



Design Task Group Update

July 2023

Changing the World's Energy Future

Andrea L Mack



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July 2023

**Idaho National Laboratory
Idaho Falls, Idaho 83415**

<http://www.inl.gov>

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July 26, 2023

Andrea Mack

Statistician

Idaho National Laboratory

Design Task Group Update:

Activities Jan. 2023 – May 2023

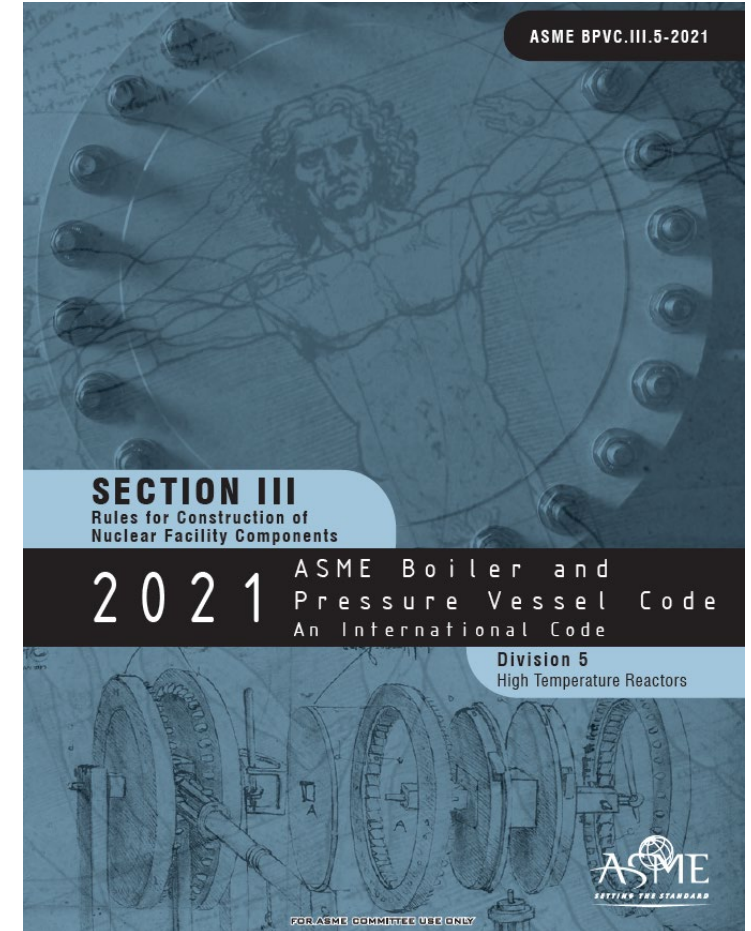
DOE ART Gas-Cooled Reactor (GCR) Review Meeting

Virtual Meeting

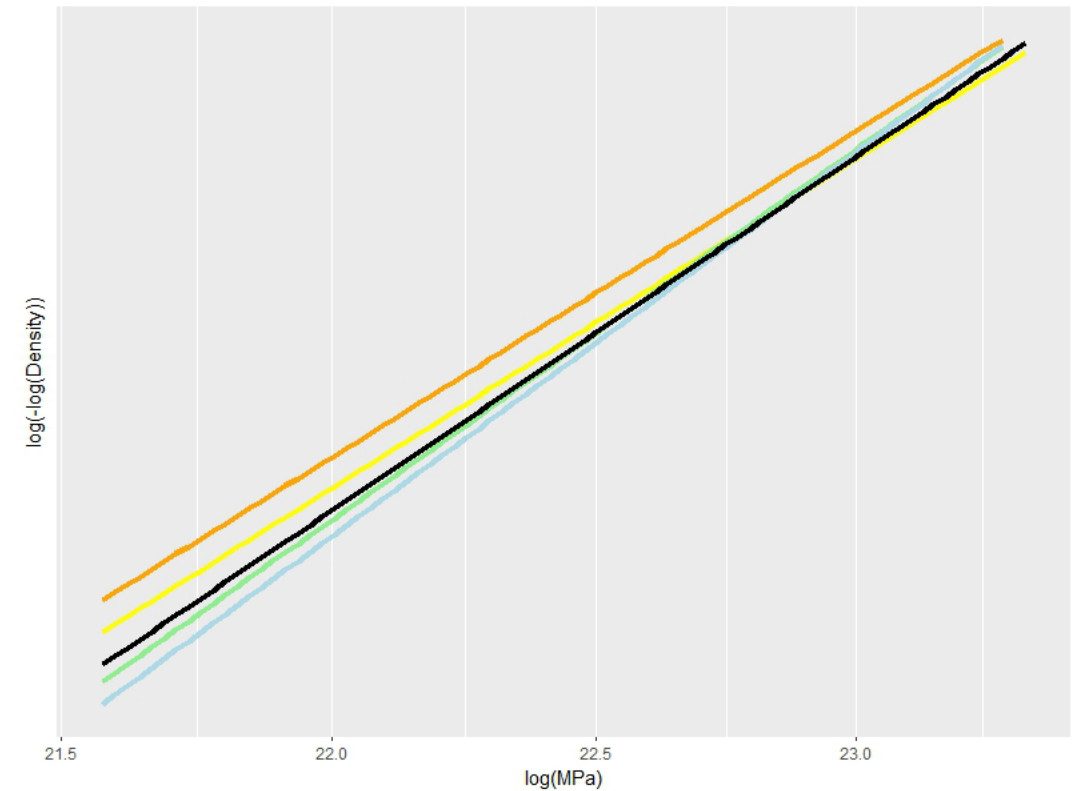
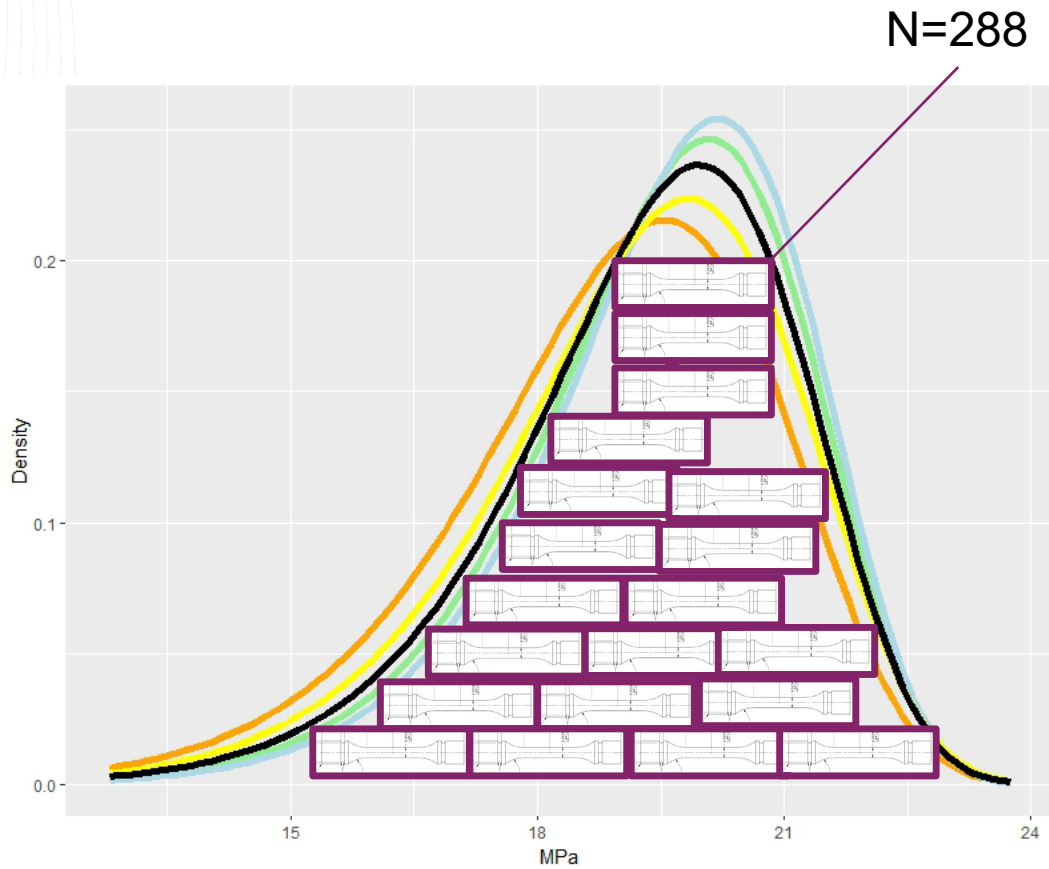
July 25 – 27, 2023

Outline of presentation

- Background
- Full Assessment
 - Disparate flaw distribution
 - Tuning V_m and Δ
 - Mesh refinement
 - Location
 - Sample size requirements
 - Margin
- Simplified Assessment
 - Stress terminology
 - R_{tf}
- Schedule to complete goal (2025 BPVC)
- Conclusions



Background – Weibull tensile strength distribution for quasi-brittle materials

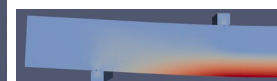
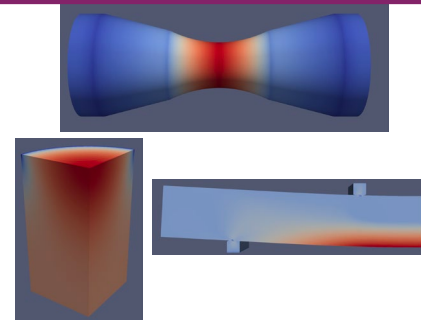
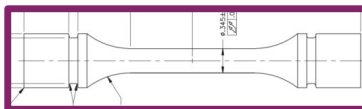


$$\text{Weibull CDF: } F(\sigma|\alpha, \beta, \mu) = 1 - e^{-\left(\frac{\sigma - \mu}{\beta}\right)^\alpha}$$

Assessments

Full

N=288 tensile strengths $\rightarrow$
 $\mu, LB(\alpha, \beta)$

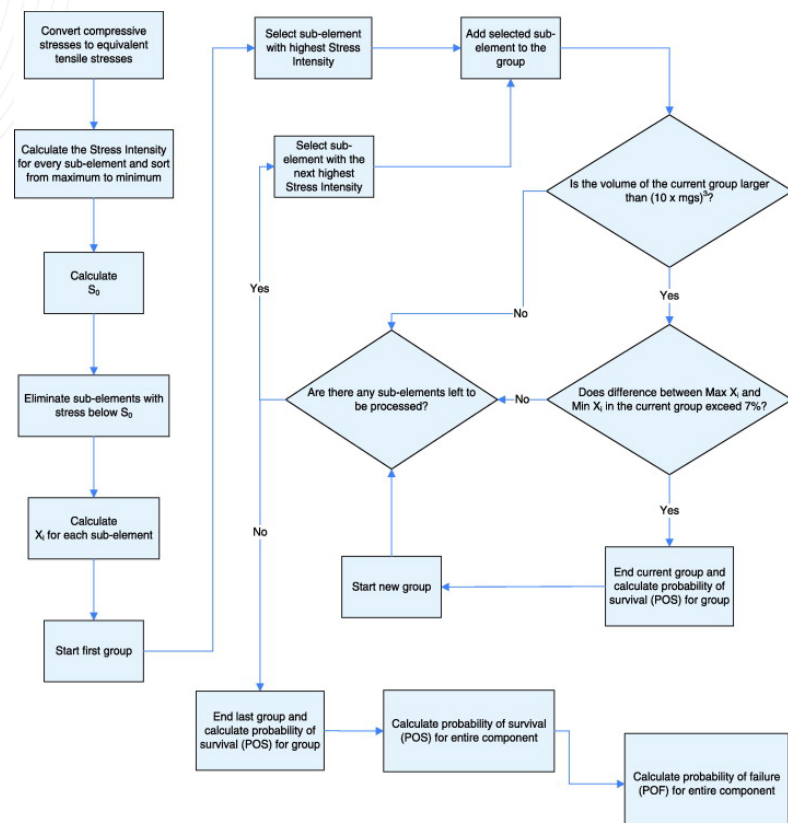
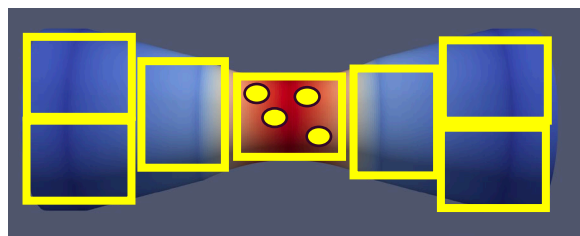


Simplified

Inputs: 3-parameter Weibull lower bounds, V_m, Δ , entire component equivalent stress distribution

Inputs: 2-parameter Weibull lower bounds, R_{tf} , membrane stress and peak equivalent stress from FEA output

Uses weakest link theory



Output: Probability of Failure

1. Using lower bounds for parameters, invert the Weibull CDF:
 $S_g(10^{-4}) =$

$$\beta(-\ln(1 - 10^{-4}))^{\frac{1}{\alpha}}$$

1. Calculate the limits for both checks:

1. $S_g(10^{-4})$ is defined as the stress associated with the 10^{-4} quantile of the 2-parameter Weibull lower bound distribution.
2. $R_{tf} * S_g(10^{-4})$ is the ratio of the flexural mean strength to the tensile mean strength (R_{tf}) times the allowable stress, resulting in an allowable stress value.

2. Calculate C_m and PES

3. Check 1: $C_m < S_g(10^{-4})$

4. If component passes Check 1, perform Check 2: $PES < R_{tf} * S_g(10^{-4})$

Output: Allowable tensile stress ($S_g(10^{-4})$) and allowable flexural stress ($R_{tf} * S_g(10^{-4})$), assuming component of SRC-1

Full Assessment: Disparate flaw distribution

Currently HHA-3217 has an engineered threshold reduction step for when there is too much separation between the lower bound strength distribution and the FEA stress output. The shape parameter depends on the threshold parameter, and it has been documented in the literature, as well as shown by the TG with the BP data, that the full assessment can become more conservative than the simplified when the threshold is reduced but the shape parameter is not updated, contrary to the spirit of the Code. A record was submitted twice to make update the shape parameter when the threshold is reduced, and disapproved. The most recent ballot was disapproved by just one, requesting that we demonstrate the full assessment would still be “conservative enough”. Upon looking into this further, we determined that not updating the shape parameter may have been intentional, to better capture the disparate flaw distribution. However, the problem still exists that not updating the shape parameter makes the full assessment more conservative than the simplified. Both cannot happen – the disparate flaw distribution cannot be captured as it currently is while ensuring the simplified assessment is always more conservative. The WG-NMD needs to decide the next steps to take.

Figures copied from:

[1] <https://www.osti.gov/servlets/purl/5283970>

[2] https://nucleus.iaea.org/sites/graphiteknowledgebase/reports/INGSM/INGSM-8%20Material/3_22.ppt

[3] Saitta, M. (2023). Justification for record 21-1581: adjusting shape parameter. Memo.

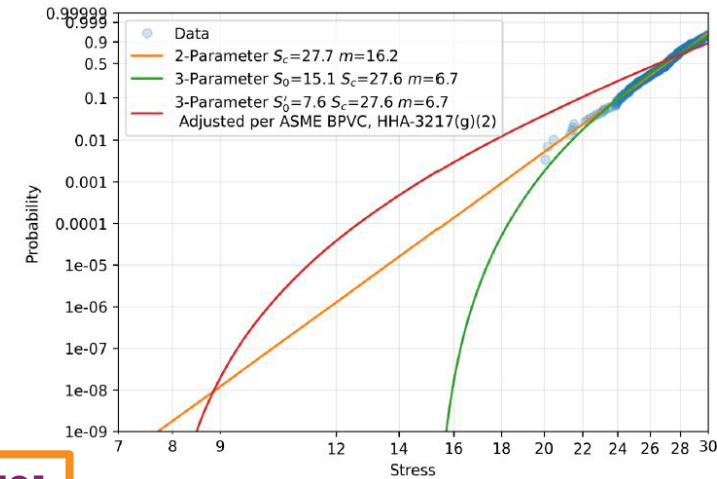
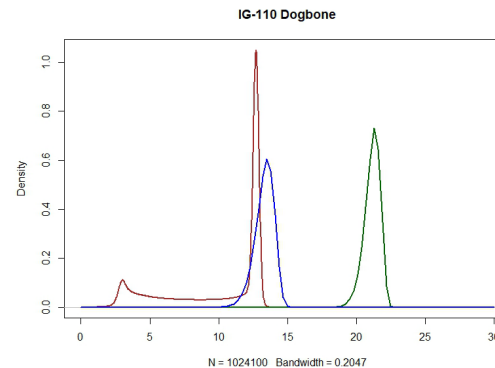


Figure 4-2. Extension of Figure 4-1

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◆ US experiments, H451 (Kennedy and Eatherly, 1986)

PROJECT TEAM:
MPR
Gwennael Biernart
Michael Saitta
INL
Andrea Mack

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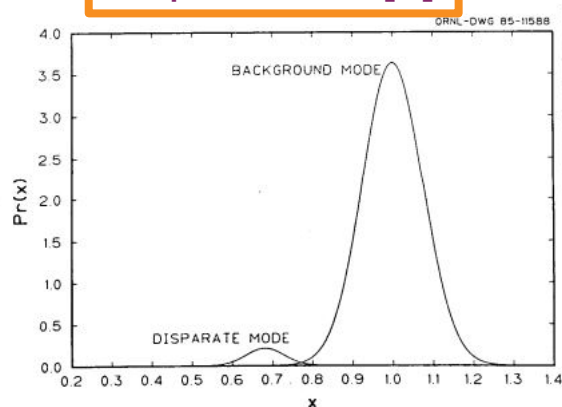
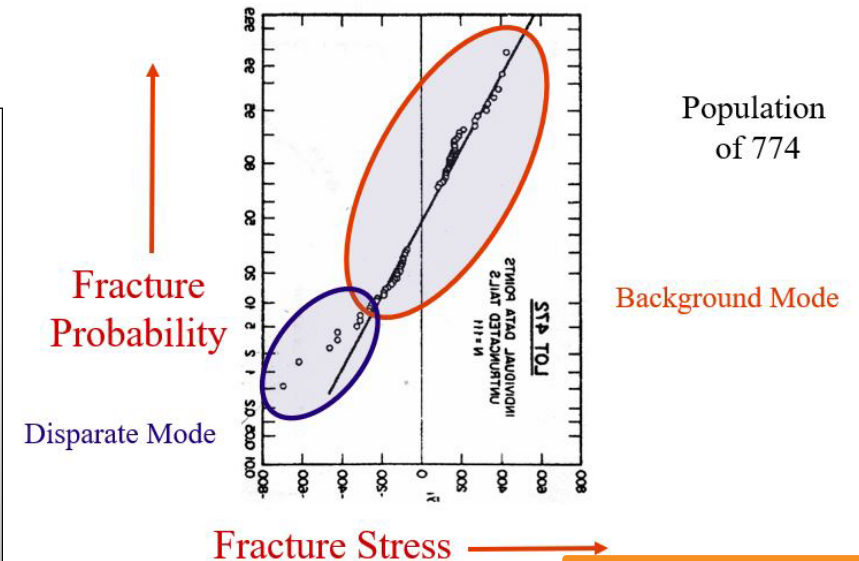
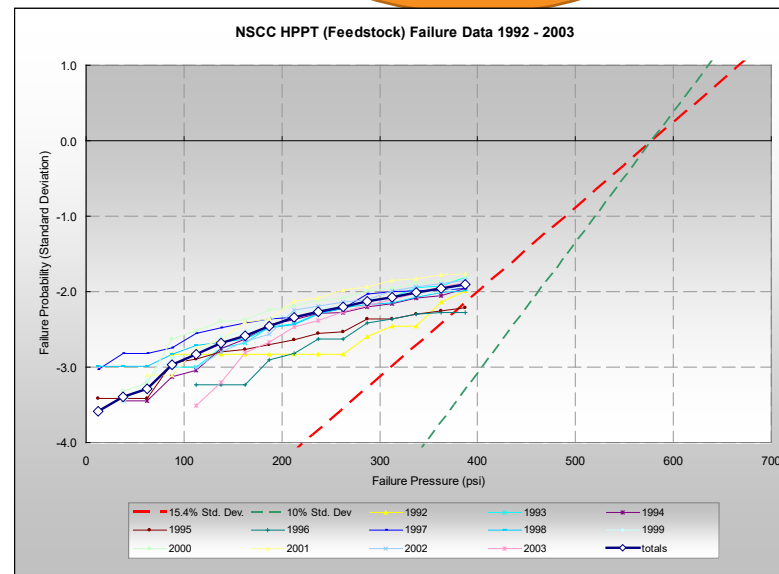


Fig. 6. Plots of normal distributions corresponding to the bimodal model normalized to the mean strength of the background flaw distribution. The disparate mode represents 3.4% of the total distribution.



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Full assessment: Tuning V_m and Δ (1/3)

PROJECT TEAM:

MPR

Gwennael Beirnaert
Michael Saitta

USNC

Jesse Quick
Jarryd Potgieter

X-Energy

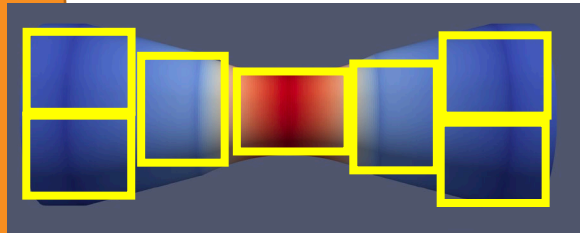
Zach Burns

Kairos Power

Pierre-Alexandre Juan
Alvaro Garnica

INL

Will Hoffman
Andrea Mack

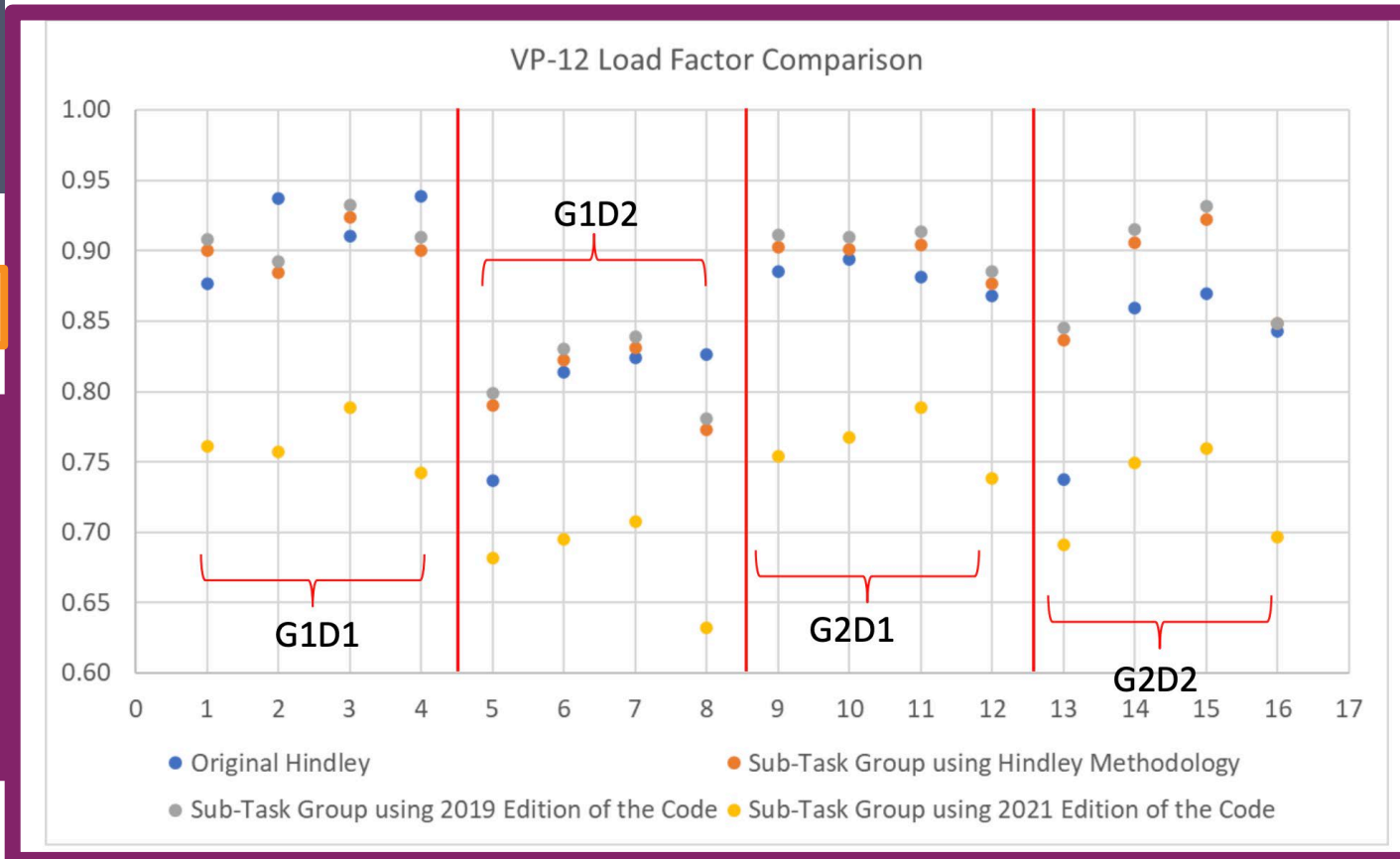


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PROBLEM

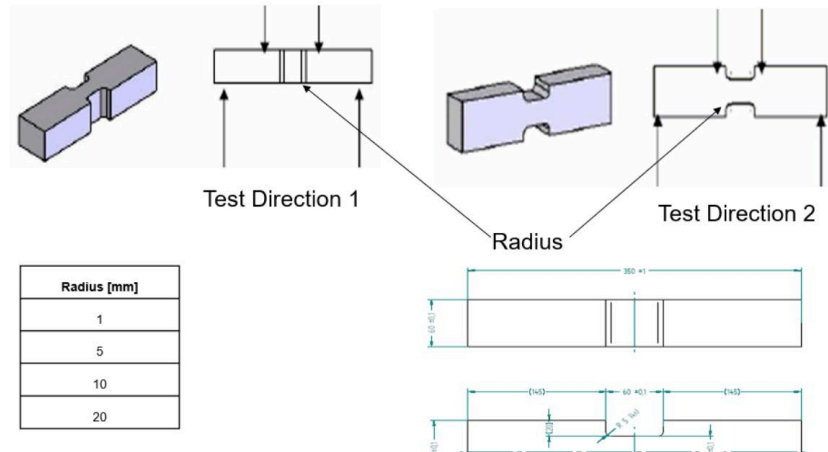
- The 2021 grouping criteria, based on fracture toughness, increased the minimum link volume for fine grain graphites relative to the 2019 grouping criteria, based on grain size, as intended.
- However, it decreased the minimum link volume for medium grain graphites, adding unnecessary conservatism.
- The 2021 V_m equation was wrong and the corrected equation creates too small of groups. Therefore, we are not trying to correct the 2021 erroneous equation.

A Load Factor of 1 indicates the full assessment methodology is perfectly estimating the median probability of failure. As the Load Factor decreases from 1 to 0, the the full assessment becomes more conservative. The G1D1-G2D2 geometries were made from NBG-18.

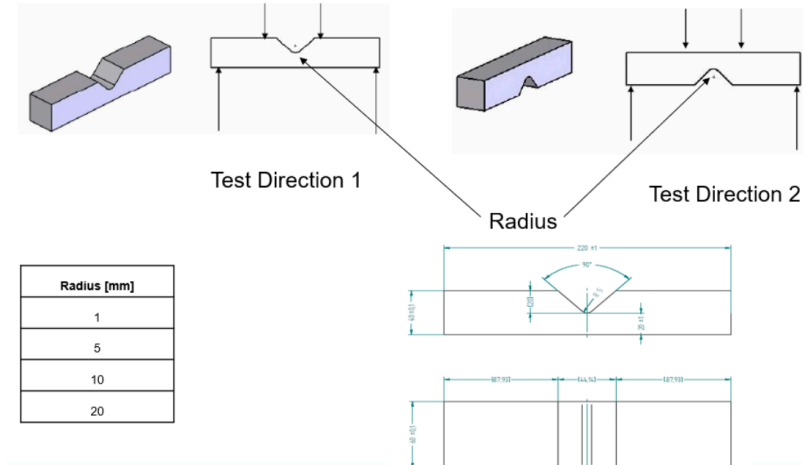


Full Assessment: tuning V_m and Δ (2/3)

VP-12 – Geometry 1 with 2 Test Directions

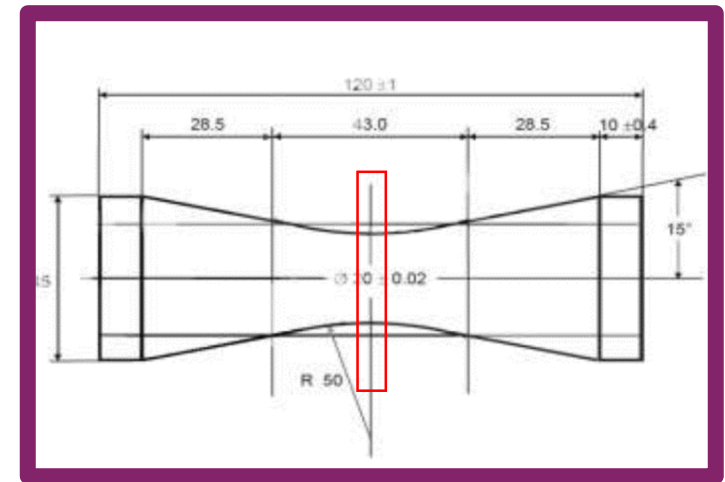


VP-12 – Geometry 2 with 2 Test Directions



Hindley's Dogbone

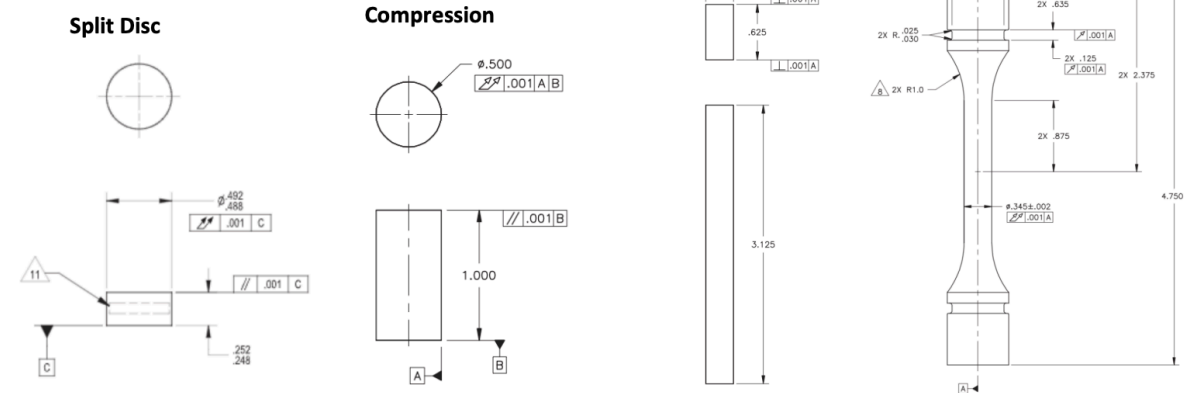
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Baseline Program Model Geometry

Grades considered: NBG18, NBG17, PCEA, IG110, 2114

- ***NBG18 test specimens are larger than other grades**
- **Dimensions shown for NBG17, PCEA, IG110, 2114**



NOTE: The split disc was not used in the tuning Vm and delta study.

If V_m is too large, the Load Factor will be greater than 1, indicating that the methodology is non-conservative in estimating the median probability of failure.

If V_m is too small, the Load factor is less than 1, indicating the methodology is conservative in estimating the median probability of failure.

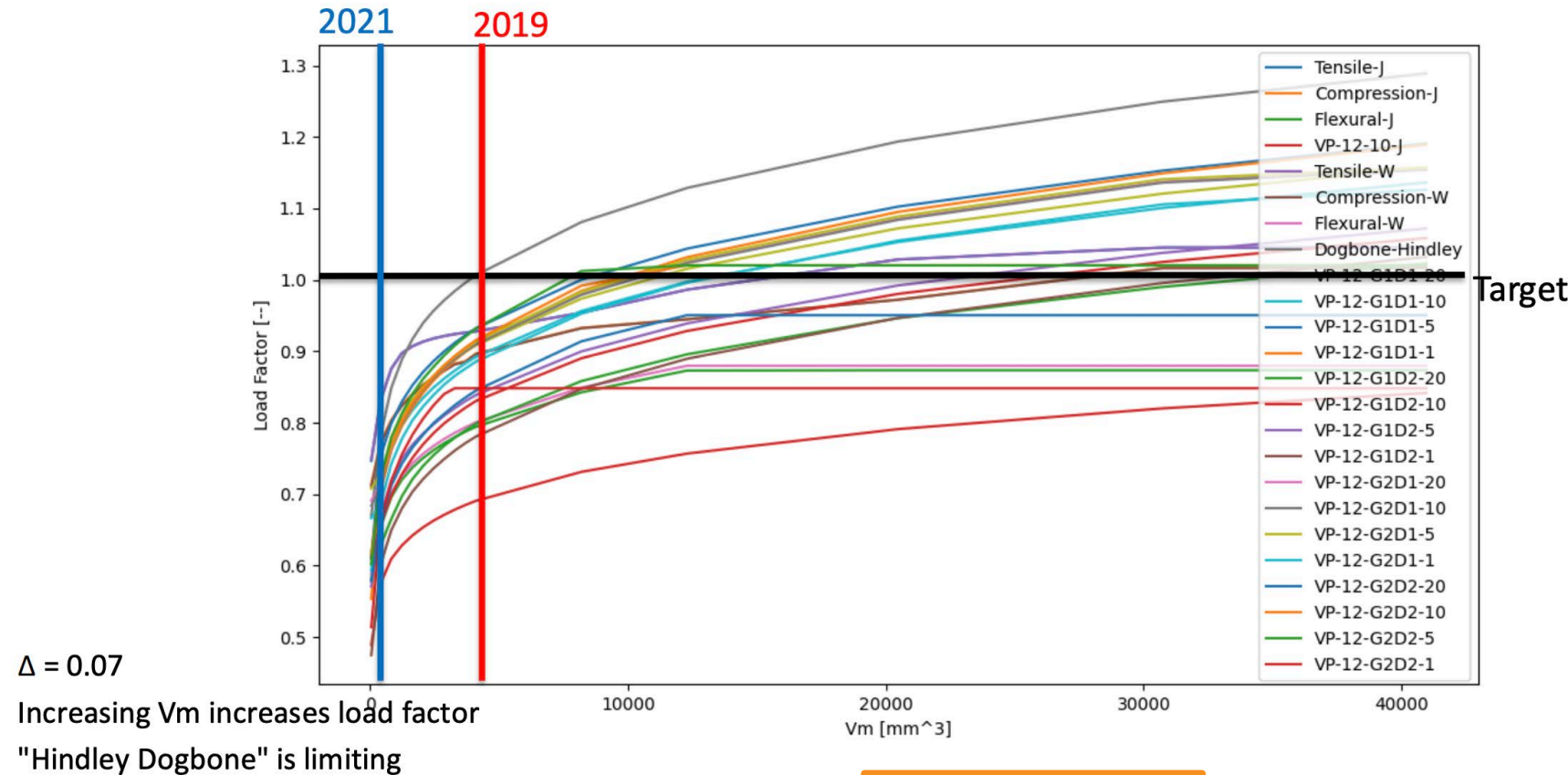
Across all grades, the dogbone gauge volume under high uniform tensile stress provides the most limiting V_m .

This work suggests V_m is not a material property, but rather based on the diameter guidelines found in ASTM C749 standard for making the dogbones. Previous Code rules based V_m on grain size and fracture toughness.

On-going work is to understand the volume effects on the strength of graphite, to ensure weakest link theory is satisfied.

Full Assessment: tuning V_m and Δ (3/3)

RESULTS FOR NBG-18

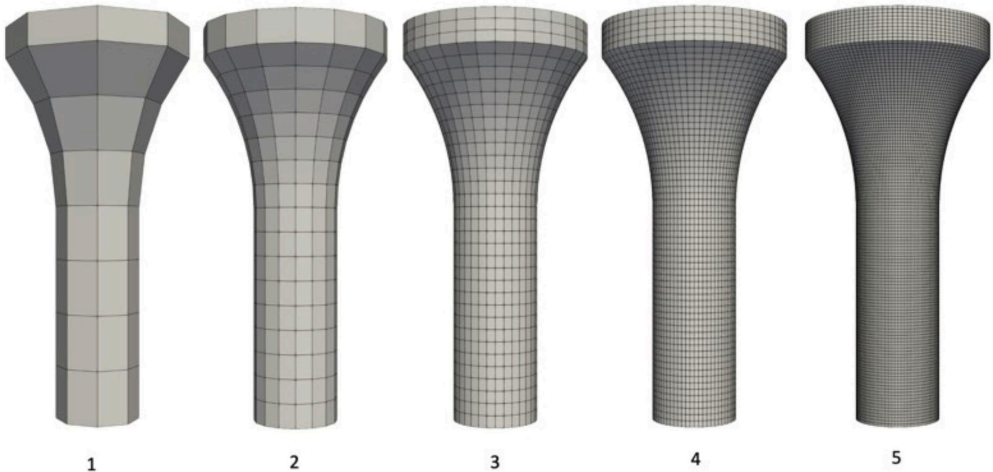


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PROJECT TEAM:
INL

Will Hoffman
Andrea Mack
Joseph Bass

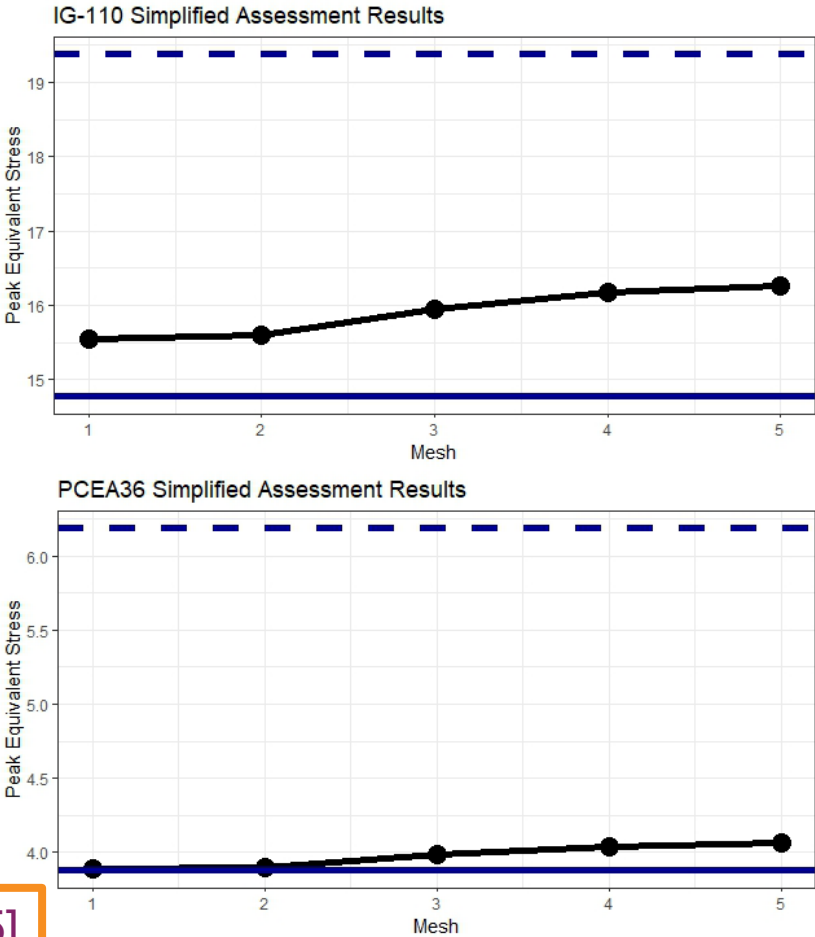
Mesh refinement (1/2)
SIMPLIFIED ASSESSMENT



[5] Mack, A., Hoffman, W., Bass, J., & Windes, W. (2023). Finite element model mesh refinement effects on qualification of nuclear grade graphite components. *Proceedings of the ASME 2023 Pressure Vessels & Piping Conference*. PVP2023-107369.

- Check 1:** Membrane stress cannot exceed S_g
- Stresses in component were scaled such that the membrane stress = S_g . Membrane stress was unaffected by mesh refinement in this application.
- Check 2:** Peak Equivalent Stress cannot exceed $S_g * R_{tf}$
- At the scaled stress state all PES are below $R_{tf} * S_g$, regardless of mesh refinement

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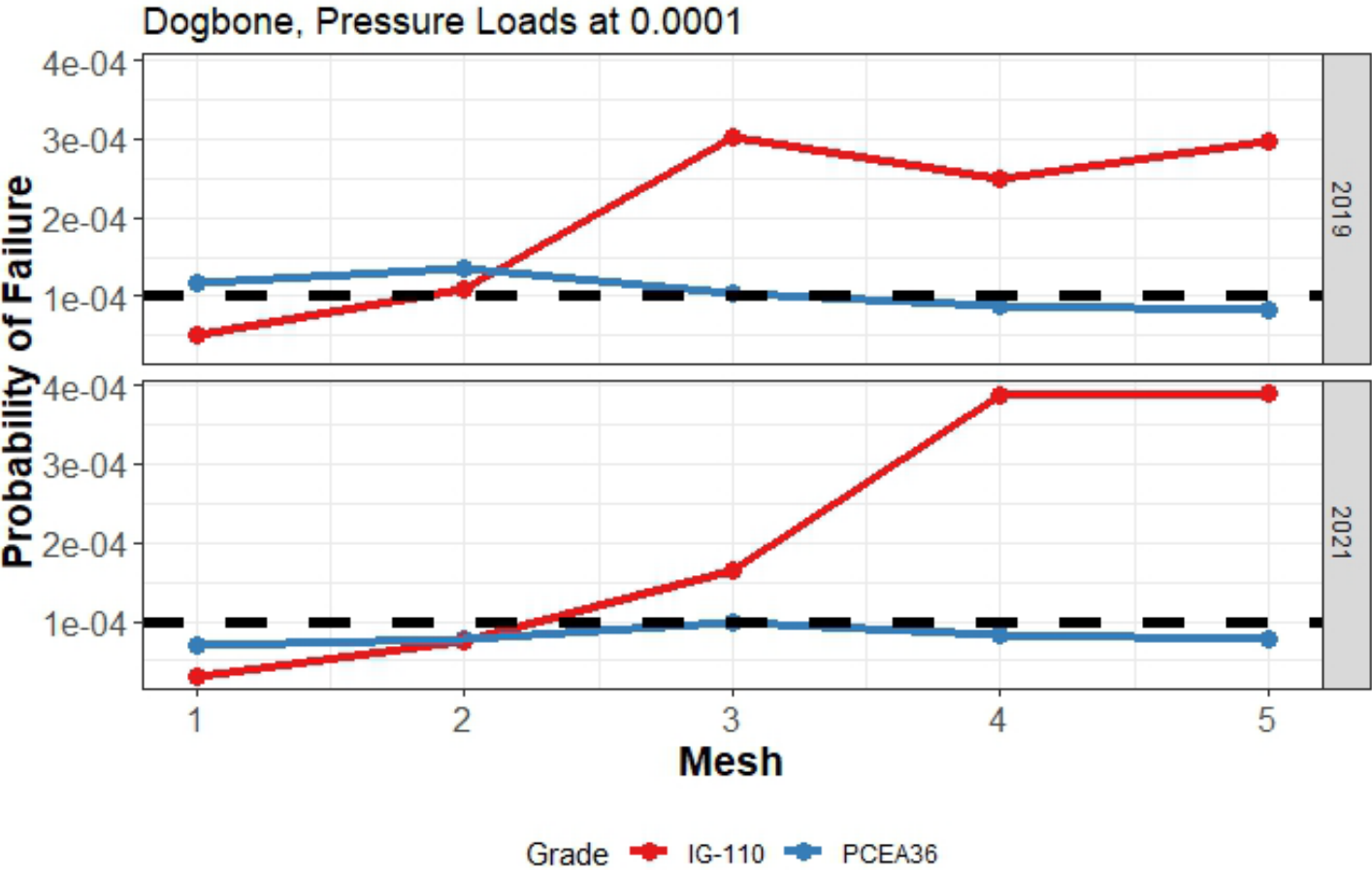


Grade	Membrane Stress Check	Peak Equivalent Stress Check
IG-110	PASS	PASS
PCEA36	PASS	PASS

Grade/Metric	$S_g (10^{-4})$ MPa	$R_{tf} * S_g (10^{-4})$ MPa
IG-110	14.77	19.386
PCEA36	3.877	6.188

Mesh refinement (2/2) FULL ASSESSMENT

Mesh refinement **did** affect the full assessment results in this application.



IG-110	V_m	Δ
2019	0.008 mm ³	0.07
2021	14.07 mm ³	0.2

PCEA	V_m	Δ
2019	512 mm ³	0.07
2021	572.1 mm ³	0.2

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The study done for PVP was limiting in that it only used simple geometries and it suggests repeating the study when Code rules are agreed upon for geometries in more complex stress states.

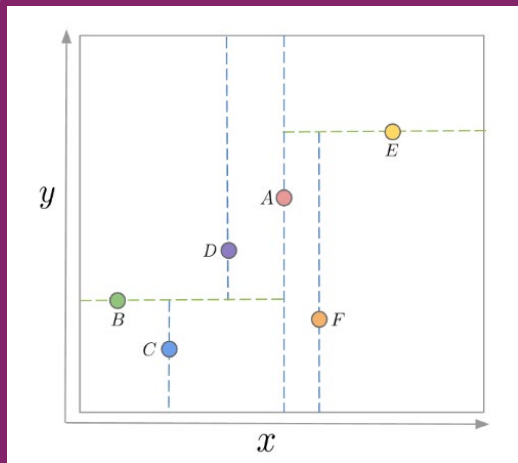
IG-110	Percent Change		
	PES	POF 2019	POF 2021
Meshes 2-4	3.7%	298.5%	210.3%
Meshes 4-5	0.5%	30.5%	15.7%

PCEA36	PES	POF 2019	POF 2021
Meshes 2-4	3.6%	33.4%	66.8%
Meshes 4-5	0.5%	-0.7%	-0.6%

Full Assessment: Location KD-TREE

A way to quickly look up K-Dimensional objects based on their location in space.

1. Create a K-D Tree



Source: Introduction to K-D Trees | Baeldung on Computer Science

2. Group using the following algorithm

Limitations of KD tree:

- Algorithm is not efficient for fine meshes
- Produces non-spatially connected groups in geometries aside from the dogbone

Moving forward, suggestion to look into agglomerative clustering.

Find element (A) with the highest stress

Locate element A's nearest neighbors (B)

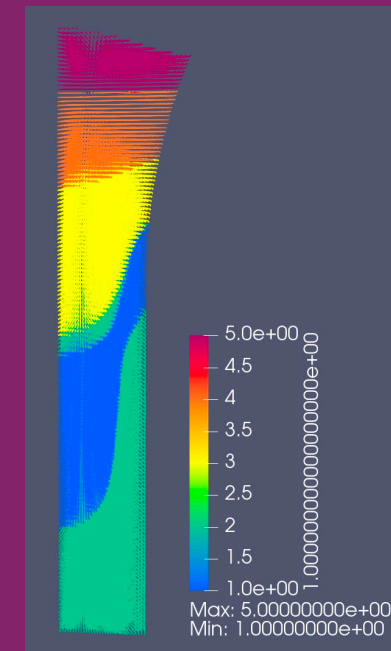
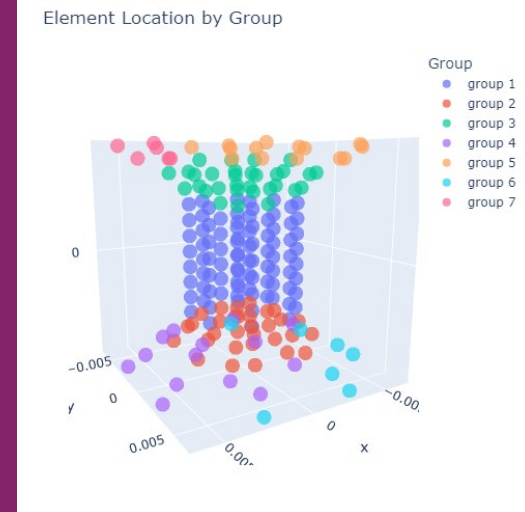
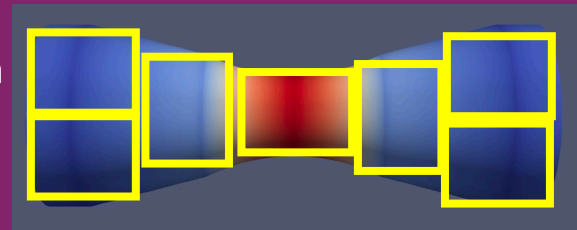
Calculate delta and V_m for the group

Conditions not met

Locate element A's nearest neighbor excluding last nearest neighbor added to group

Conditions met

Create group with elements and add used elements to a list so that there are no repeats (truncating is not available without remaking the KD-Tree)



PROJECT TEAM:

INL

Abby Moody

Will Hoffman

Andrea Mack

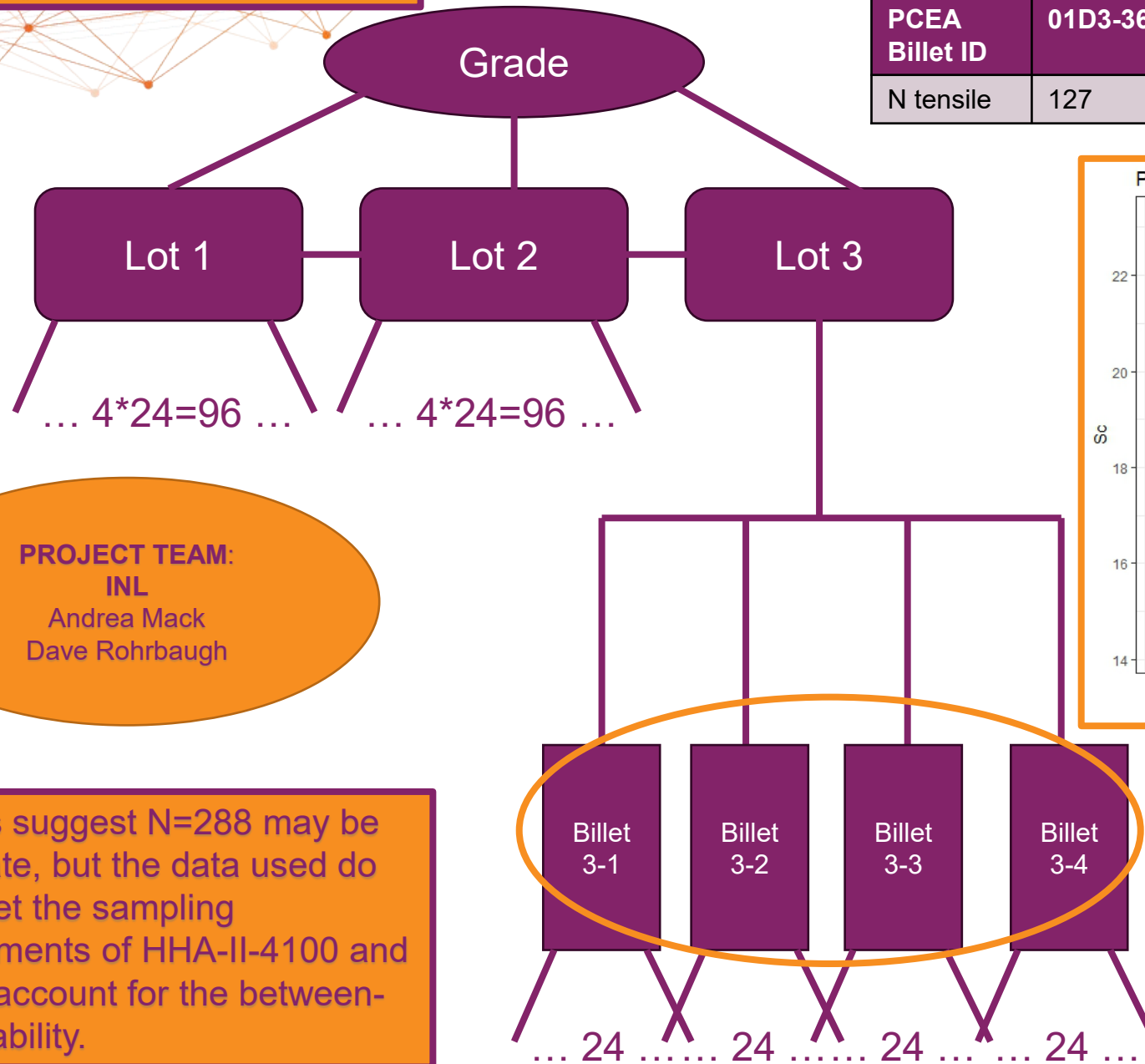
Ben Spencer

MPR

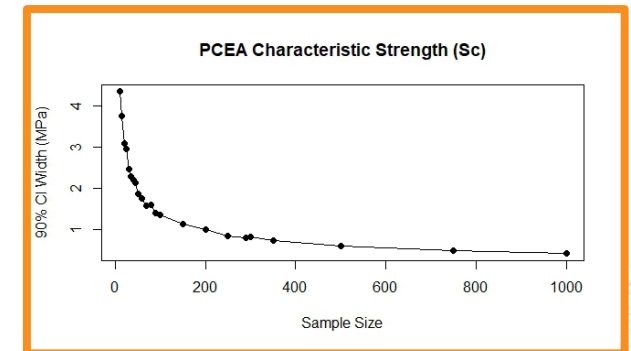
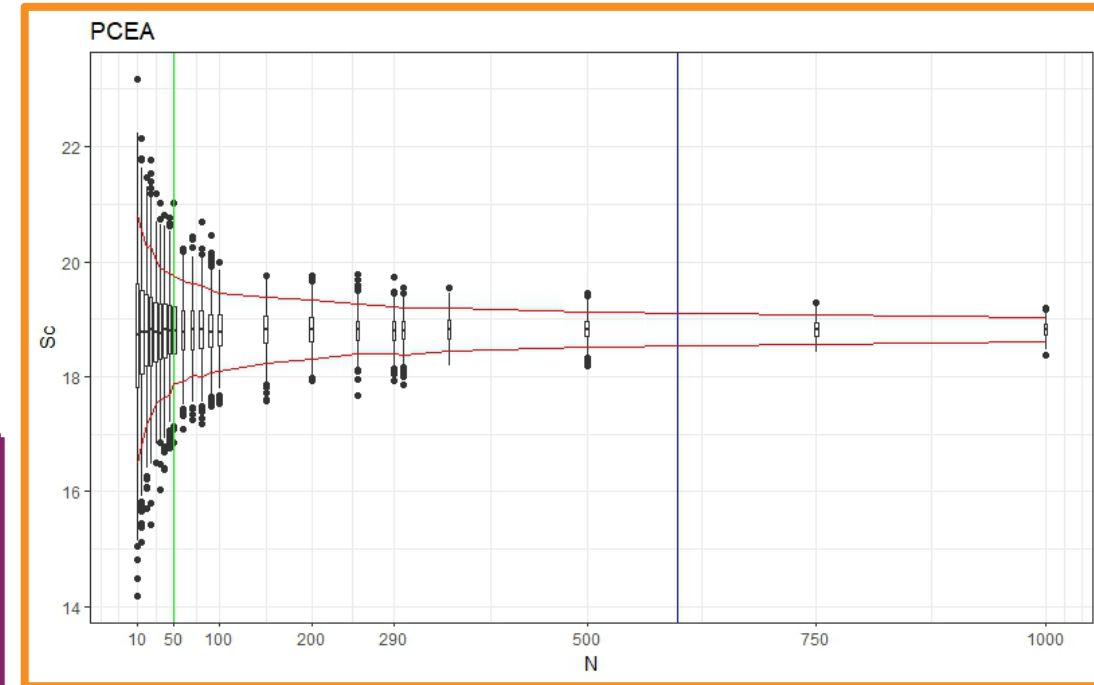
Gwennael Bieranart

Full Assessment: Sample size requirements

PCEA Billet ID	01D3-36	02S8-5	02S8-7	01S8-9	01S8-11	Total
N tensile	127	120	192	160		599

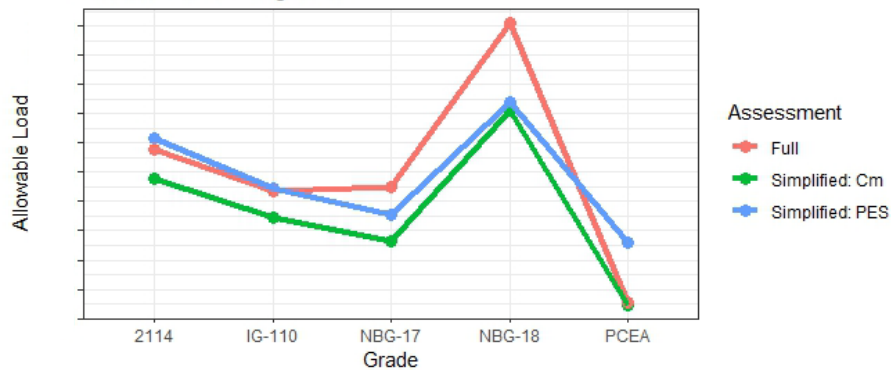


PROJECT TEAM:
INL
Andrea Mack
Dave Rohrbaugh

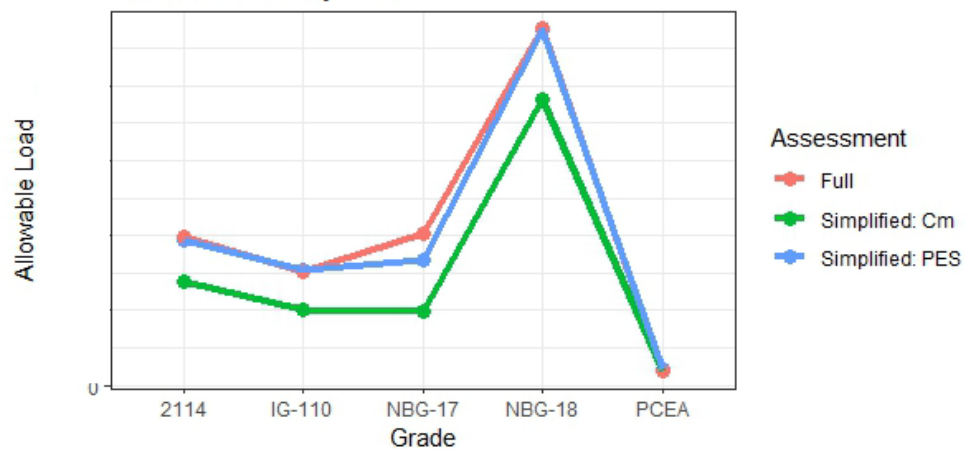


Results suggest N=288 may be adequate, but the data used do not meet the sampling requirements of HHA-II-4100 and do not account for the between-lot variability.

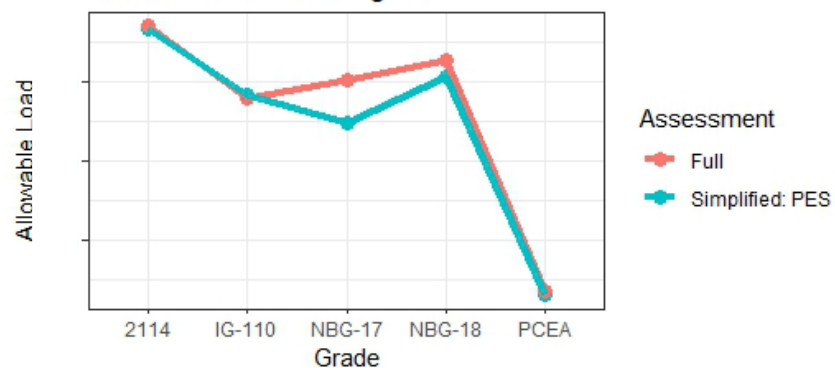
Assessments: Dogbone



Assessments: Cylinder



Assessments: Bending Bar



Margin (1/2)

Let the margin (M) be defined as:

$$M = \left(1 - \frac{l_{0.0001}^{LB}}{\hat{S}_c}\right)$$

Where:

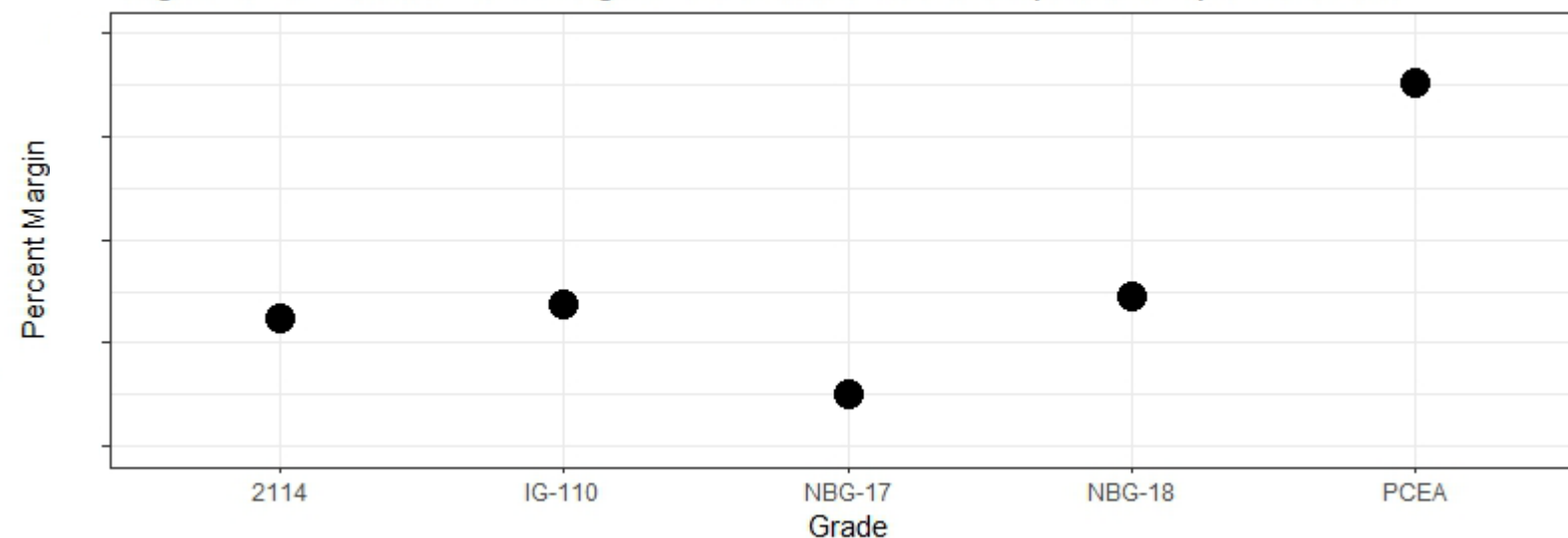
$l_{0.0001}^{LB}$ is the allowable load, which gives a POF=0.0001 when applying the full/simplified assessments

$\hat{S}_c$ is the characteristic strength estimated from the experimental data

PROJECT TEAM:
INL

Will Hoffman
Andrea Mack

Dogbone Full Assessment Margins: 2019 Code Version, Update Shape Parameter



Margin: Future Work (2/2)

- Future work will involve breaking down the margin into its components, to understand the proportion of margin added in at each step.

Margin is added at the following steps of the full assessment:

– V_m

- V_m is tuned such that the load that results in the full assessment POF=0.5 when using MLEs perfectly matches the experimental median for the “most limiting” geometry, which has been determined to be a purely tensile specimen with minimum gauge length.
- The most limiting V_m will also be used for all other geometries, but will result in conservative results.
- Define $l_{0.632}^{MLE}$ as the full assessment load which gives a POF=0.632 when using the parameter MLE's.
- Define: $M(V_m) = 1 - \frac{l_{0.632}^{MLE}}{\hat{S}_c}$

– LB

- Margin is added into the full assessment by using 95% one-sided Weibull parameter lower bounds to account for sampling uncertainty in the parameter estimates.
- Define $l_{0.632}^{LB}$ as the full assessment load which gives a POF=0.632 when using the parameter LB's
- Define: $M(LB) = 1 - \frac{l_{0.632}^{LB}}{\hat{S}_c}$

– SRC

- Margin is again added into the full assessment by using the POF limit allowed by the component's structural reliability class (SRC). For these purposes, we are using the SRC limit of 0.0001.
- Define $l_{0.0001}^{MLE}$ as the full assessment load which gives a POF=0.0001 when using the parameter MLE's
- Define: $M(10^{-4}) = 1 - \frac{l_{0.0001}^{MLE}}{\hat{S}_c}$

- Then the total margin (M) can be broken into parts as:

$$M = M(V_m) + M(LB) + M(10^{-4}) - [2 * M(V_m)]$$

Note that $M(LB)$ and $M(10^{-4})$ both contain $M(V_m)$, there is no easy way to remove it, so it must be subtracted off.

$$M = M(LB) + M(10^{-4}) - M(V_m)$$

We can use this equation to understand where the most amount of conservatism is coming from in the full assessment.

Simplified Assessment: Stress terminology & R_{tf}

PROJECT TEAM:

Kairos

Pierre-Alexandre Juan

Westinghouse

Adam Walker

USNC

Jesse Quick

Jarryd Potgieter

INL

Will Hoffman

Andrea Mack

MPR

Gwennael Biernart

PROBLEM

- There are two checks for the simplified assessment:
 - Membrane stress check
 - “Peak” stress check
- The second check raises the allowable stress by a factor of R_{tf} . There is concern R_{tf} makes the simplified assessment less conservative than the full.

ACCOMPLISHMENTS

- Determined R_{tf} effectively raises the 10^{-4} tensile limit to a 10^{-4} flexural limit
- Showed by comparison with tensile, compressive, and flexural experimental data that the simplified method is conservative as long as the two criteria are being met (if updating the shape parameter in the full assessment)
- Determined normal stress-based failure criteria are overly conservative for compressive load cases

ACTION ITEMS

- R23-473: will change stress terminology to MDE not normal stress
- Further understand the implication of the use of the R_{tf} on the method's conservatism and the possibility to use a single failure criterion

Schedule

Subtask groups
meet every other
week between
the TG meetings.

Jan. '23

NRC meeting: R_{tf}

TG meeting:
Mesh refinement
and shape
parameter update

April '23

May '23

ASME Code Week:
*Simplified assesment
and tuning V_m and
 Δ*

TG meeting:
Disparate flaw
distribution and
shape parameter
update

July '23

Aug. '23
ASME

ASME Code Week:
Simplified
assessment and
tuning V_m and Δ

Goal:
Code rule
changes by
2025 BPVC

Conclusions

- Disparate flaw distribution
- Tuning V_m and Δ
- Feasibility study on incorporating location in full assessment
- Margin 2019 Code rules
- Margin 2025 Code rules
- Mesh refinement study more complex geometry
- Volume effects on strength of graphite
 - When is weakest link theory valid
 - Effect of scaling strength distributions to realistic size components
 - Experimental validation of full assessment using a realistic component in a complex stress state
- Adequate sample size to characterize graphite tensile strength distribution

KEY FOR COMPLETION TARGETS:

Purple: Dec. 2023, technical work complete

Dec. 2024, results submitted for publication and records accepted

Yellow: 2024 technical work

Red: Missing information, not able to complete

Concern in meeting targets: all subtasks are related, so many cannot be completed until all are completed.

Goal:

All Design changes to code rule approved for the **2025 version** of the Boiler and Pressure Vessel Code (BPVC)