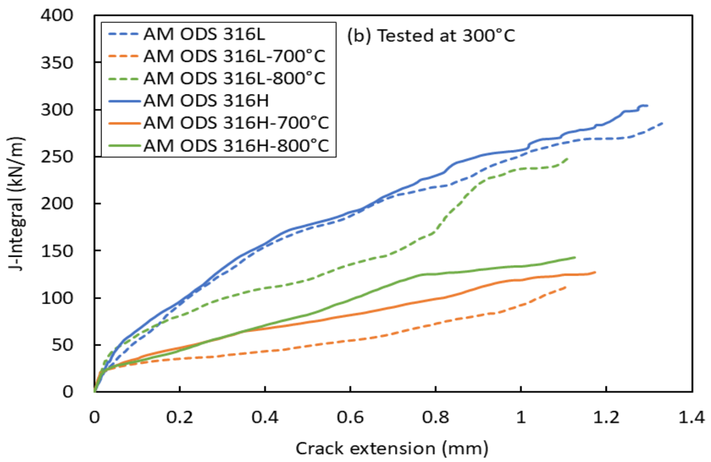
System being set for IMET hotcell

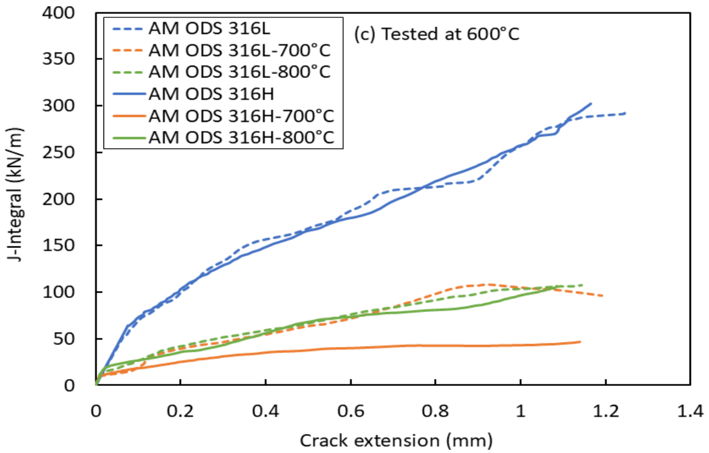
Result of Fracture Toughness Testing using MBS Design

No.	Material	Status
1	AM 316H	J-R test complete
2	AM ODS 316H	J-R test complete
3	AM ODS 316L	J-R test complete
4	AM ODS 316H+TMT	J-R test complete
5	AM ODS 316L+TMT	J-R test complete
6	Fe-9Cr FM Steel (G92 et al.)	J-R test complete
7	Fe-14Cr ODS FM Steel	J-R test complete
8	***This technology in application stage: Irradiated and nonirradiated materials to be tested.***	



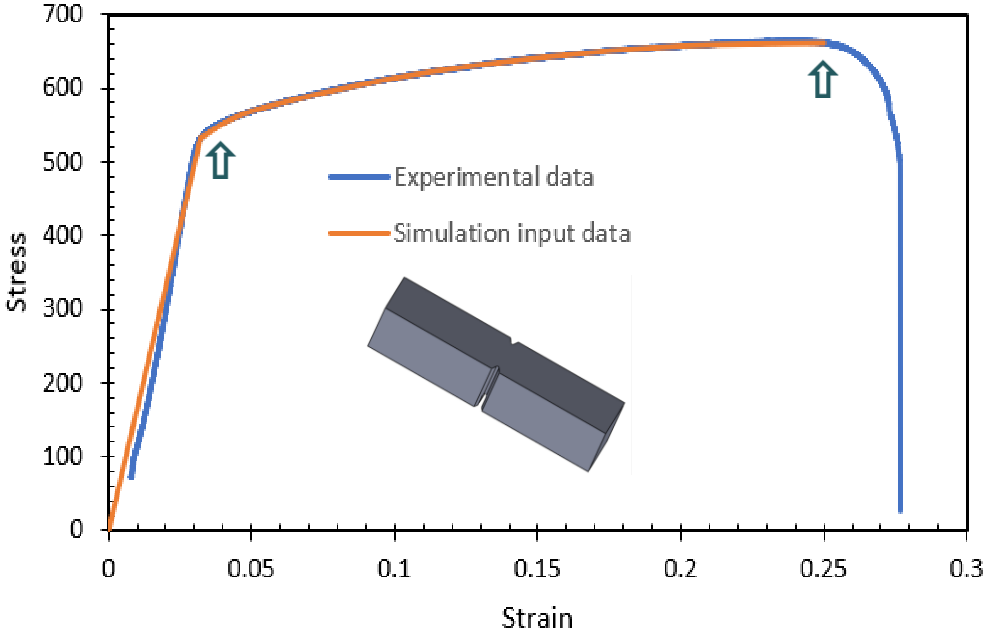






FE Simulation: Fracture specimen model

- **Material : ODS-AM-316H-RT**
- **Fracture Specimen type: MBS with and without (2 x 15%) side grooves**
- **Subjected to three-point bending (TPB)**
- **Specimen dimension:14.8mm x 4.5mm**
- **Specimen thickness: 1mm, 3mm, 4mm**
- **Employs hexahedral linear dominated finite element mesh**
- **3D solid model was created within SolidWorks 2022 environment**



Load-Displacement curves for ODS-AM-316H-RT

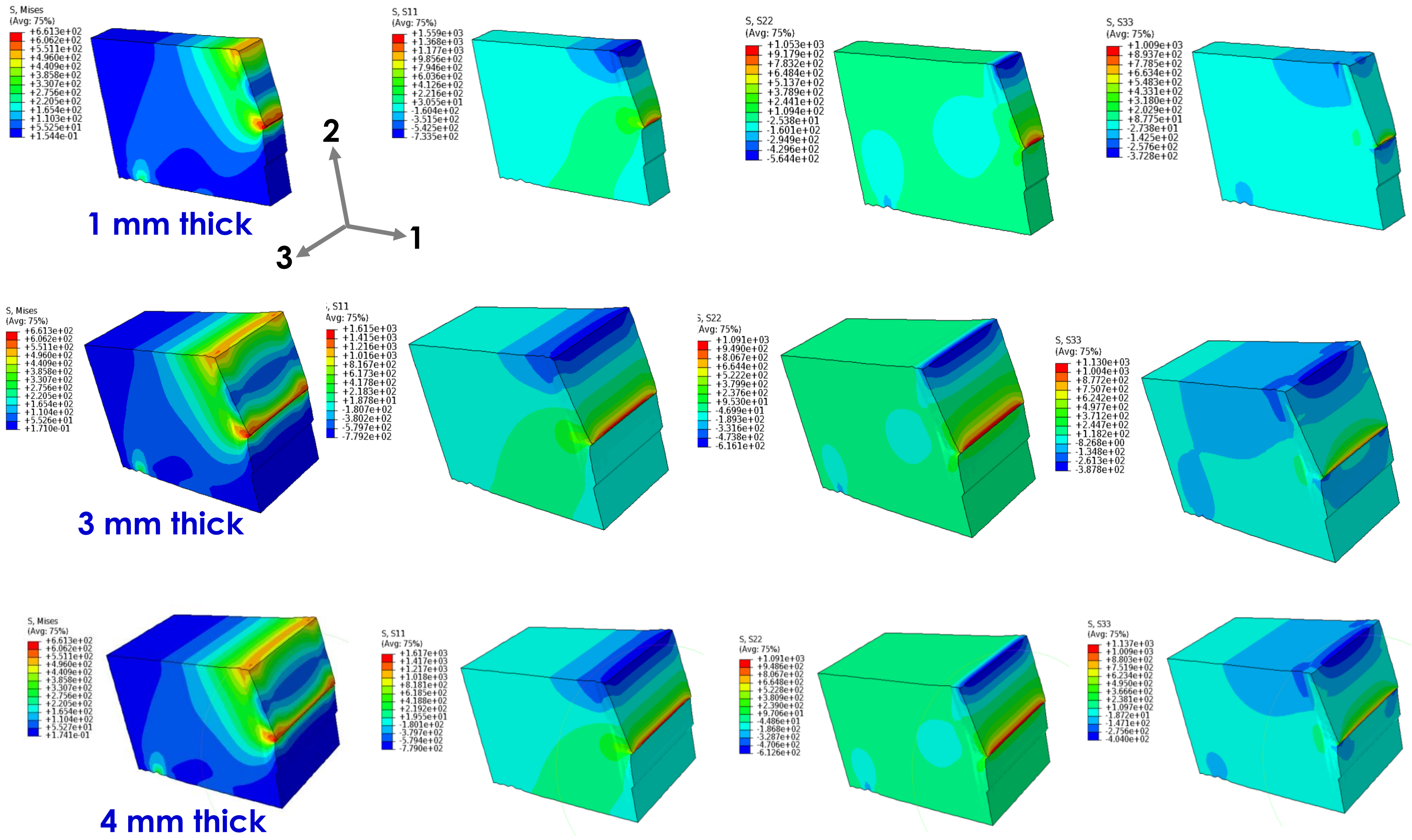
MBS without side-groove under TPB

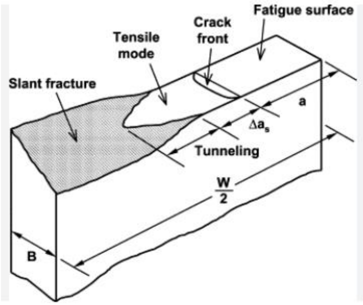
MBS with side-groove under TPB

Finite Element mesh

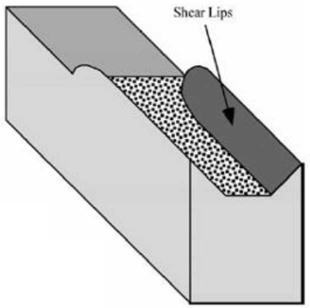
Model	Thickness	Elements	Nodes
Un-Notched-1	1mm	20,036	26,022
Un-Notched-3	3mm	55,135	68,222
Un-Notched-4	4mm	74,041	90,918

Mode-I Stress Fields at Crack Tip: Thinness Effect





James, M. A., and J. C. Newman Jr. EFM (2003)

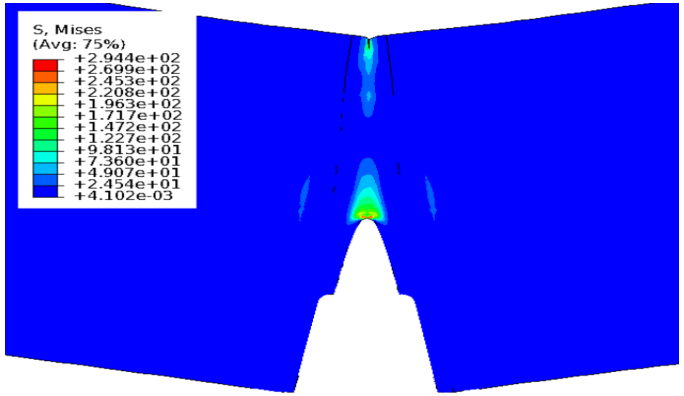


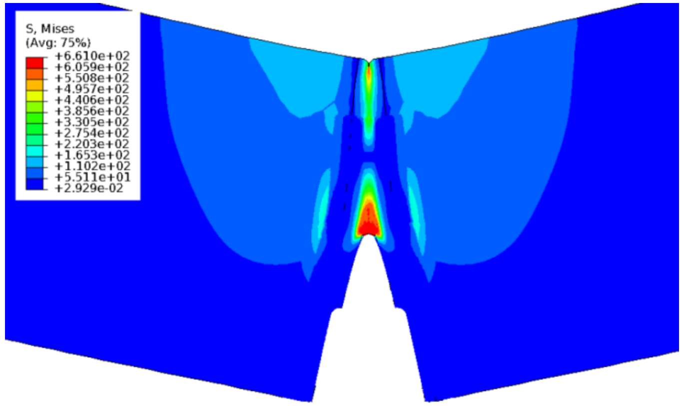
Anderson T.L. (2005) (3rd edition)

Mode-I Plastic Zone at Crack Tip: Assessment of High Strain/Strain Constraint in MBS

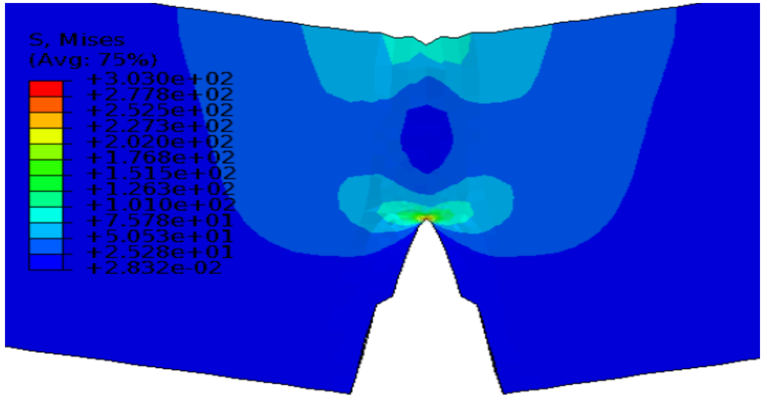
- Mode-I high-stress field shape is smaller in the specimen with side grooves than the specimen without.
- Side-grooved specimen exhibits additional spear–shaped high-stress zone at edges but with low stress level.
- Material inside the plastic zone should be capable of carrying higher stresses and narrower distribution for a high strain constraint.

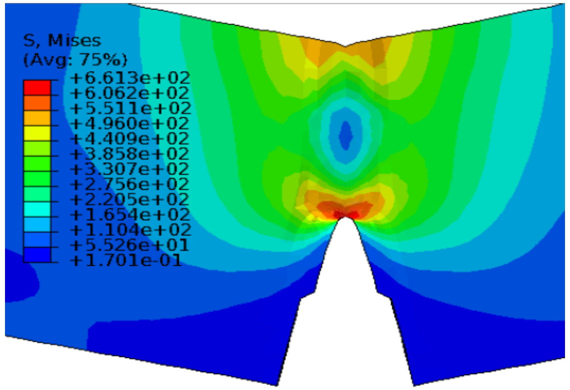
❖ *Assessment-1: MBS specimen with 15% side groove at each side has a well-confined stress/strain zone at crack tip.*





Side-grooved specimen

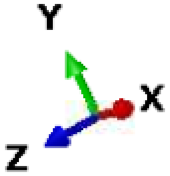


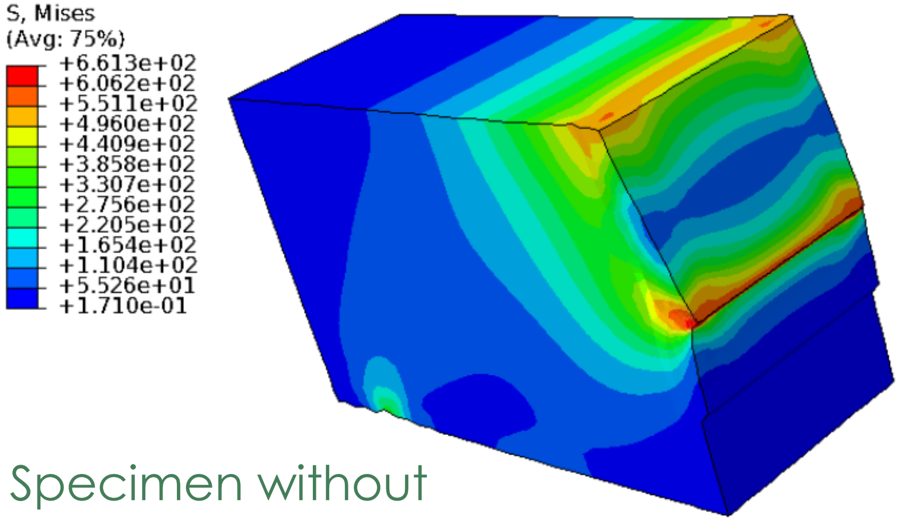


Specimen without side grooves

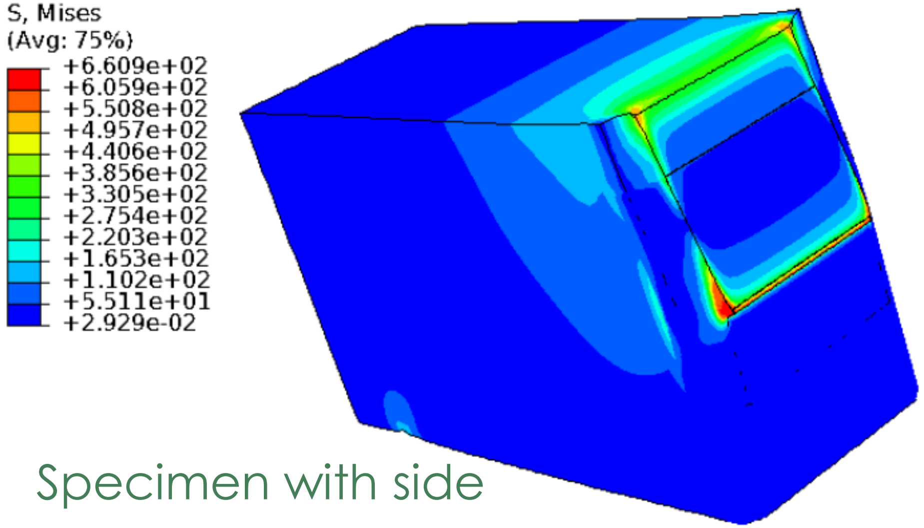
Effect of Side Grooves on Equivalent (Von Mises) Stress

- Snapshots taken after yielding and max loads at the crack tip.
- Clearly defined and large Mode-I (plane strain) plastic zone shape.
- Mode-I plastic zone shape is smaller in the side-grooved specimen.
- Specimen without side grooves has varying stress across the crack width near the crack tip (could produce shear lips/tunnelling)
- Side-grooved specimen has a constant stress across crack width (B)





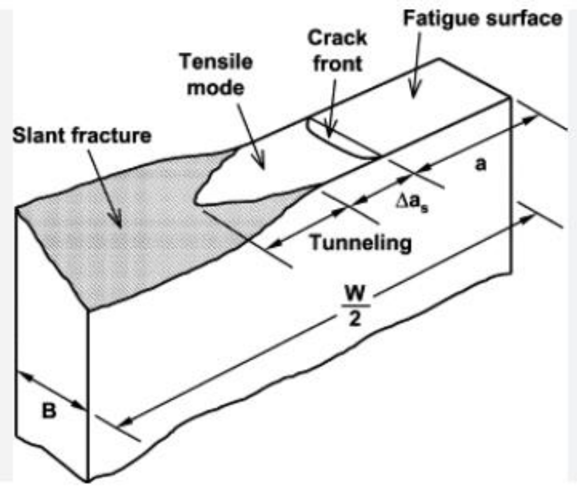
Specimen without side grooves



Specimen with side grooves

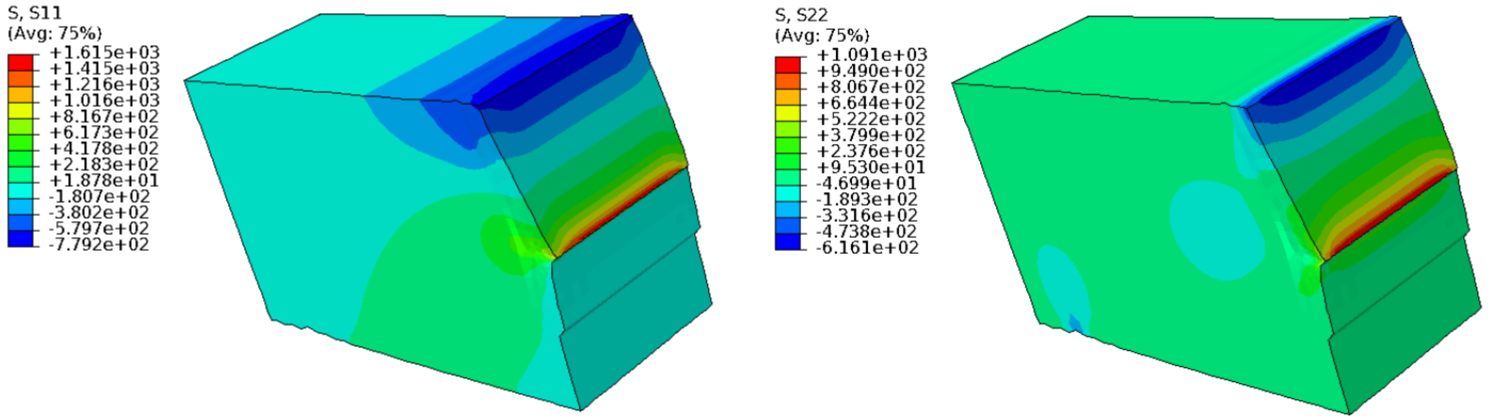
- *The material inside the plastic zone can carry higher stresses, reducing the need for stress redistribution.*

James, M. A., and J. C. Newman Jr. EFM (2003)

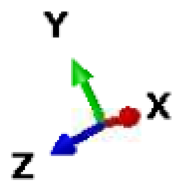


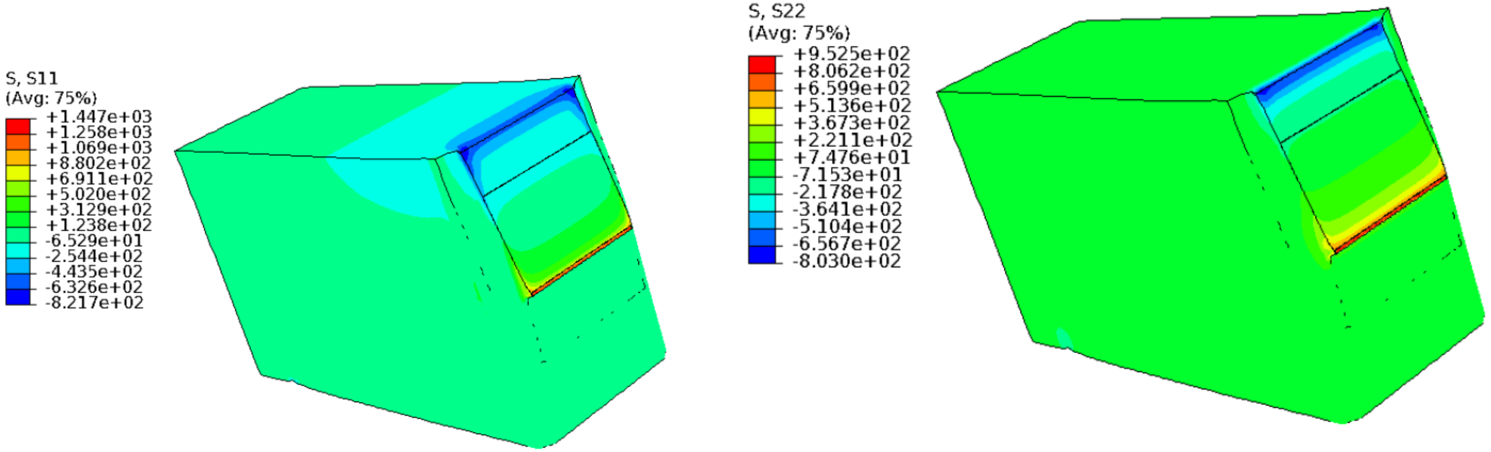
Effect of Side Grooves on Stress Components S11 & S22

- Stress contour plot for normal stresses in 11 and 22 are plotted for specimens with and without side grooves.
- Stress concentration zone is smaller in the side-grooved specimen than in the flat surface specimen.
- S22 plot show a clearly defined tension at the region closer to the crack tip and compression at the load edge of the crack surface over the whole thickness (expected).



Specimen without side grooves





Specimen with side grooves

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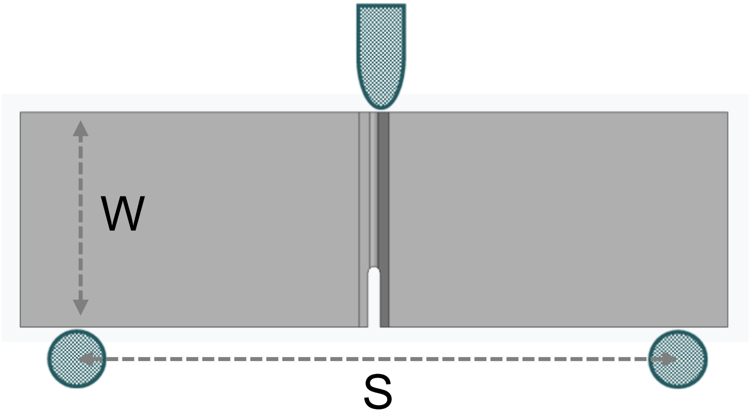
Discussion: Limitations with MBS-1 Design and Testing Method

❑ Specimen Thickness

- Required 1 ≤ W/B ≤ 4 (B = thickness; W = specimen width); MBS-1 W(=4.5mm)/B(=3mm) = 1.5
- Satisfied with this requirement but the absolute value of B (3 mm) is small for soft materials.
- Resolution: Incorporated deep (total 30%) side grooves (ref. 25%).
- *Materials with YS > ~ 300 MPa are expected to show no evidence of significant thickness contraction: MBS-1 useful for FM steels, ODS steels, AM austenitic steels, AM ODS steels, irradiated steels etc.*

❑ Specimen Length

- Required S = 4W±0.2W (S = pin support span; W = specimen width)
- MBS-1 S(14.8mm)/W = 2.8
- J-integral value is correct in low-Δa region (initial crack intension) but can become overestimated in high-Δa region.
- Needs to subtract the energy contribution from the rotation (non-vertical loading) for later part of J-R curve.



Concluding Remarks

1) Drawing on extensive experience with subsize specimens and ongoing efforts to integrate advanced testing methodologies, a robust irradiation and fracture testing framework has been developed to qualify advanced nuclear structural materials using miniaturized specimens.

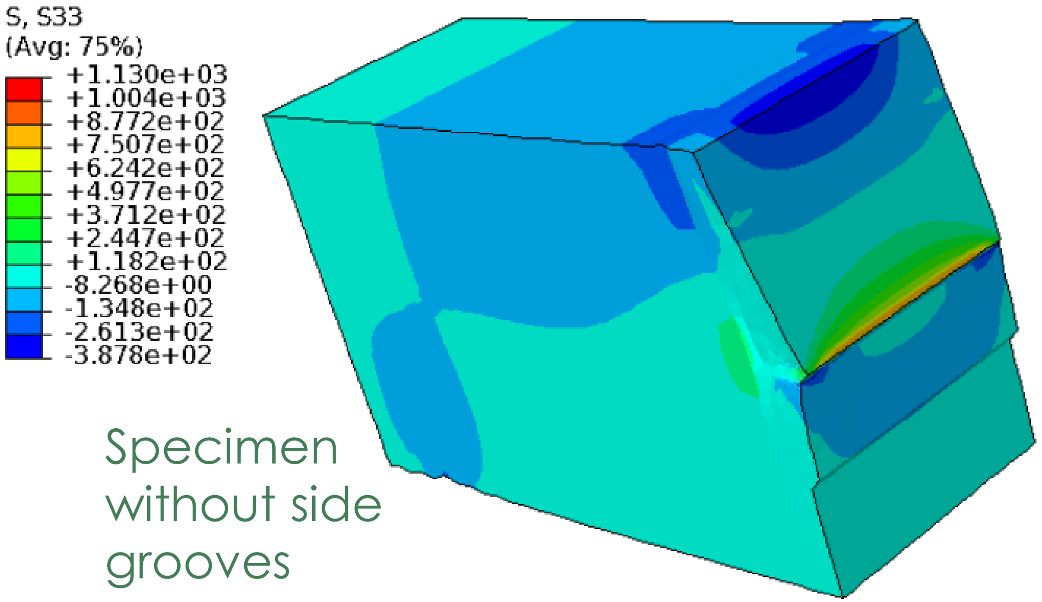
2) **An essential investigation has been conducted to establish a foundational understanding of the deformation and fracture behavior inherent in miniature bend-bar specimens.**

3) Specifically, a comprehensive assessment of the advantages and limitations of using miniature specimens to qualify high-temperature materials is necessary. Achieving consensus through collaboration among research communities and regulatory agencies is essential.

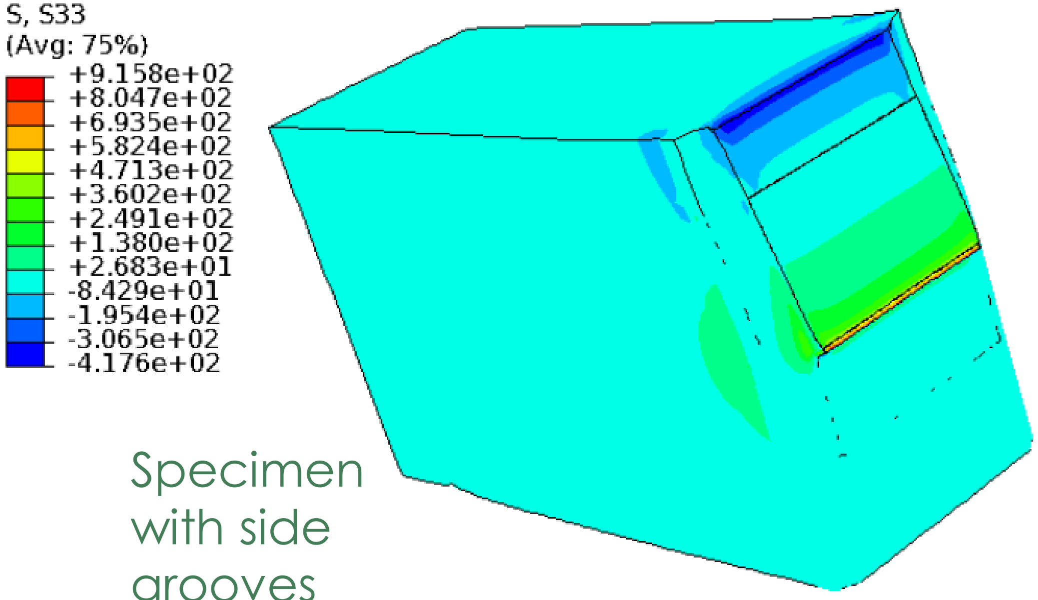
4) **The application of this miniaturized fracture testing and evaluation has commenced in multiple DOE-NE and industry NE programs. Publications detailing the outcomes of this effort will follow.**

Effect of Side Grooves on Stress Component S33

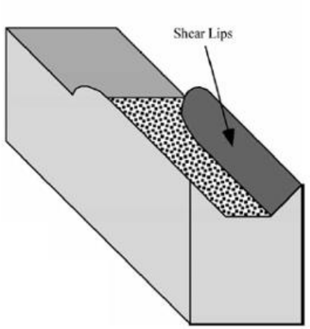
- The specimen without side grooves exhibits plane strain condition near the crack tip on the crack surface: Stress at the crack tip of the specimen without side grooves would produce shear lips while the specimen with side grooves will maintain straight crack front.
- The stress on the crack surface and the near the crack tip of the side-grooved specimen is constant on the crack surface (plane stress): (i) Low-stress triaxiality zone is removed. (ii) Side-grooved specimen will maintain straight crack front.
- Side-grooved specimen has no compression on the initial crack surface.
- No lateral singularities; Crack will not grow more rapidly at the outer edges. This shows that the side grooves are not too deep



Specimen without side grooves



Specimen with side grooves



Anderson T.L. (2005) (3rd edition)

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2024 NSUF Research Scope for MBS-1 TPB Design

Aims to assess the fracture testing and calculation method using 3-mm thick miniature bend bar specimen, the MBS-1 design which was standardized for HFIR irradiation, to characterize the fracture resistance of high-temperature reactor materials before and after irradiation.

- ***Experimental assessment of the high-temperature fracture testing method using the MBS-1 design and validity check for the fracture testing and J-R curve calculation methodology:***

RT and HT fracture toughness testing will be carried out for selected materials including additively manufactured (AM) 316L/316H steels, their oxide dispersion strengthened (ODS) material versions, and ferritic-martensitic (FM) steels. Fracture resistance (J-R) curves will be constructed and their dependences on materials and test temperatures and validity of fracture toughness values will be evaluated.

- ***Finite Element Analysis (FEA) on the deformation and cracking behavior of the miniature bend bar specimen (includes investigation of size effect):***

The detailed distribution of the three-dimensional stress and strain in the cracking specimens will be calculated, from which more information on characteristic parameters, including local stress states, stress and strain concentrations near the side grooves, evolution of strain constraint at crack tip with crack extension and with increasing test temperature, will be evaluated for assessing the specimen's deformation and cracking behavior and thus validity of fracture toughness testing methodology.

- ***Comparative study on the effects of specimen type and volume (to be integrated for publication):***

Fracture toughness data will be compared with the data from other types of specimens such as the disk compact tension (DCT) specimen and rectangular compact tension (CT) specimen. Existing fracture toughness data from these types of specimens will be collected and compared with the data from the miniature bend bar specimen. In particular, the effect of relatively small crack extension limit with the bend bar will be elucidated by comparing with the data for the DCT and CT specimens.