Life Modelling of Critical Steam Cycle Components in Coal-Fueled Power Plants

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Outline

- Big Picture
- Last Stage Bucket Project Update and Accomplishments
- Wye-Block Project Update and Accomplishments
- Questions

Big Picture

Calibrate life prediction as well as Maintenance & Operation scheduling models to enhance the performance and cost-effectiveness of existing coal-based power generation in the U.S.

TODAY: Update on life modelling of two primary challenges facing existing coal-fueled power plants

- L-0 Last Stage Bucket (Power Generation Turbine Blade) Water Droplet Erosion life estimation (and M&O) model calibration is complete.
- P22 main steam piping materials (forged pipe, forged fittings (Wye Block), and their welds) life prediction. LCF testing and constitutive modeling substantially complete. Creep testing expanded and under way.

LSB Background and Objectives

L-0 Last Stage Bucket (Turbine Blade) Water Droplet Erosion is a somewhat common, and a very severe issue facing steam turbine operators

- Most remaining coal-fired plants are operating under conditions not considered during initial design and engineering
  - Original design: HCF with stable mechanical and thermal loads
  - Current and future operational paradigm: HCF over LCF

Can LSB failures be predicted/mitigated by use of operational data and inspection findings?

This work:
Calibrate life prediction and M&O scheduling models to enhance the performance and cost-effectiveness of existing coal-based power generation in the U.S.

LSB Background and Objectives

- L-0 Last Stage Bucket (Turbine Blade) Water Droplet Erosion
  - Calibrate M&O scheduling and life model for L-0 buckets experiencing water droplet erosion by use of:
    - Operational data for four turbines over a 15-year period
    - Erosion inspection data for same four turbines over same 15-year period
    - Virgin material characterization
    - Bucket(s) pulled from service (for modelling and testing purposes)

LSB Background and Objectives

- L-0 Last Stage Bucket (Turbine Blade) Water Droplet Erosion

Last Stage Bucket Leading Edge Erosion is a serious concern for plant operations

Failures Linked to Water Droplet Erosion (Bucket Tip Liberation)

- Several failures occurred in the early 2000's on GE "self-shielded" Jethete buckets.
- In 2005, GE released information indicating that self-shielded rows' 25-year failure rate was 1.4%
- Cracks initiated at erosion crevices near the bucket tip.

Material of Interest:
Jethete M-152 Stainless Steel

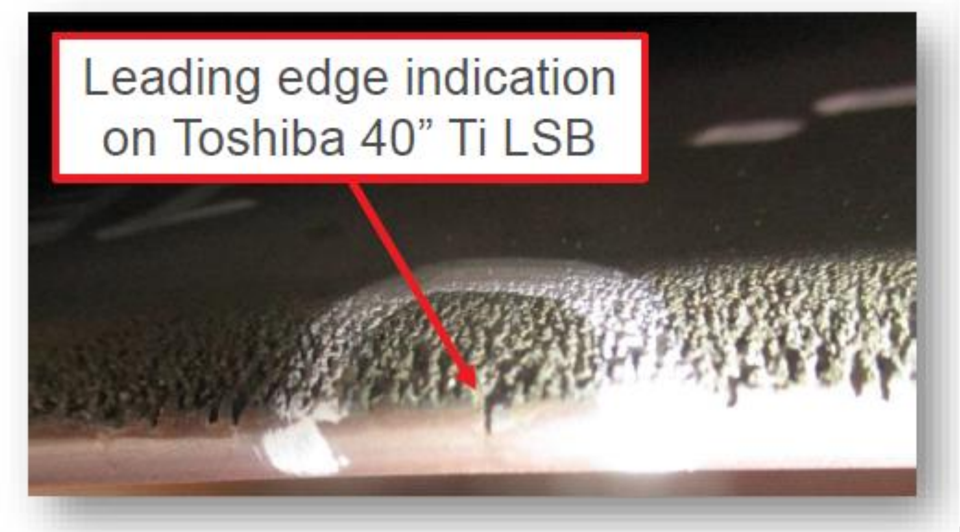
Failure Mechanism of Interest:
Cracks emanating from erosion pits

LSB Background and Objectives

- L-0 Last Stage Bucket (Turbine Blade) Water Droplet Erosion

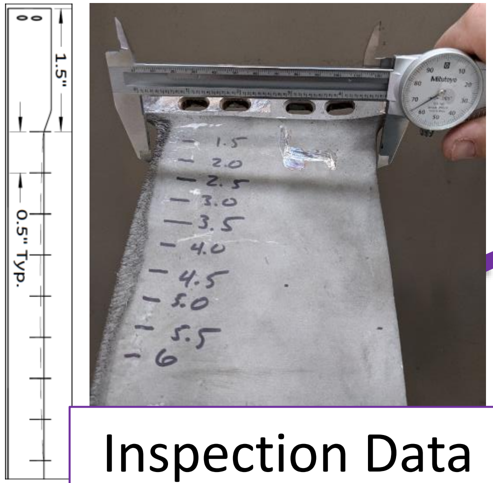
Coal fleet challenges related to LSB erosion:

- LSB failure could result in retirement of an older coal unit
  - Must reduce risk of failure
- Budget impact
  - Monitor/predict LSB life to prevent catastrophic failure *AND/OR premature replacement*

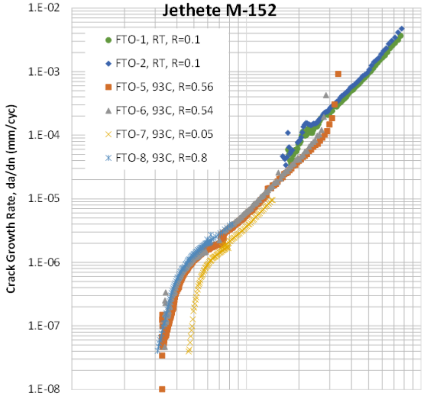


- Southern Company has supplied six 33.5" GE self-shielded LSBs for this research.
- Model V&V will incorporate these blades (late 2022)

LSB Background and Objectives

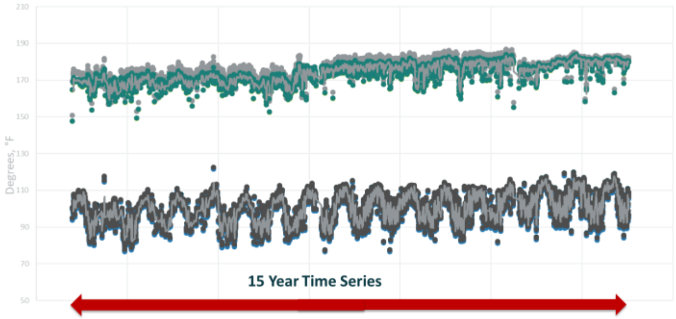


Inspection Data

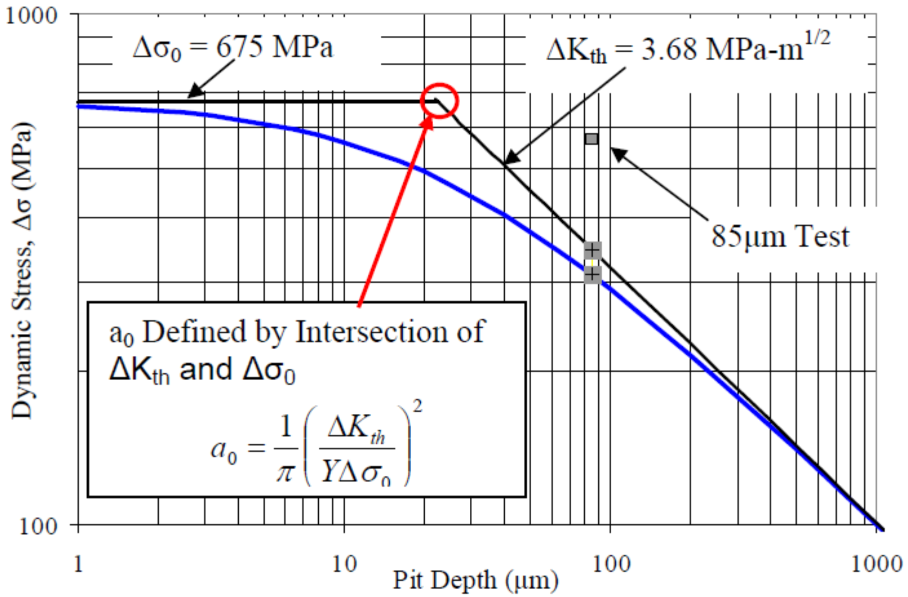


Experimental Data

Solid Modelling

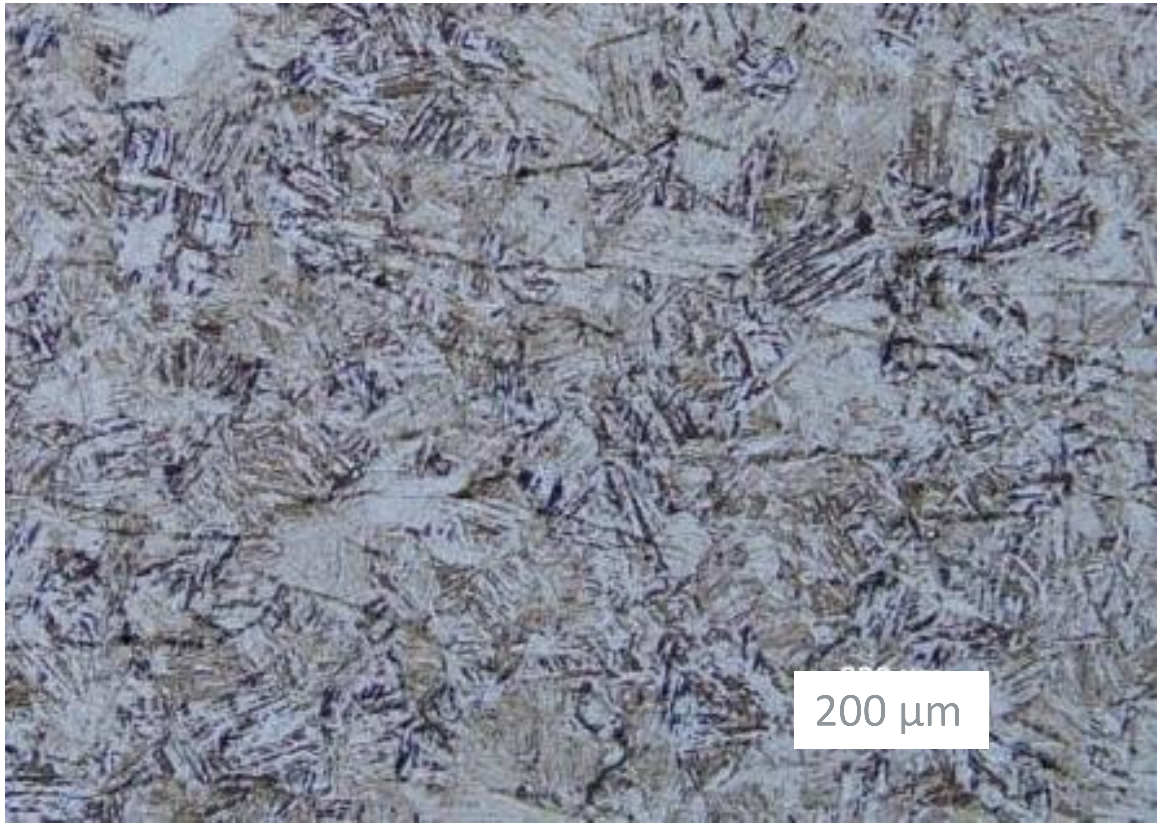


Operations Data

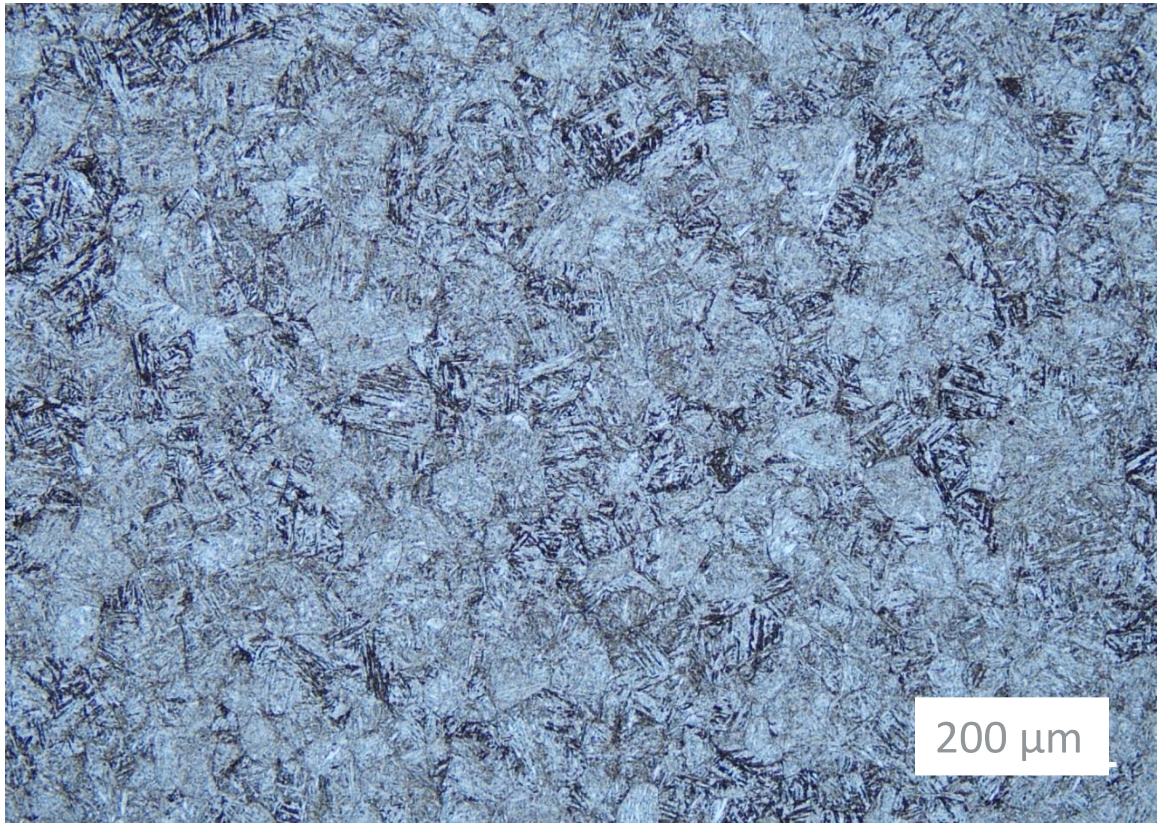


Predictive Life Model

LSB Material Data



SoCo-supplied Jethete, LSB pulled from service



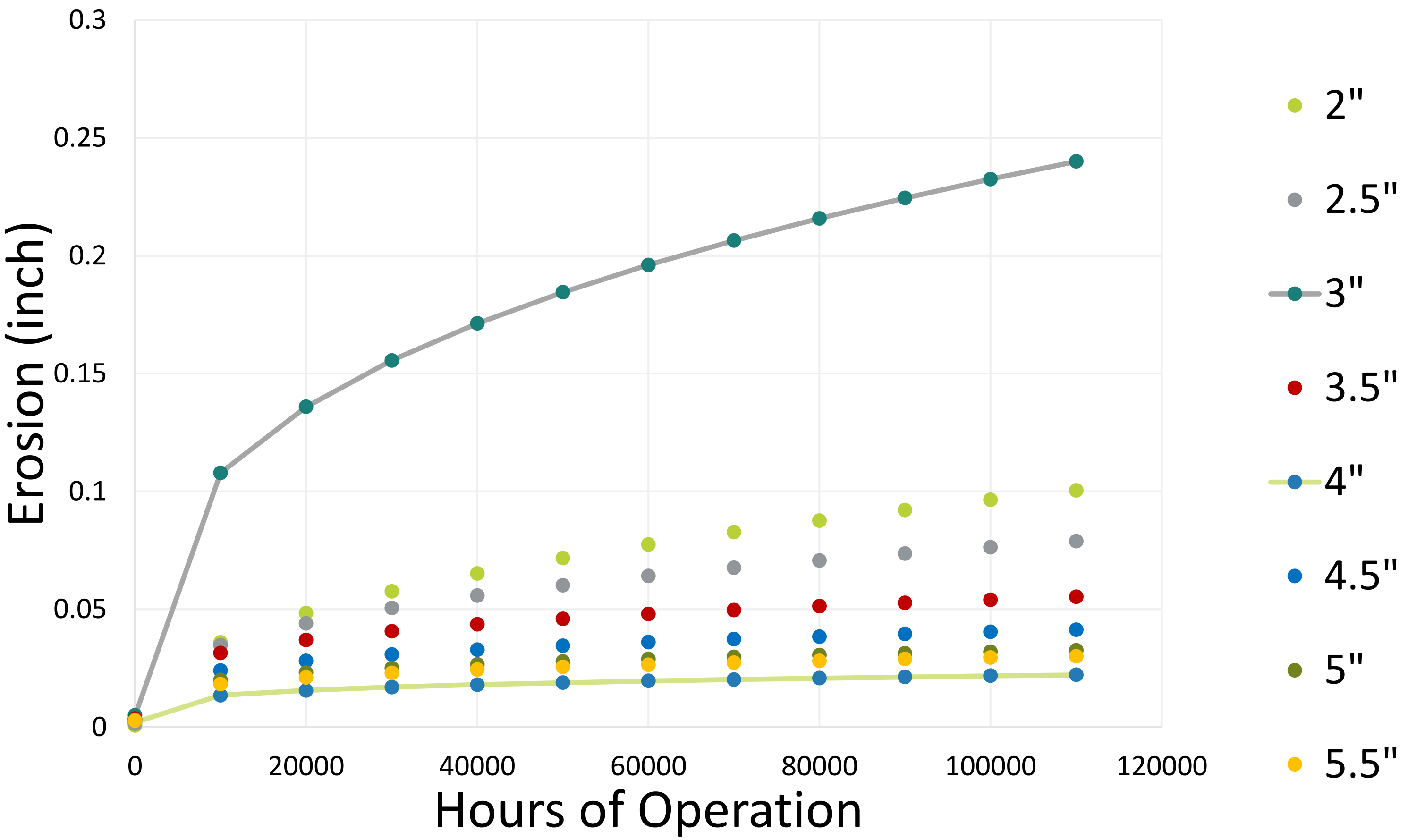
Wrought Jethete, virgin

Jethete Pulled from Service	
Orientation	d (µm)
Longitudinal	132.4
Transverse	129.6

Wrought Jethete	
Orientaiton	d (µm)
Longitudinal	52.7
Transverse	50.2
Through Thickness	51.2

* d represents average grain diameter and not Martinsite packet size

LSB Erosion Inspection Data



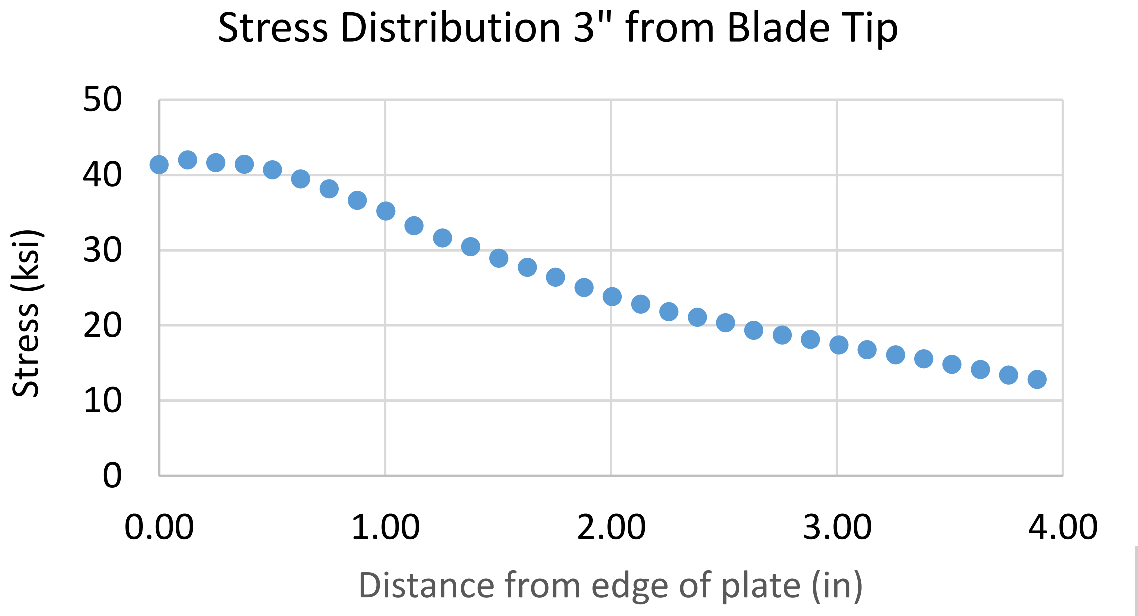
Analysis of 18 years of erosion inspection data for four facilities indicates:

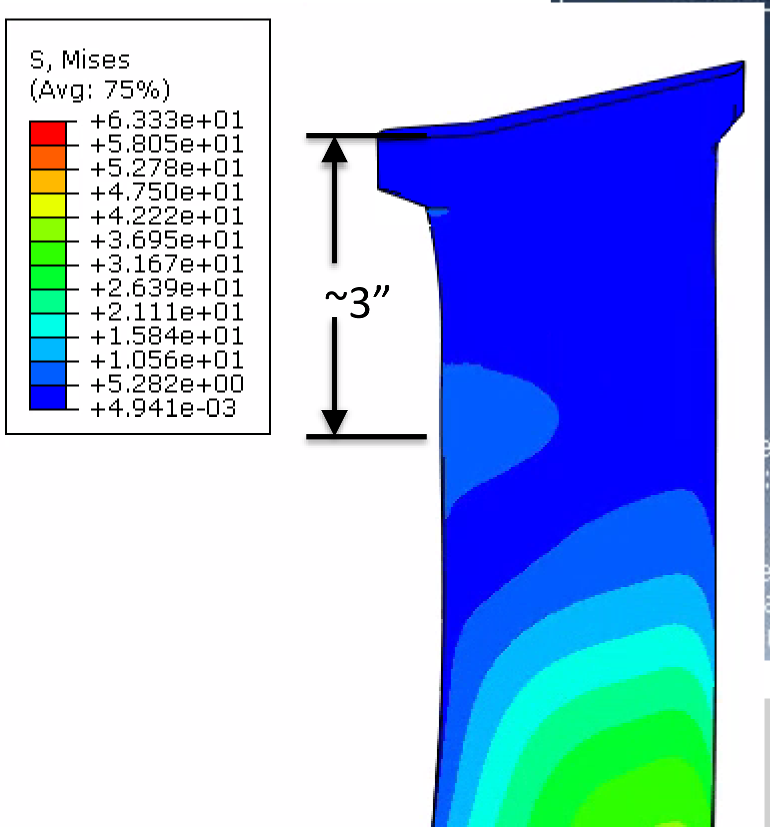
- Single location of dominant erosion kinetics (~3” from tip of LSB)
- Clear correlation between turbine “starts” and erosion rate at location of interest

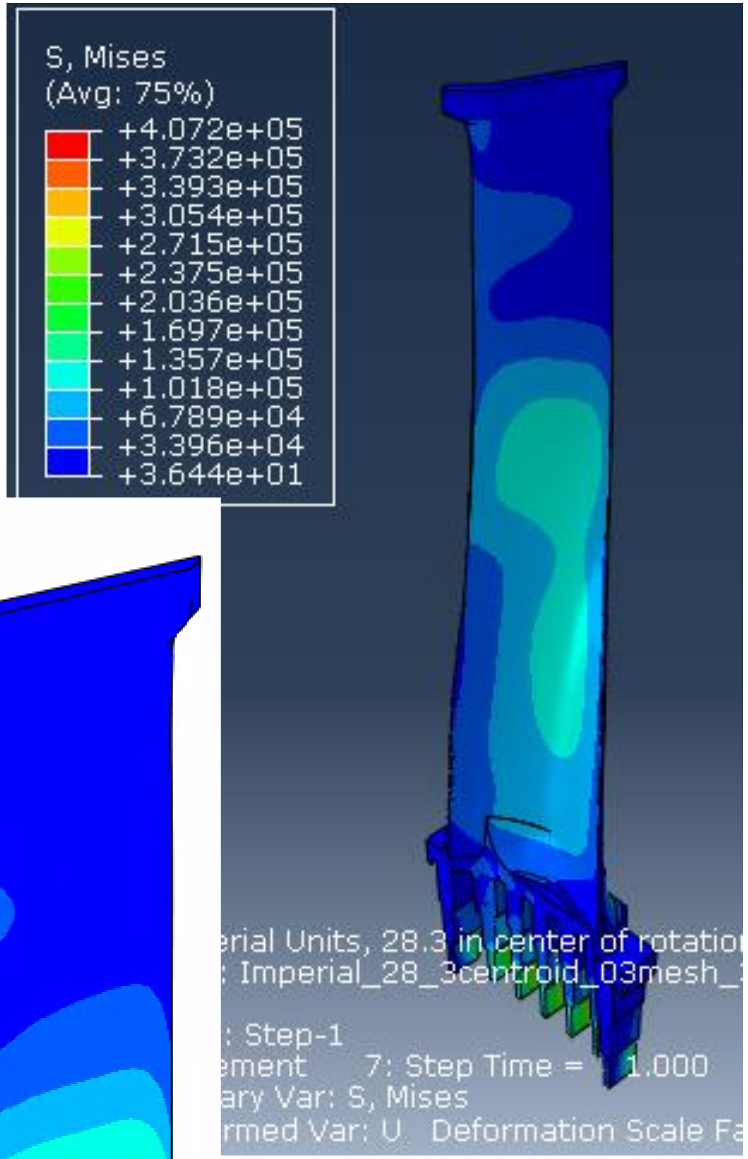
(Correlation also exists between hours of operation and erosion rate at location of interest).

LSB Modelling + Operations Data

- 3D solid model of LSB created by use of laser scan data
- Boundary conditions:
  - Fixed at “fir tree”
  - Circumferentially fixed/dampened at tip
  - Circumferentially fixed/dampened at mid-blade connection
- Loading Conditions:
  - Centrifugal acceleration resulting from operational rotational speeds



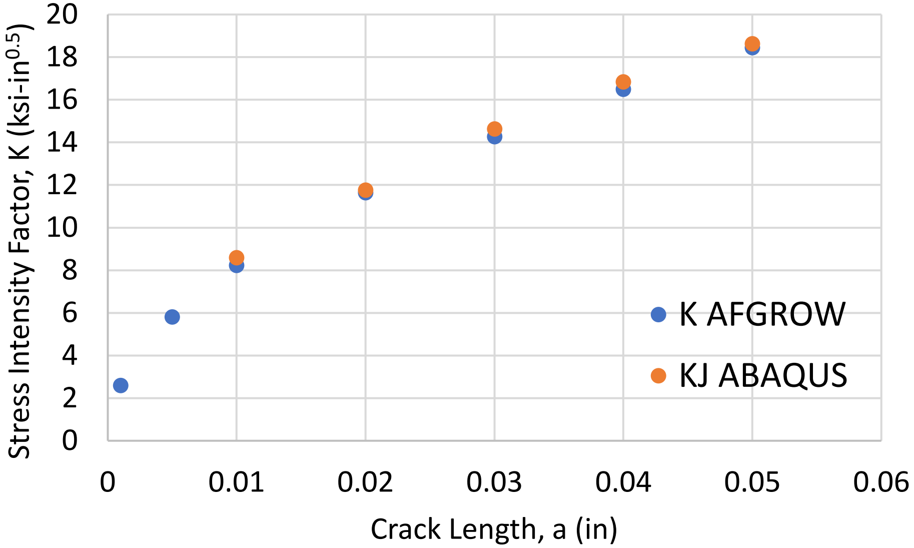


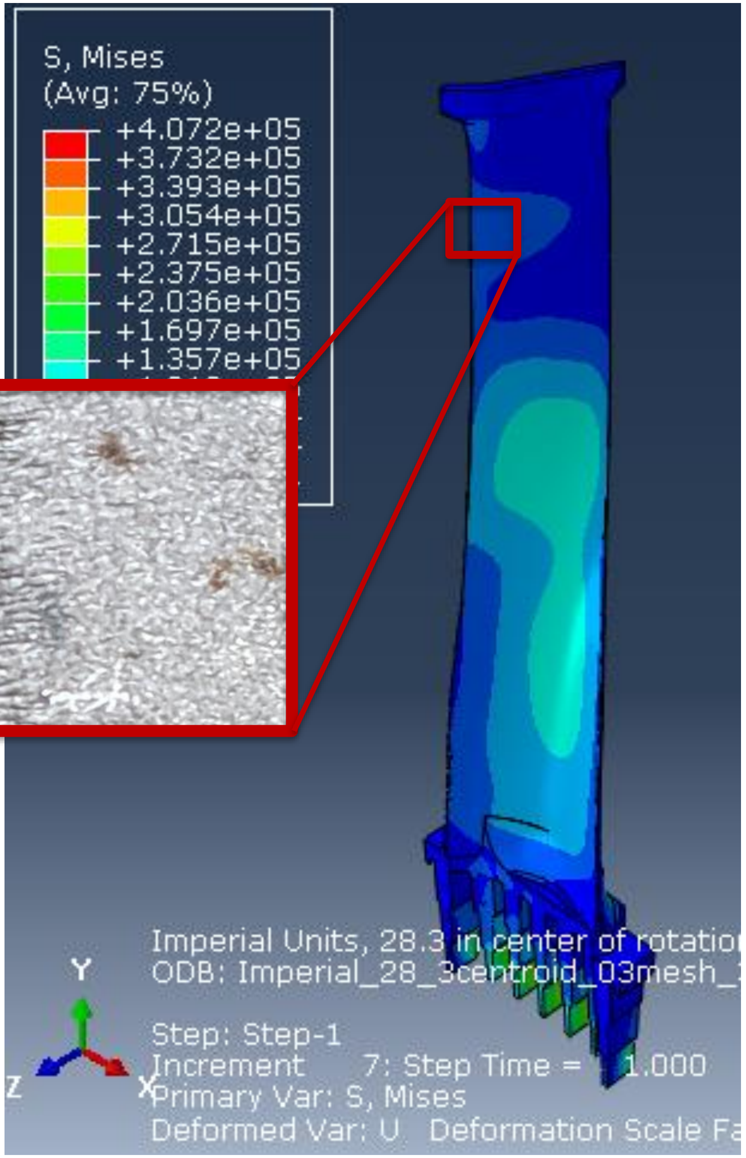


LSB Modelling + Operations Data

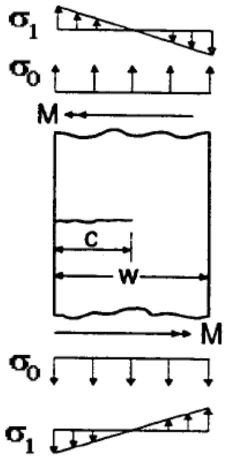
Cracks emanating from leading edge of LSB may be modeled as simple "Through Crack at Edge of Finite Plate"

- ABAQUS model utilized crack having 5 µm radius and 0.5 µm mesh size



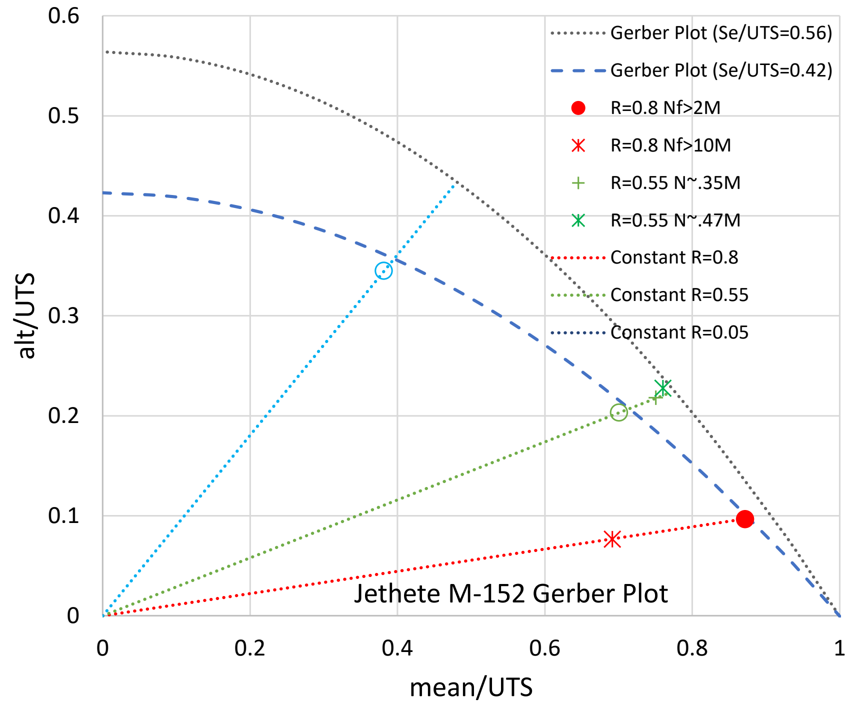


Through Crack at the Edge of a Plate	*Tension* $K_0 = F_0 \sigma_0 \sqrt{\pi a}$ *Bending* $K_1 = F_1 \sigma_1 \sqrt{\pi a}$ $K_2 = F_2 \sigma_2 \sqrt{\pi a}$	$F_0 = \sec\beta \left(\frac{\tan\beta}{\beta}\right)^{\frac{1}{2}} \left[0.752 + 2.02\left(\frac{a}{W}\right) + 0.37(1-\sin\beta)^3\right]$ $F_1 = \frac{F_0}{2}$ $F_2 = \sec\beta \left(\frac{\tan\beta}{\beta}\right)^{\frac{1}{2}} \left[0.923 + 0.199(1-\sin\beta)^4\right]$ $\beta = \frac{\pi a}{2W}$



AFGROW Hand Book of Damage Tolerant Design, downloaded 2021

LSB Experimental Data

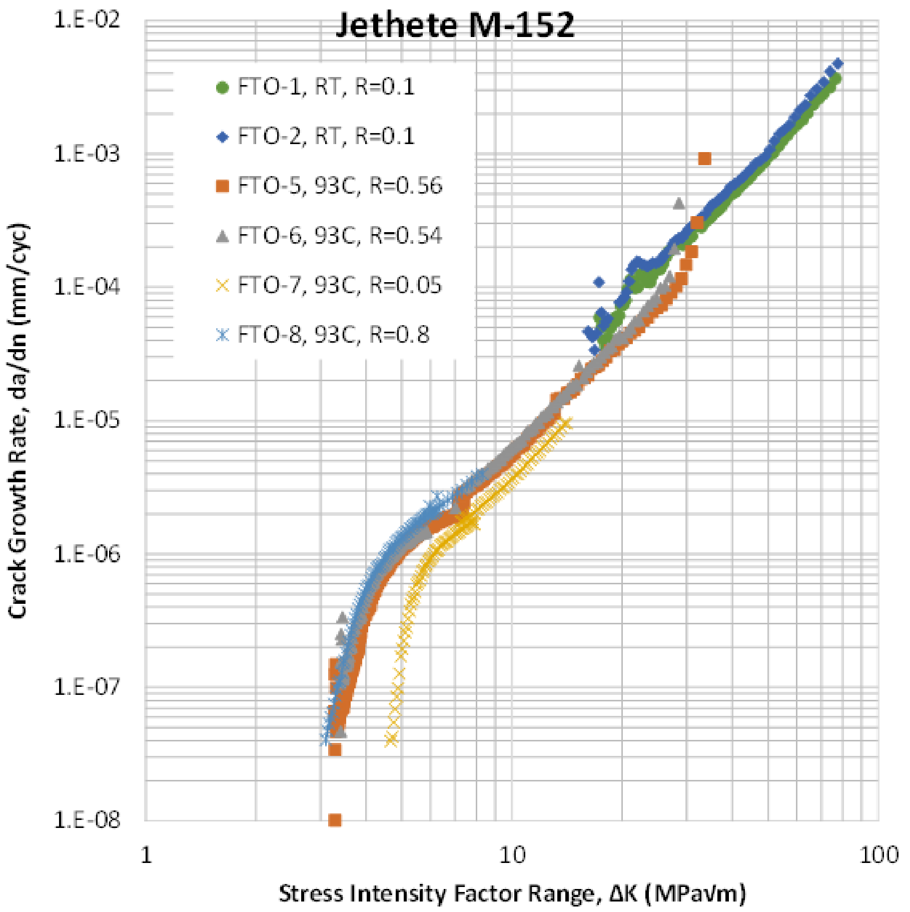


R	$\Delta\sigma 0$	ΔK_{th}
(-)	(Mpa)	MPa-√m
0.05	674.9	4.7
0.55	397.9	3.4
0.80	189.5	3.2

Specimn	Temp	Test	R	C	m
(#)	(deg C)	Control	(-)		
FTO-5	93	Load- increasing ΔK	0.56	1.11×10^{-8}	2.73
FTO-6	93	Load- increasing ΔK	0.54	1.21×10^{-8}	2.73
FTO-7	93	Load- increasing ΔK	0.05	8.89×10^{-9}	2.62
FTO-8	93	Load- increasing ΔK	0.8	N/A	N/A
FTO-1	27	Load- increasing ΔK	0.1	1.44×10^{-8}	2.84
FTO-2	27	Load- increasing ΔK	0.1	1.15×10^{-8}	2.94

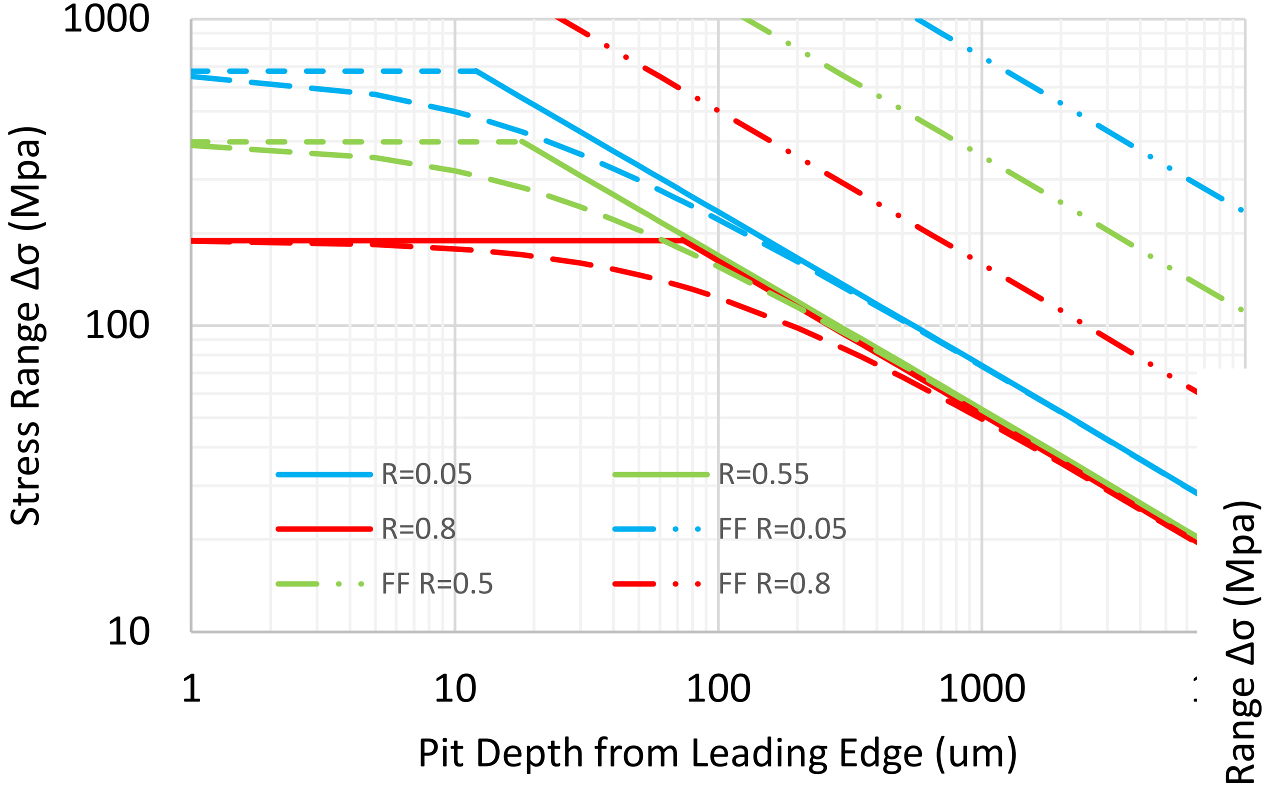
Specimn	Temp	Test	ΔK_{th}	R
(#)	(deg C)	Control	MPa-√m	(-)
FTO-5	93	constant K_{max}	3.4	0.56
FTO-6	93	constant K_{max}	3.5	0.54
FTO-7	93	K decreasing	4.7	0.05
FTO-8	93	K decreasing	3.2	0.8

Specimn	Temp	Test	ΔK_{th}	R
(#)	(deg C)	Control	MPa-√m	(-)
FTO-5	93	constant K_{max}	3.4	0.56
FTO-6	93	constant K_{max}	3.5	0.54
FTO-7	93	K decreasing	4.7	0.05
FTO-8	93	K decreasing	3.2	0.8

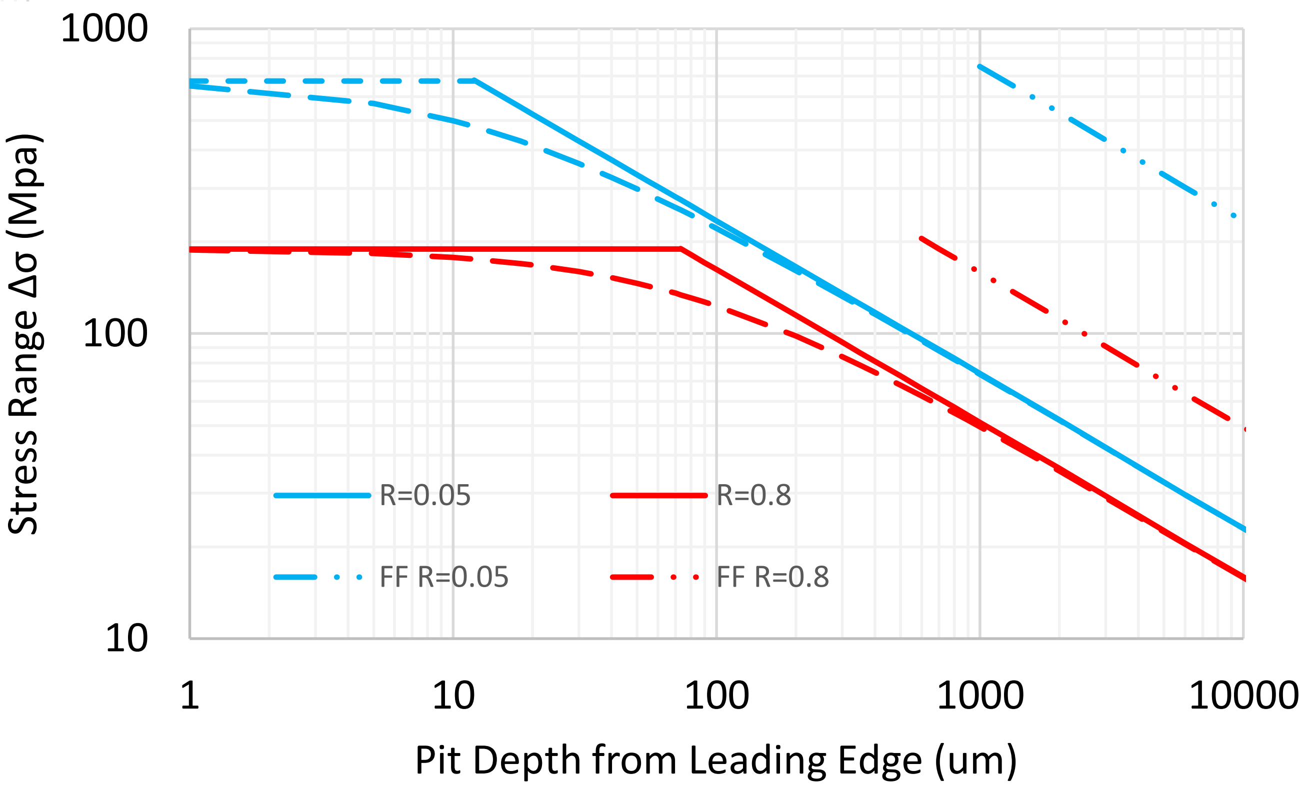


Specimen	Temp	Mean	Alt	Min	Max	Max/UTS	$\Delta\sigma_0$	R	Nf
(#)	(deg C)	(Mpa)	(Mpa)	(Mpa)	(Mpa)	(%)	(Mpa)	(-)	(10^6 cycles)
JH03L	93	676.5	75.0	601.5	751.5	77%	150.0	0.80	>10
JHC2L	93	852.6	94.7	757.8	947.3	97%	189.5	0.80	>2.5
*N/A**	*93*	*685.2*	*198.9*	*486.3*	*884.1*	*90%*	*397.9*	*0.55*	*N/A*
*N/A**	*93*	*373.0*	*337.5*	*35.5*	*710.5*	*73%*	*674.9*	*0.05*	*N/A*
JHC1	93	734.0	213.0	521	947	97%	426.0	0.55	341,768
JHD1	93	748.5	217.5	531	966	99%	435.0	0.55	476,694
JHB1	93	734.0	213.0	521	947	97%	426.0	0.55	345,230

LSB Modelling + Experimental Data

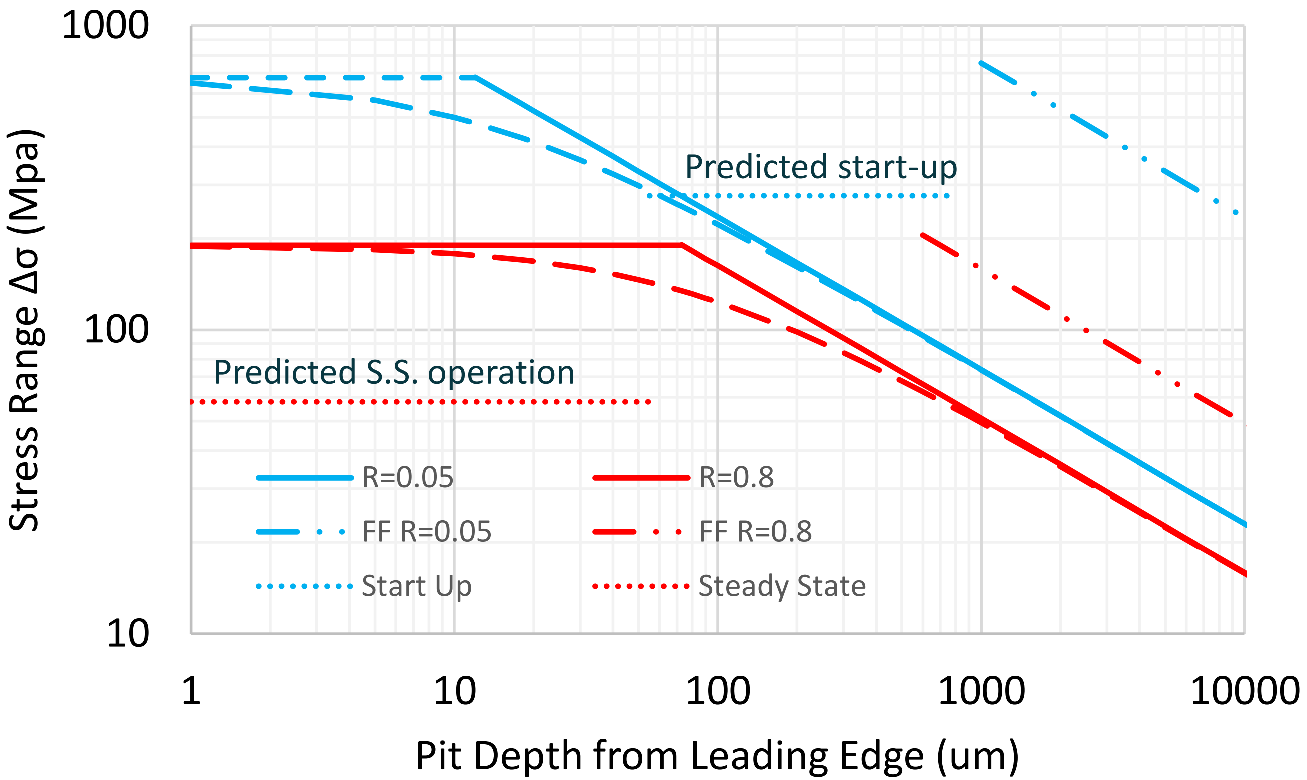


Updated MP159 Kitagowa Diagram *specifically* applicable to LSB Loading conditions, boundary conditions, and cracks of interest



R	Δσ0	ΔK_{th}
(-)	(Mpa)	MPa-√m
0.05	824.9*	4.7
0.55	426.3*	3.4
0.80	189.5	3.2

LSB Life Modelling



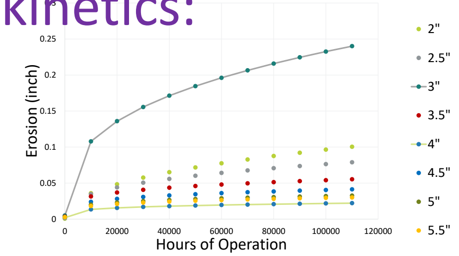
- An edge crack can be up to 800 μm (0.031”) long prior to extending during steady state (S.S.) operating conditions (R=0.8).
- An edge crack at 60 μm (0.002”) in size will extend as a function of “start-up” procedure (R=0.05)

One would like to be capable of detecting a crack having length of a = 0.002”

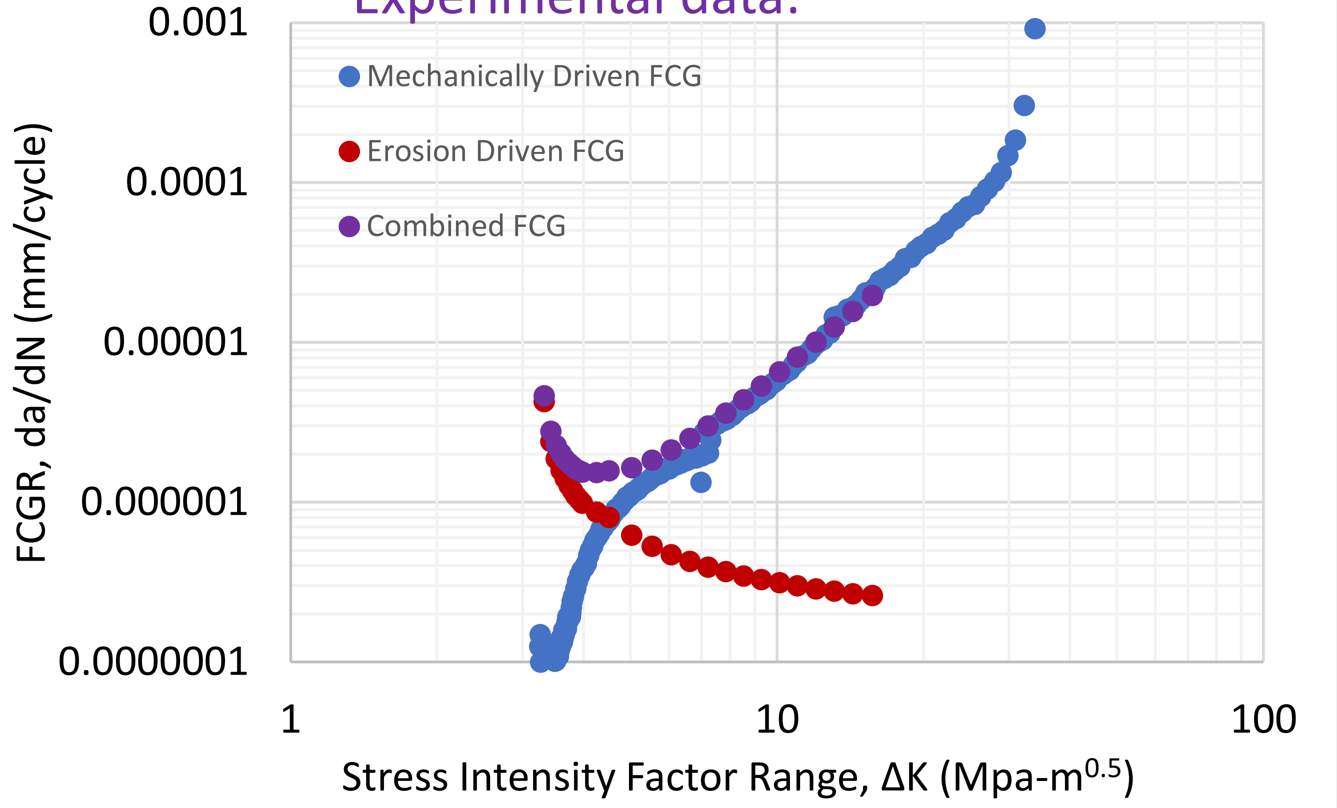
One MUST be capable of detecting a crack having length of a = 0.031”

LSB Life Modelling

Recall LSB erosion kinetics:

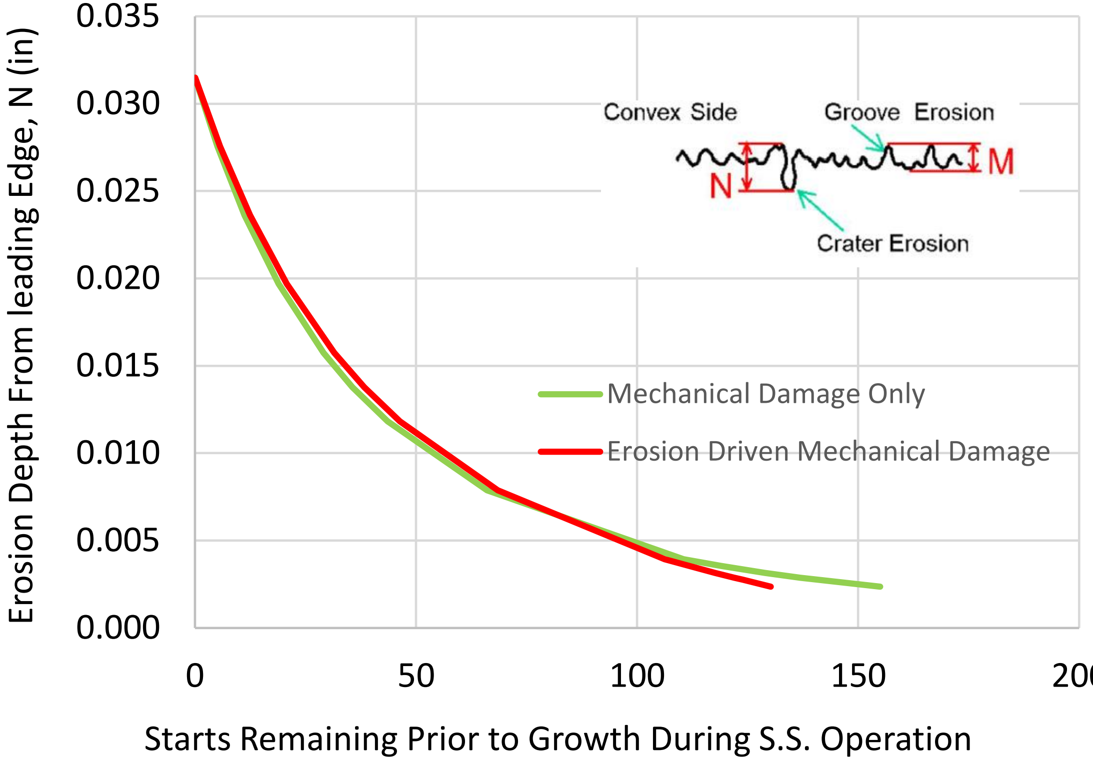


Experimental data:



Erosion-assisted crack extension

Life remaining when crack exists of known size:



One would like to be capable of detecting a crack having length a = 0.002”

One MUST be capable of detecting a crack having length a = 0.031”

LSB Future Work and Program Impact

Future work:

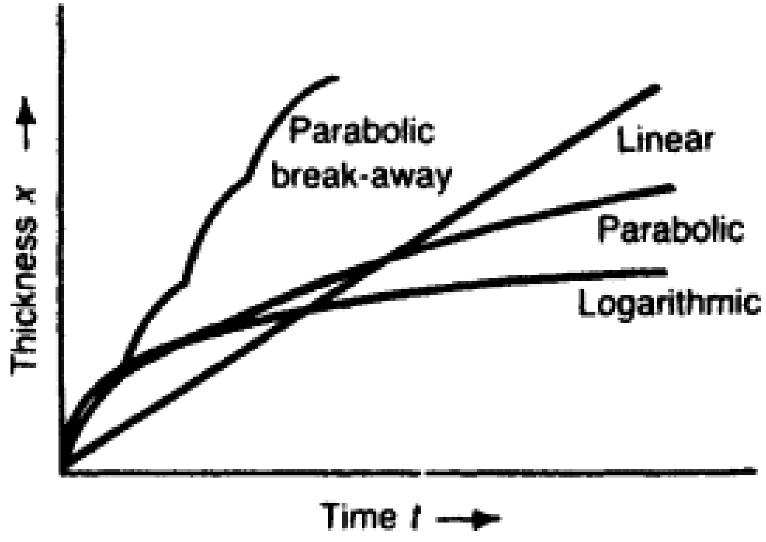
- Model Verification and Validation by use of LSB’s pulled from service

Outcomes:

- Calibrated model to predict remaining life of LSB’s experiencing water droplet erosion given inspection findings

Impacts:

- Reduction in the M&O costs as a result of
  - data-driven inspection and repair scheduling
  - “retirement for a cause” replacement protocol
- Extension of the useful life of coal-fueled power plants



A parabolic law follows for p-type semiconductors and a cubic law for n-type semiconductors (Cabrera and Mott [1949];

Questions

This material is based upon work supported by the Department of Energy Award Number DE-FE0031811

WYE Block Background and Objectives

P22 pipe-to-WYE Block welds often require field-repairs resulting from creep-fatigue damage interactions

- Most remaining coal-fired plants are operating under conditions not considered during initial design and engineering
  - Original design: HCF with stable mechanical and thermal loads (creep)
  - Current and future operational paradigm: HCF over LCF (creep-fatigue)

- Can the remaining life to crack initiation be predicted by use of past, present, and future operational conditions?

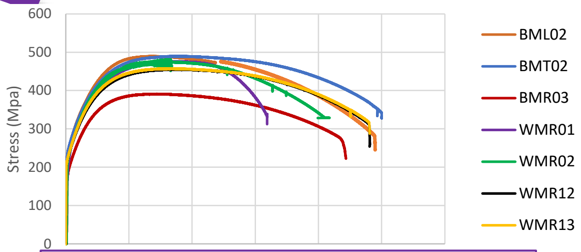
This work:
Calibrate life prediction and M&O scheduling models to enhance the performance and cost-effectiveness of existing coal-based power generation in the U.S.

WYE Block Background and Objectives

- Main Steam Wye-Block Life Modelling
  - Create a life prediction model for P22 welds experiencing creep and/or fatigue-creep by use of:
    - Operational AND Inspection Data from “Unit A” over an 18-year period
    - Drawings and schematics of main steam piping and facility interactions from “Unit A”
    - Representative (aged) P22 Wye-block material with shop and field (repair) welds removed from “Unit B”

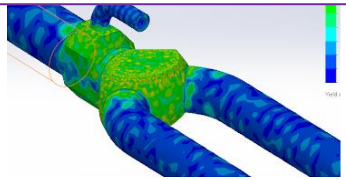
WYE Block Background and Objectives

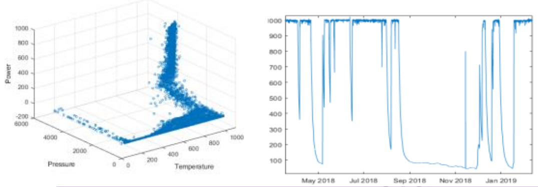
Inspection Data



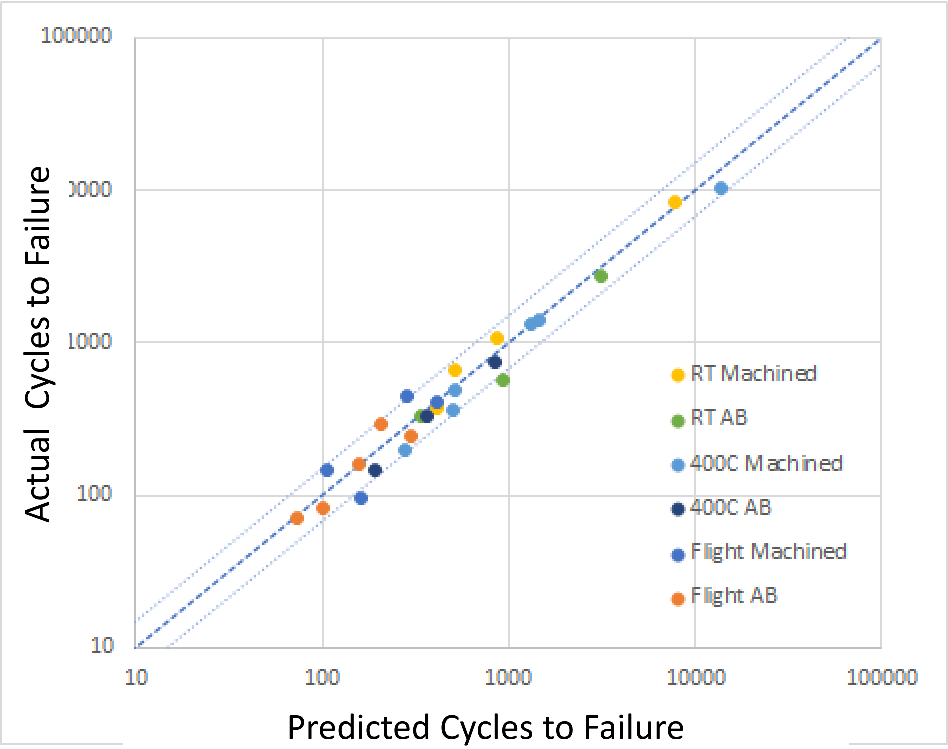
Experimental Data

Solid Modelling



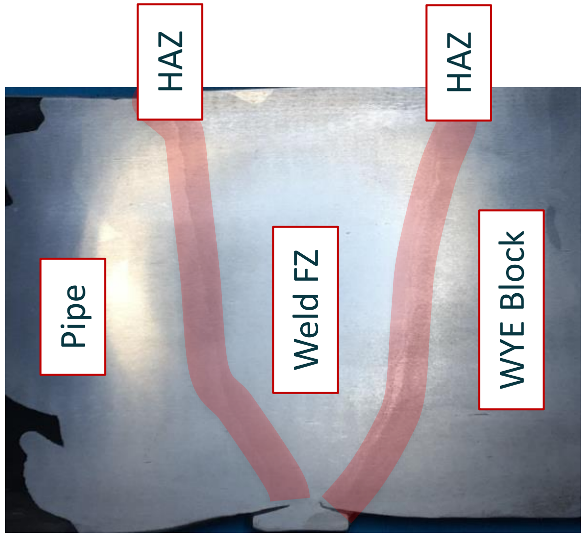


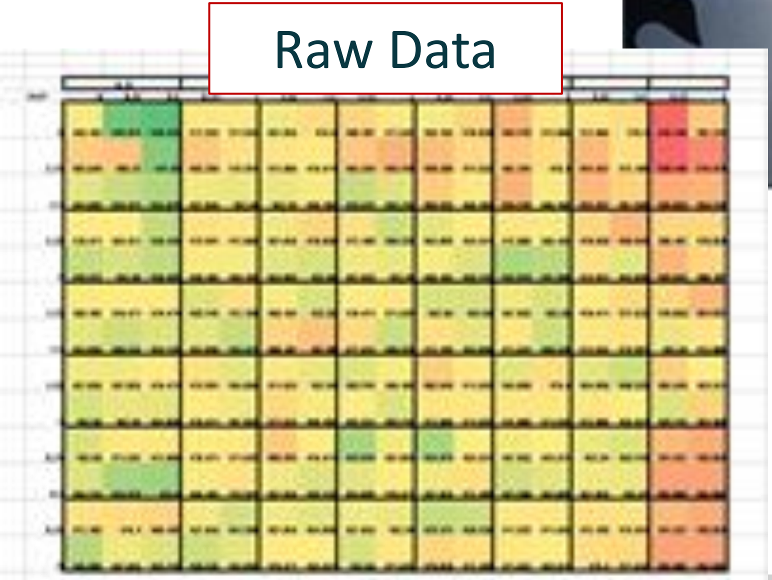
Operations Data

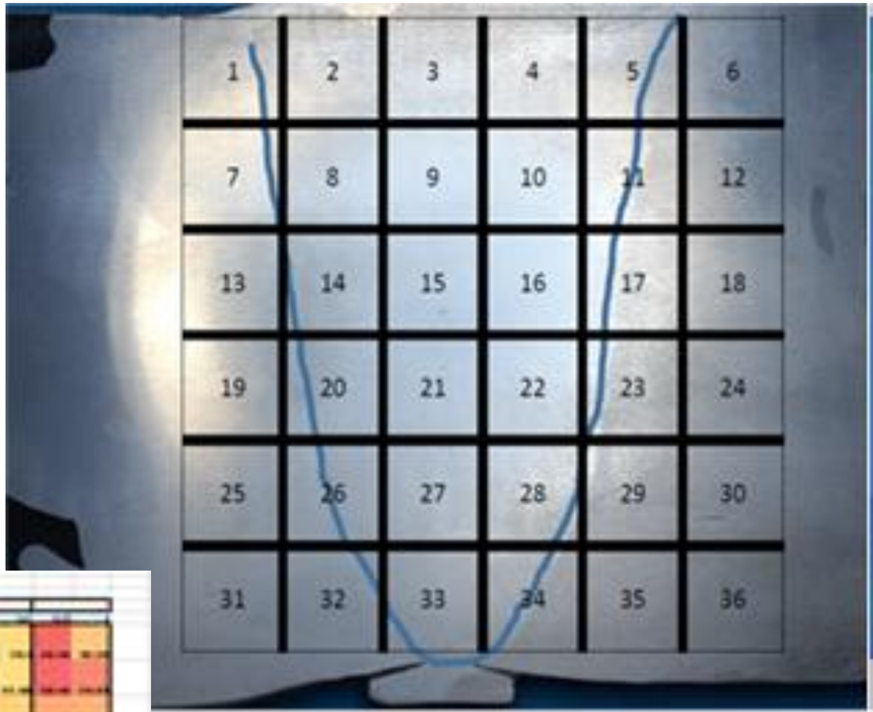


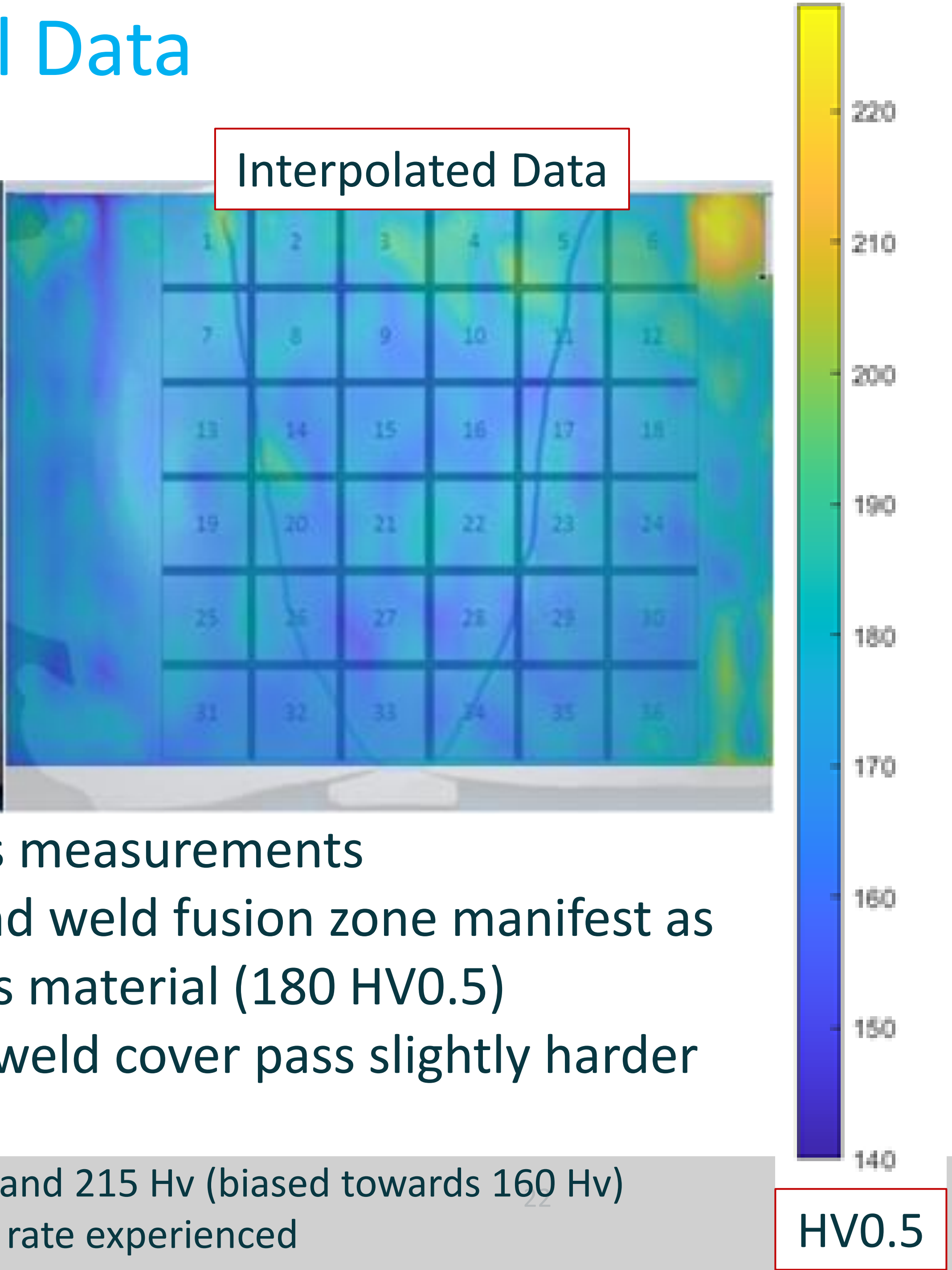
Predictive Life Model

WYE Block Material Data





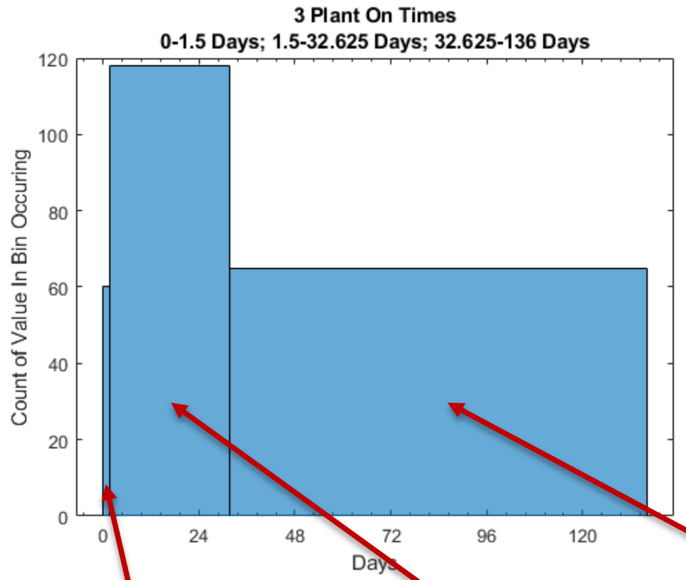




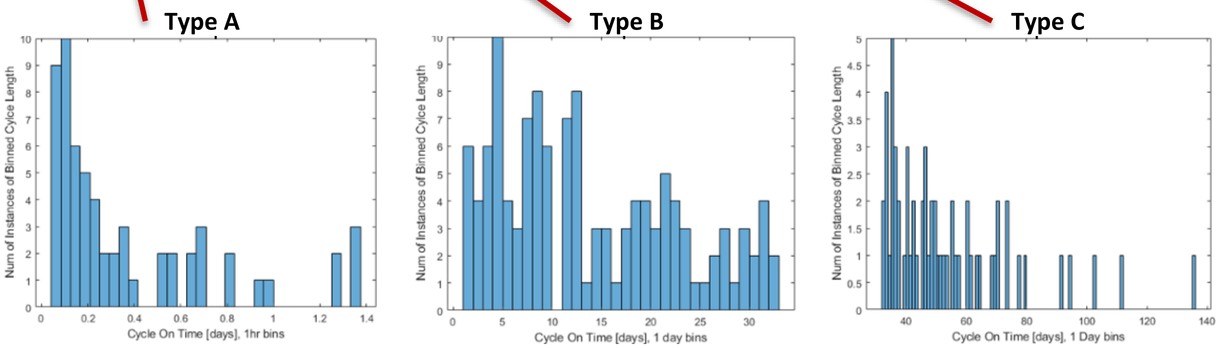
- 624 individual hardness measurements
- Pipe BM, weld HAZs, and weld fusion zone manifest as relatively homogeneous material (180 HV0.5)
- WYE Block forging and weld cover pass slightly harder

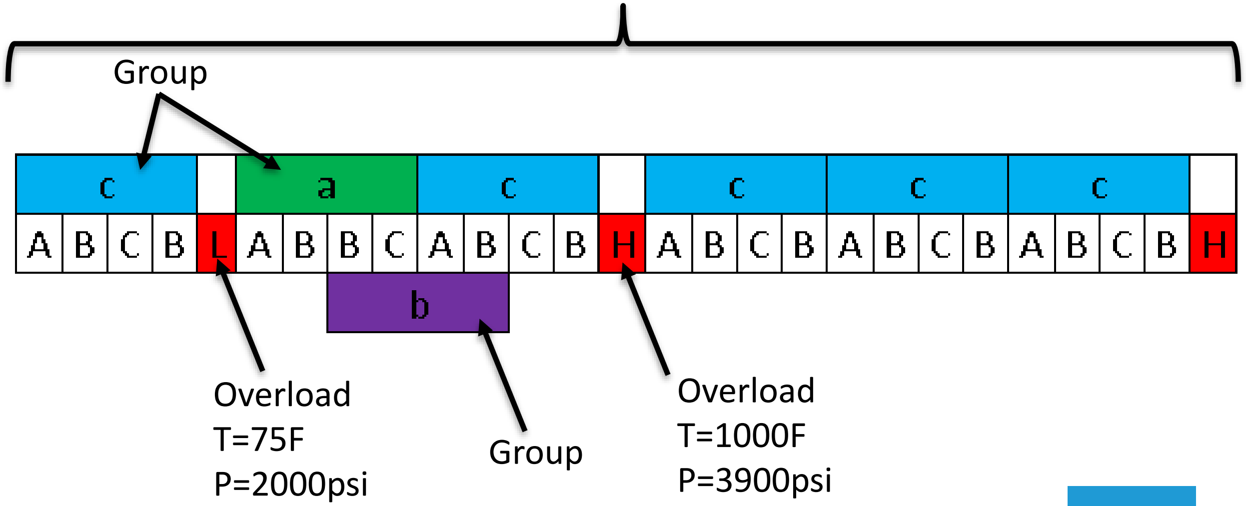
- Post-weld P22 between 160Hv and 215 Hv (biased towards 160 Hv) depending upon PWHT cooling rate experienced

WYE-Block Modelling + Operations Data

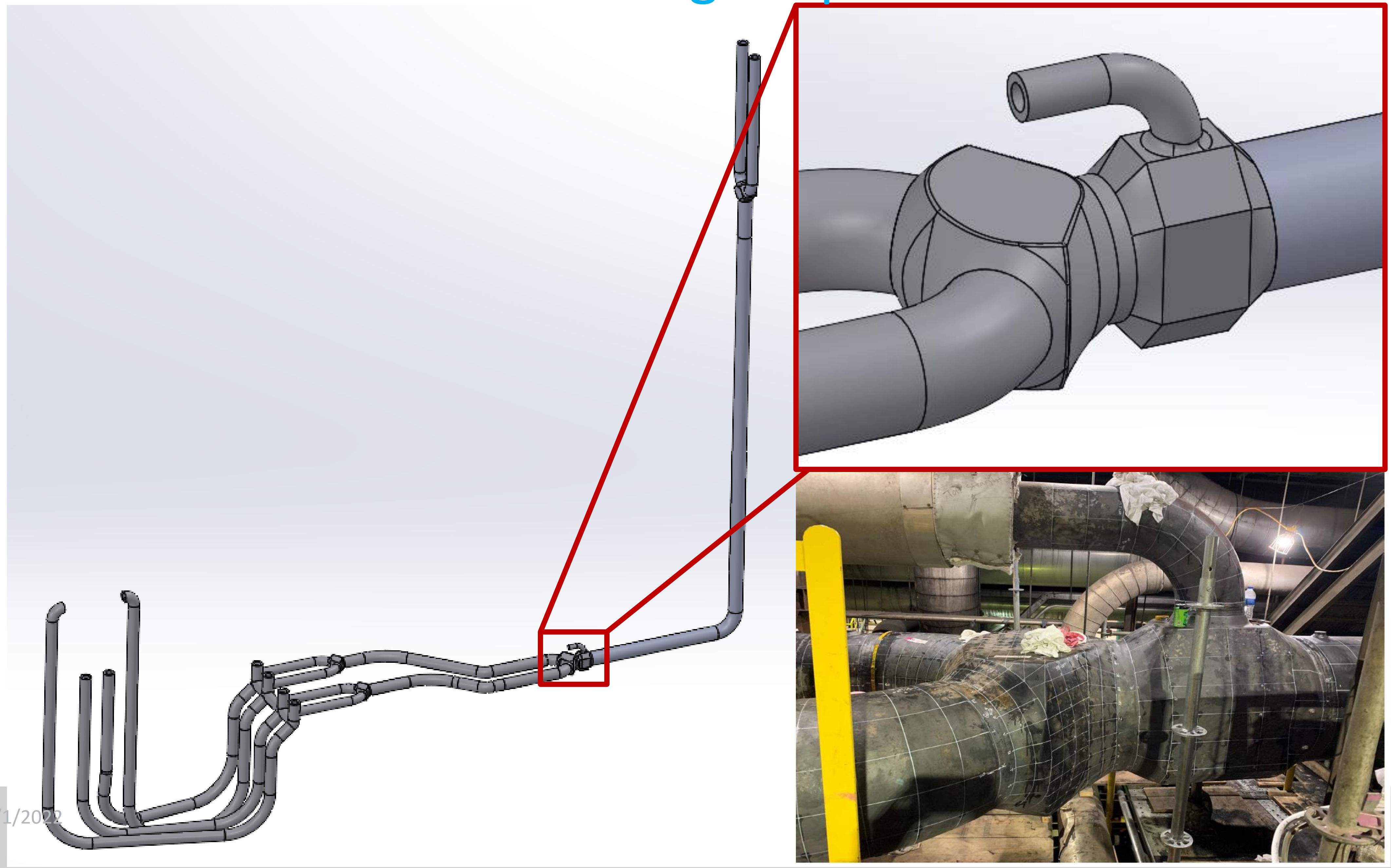


- Plant operating from 1.5 to 32 days (“Type B”) is 2X more likely than operation < 1.5 days (“Type A”) and operation > 32 days (“Type C”)
- Assigned a single “Plant On Time” to represent each operational duration “Type”
- Determined most common ordering of the three operational duration “Types.” Ordering of “Types” creates a “Group”
- Determined appropriate inclusion of overload events relative to “Groups”
- Created a single 5 hr “cycle” that captures 2 years of operational damage



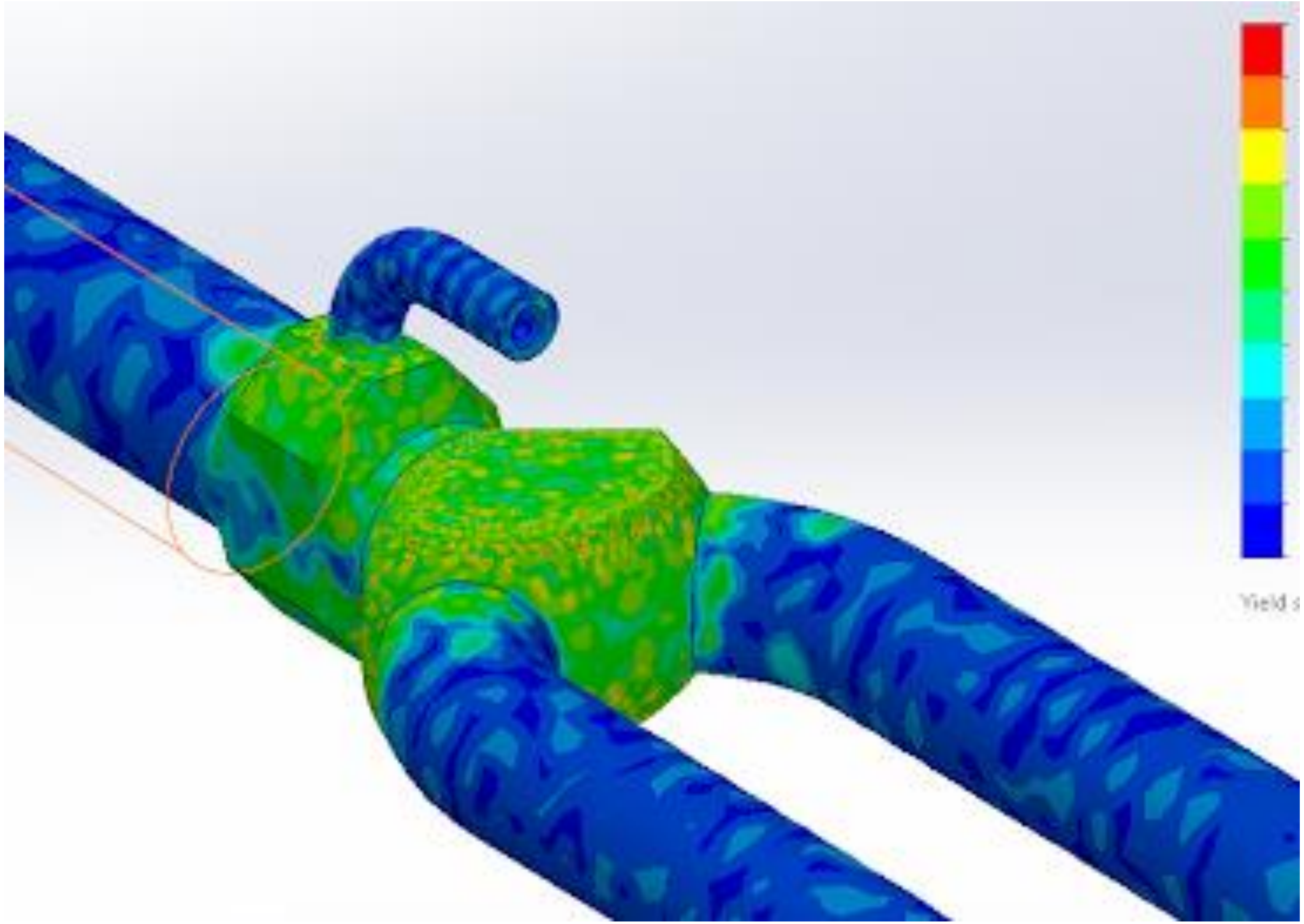


WYE-Block Modelling + Operations Data



WYE-Block Modelling + Operations Data

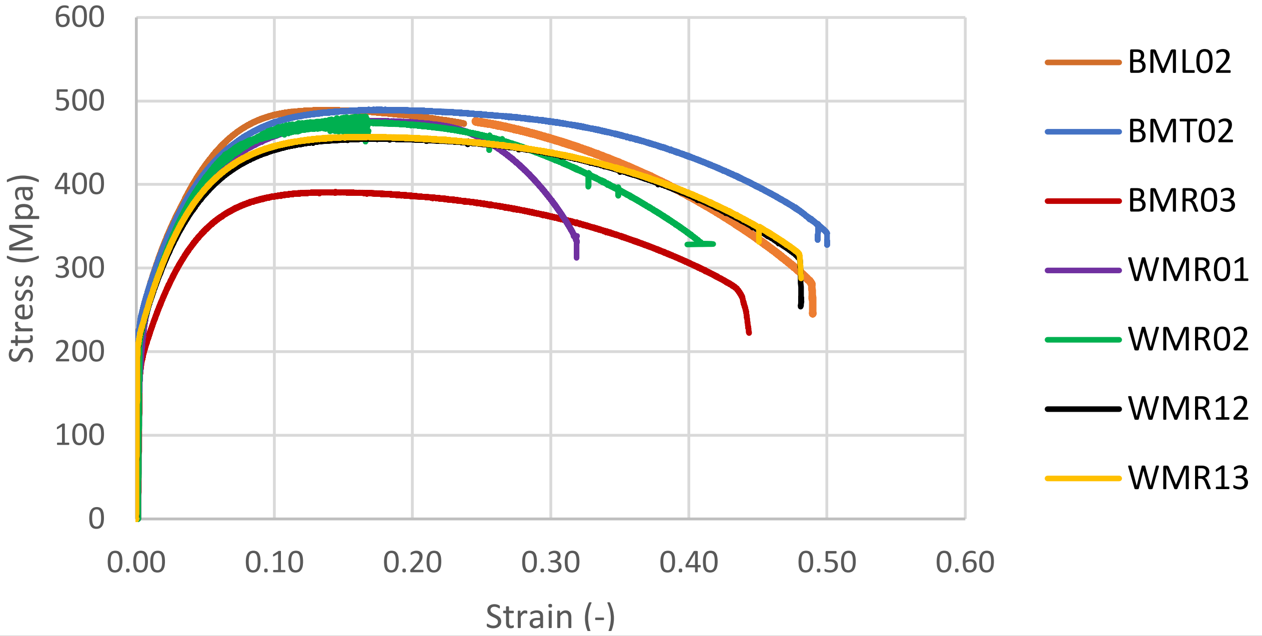
- BC's:
  - Vertical fixity at top-most pipe header
  - Full fixity at turbine connections
- LC's
  - 3500 psi internal
  - 1000°F saturated
- Constitutive Model
  - *Initial* P22 BM with temperature-dependent yield stress



Initial constitutive model calibrated for monotonic loading only.
Not capturing material evolution.

WYE-Block Experimental Data

Specimen	Material	Location	Orientation	E (Gpa)	Sig_Y (Mpa)	UTS (Mpa)	E_f (-)
BML02	P22	Base Metal	Longitudinal	204.6	239.0	489.5	48.9
BMT02	P22	Base Metal	Transverse	199.2	241.0	489.8	50.0
BMR03	P22	Base Metal	Radial/Out	170.4	194.0	391.2	43.8
WMR01	P22	Weld HAZ	Radial/Out	200.0	188.0	476.1	32.0
WMR02	P22	Weld HAZ	Radial/Out	212.3	228.9	481.5	50.0
WMR12	P22	WELD	Radial/Out	212.0	222.7	455.8	48.1
WMR13	P22	WELD	Radial/Out	210.2	223.9	457.5	48.1

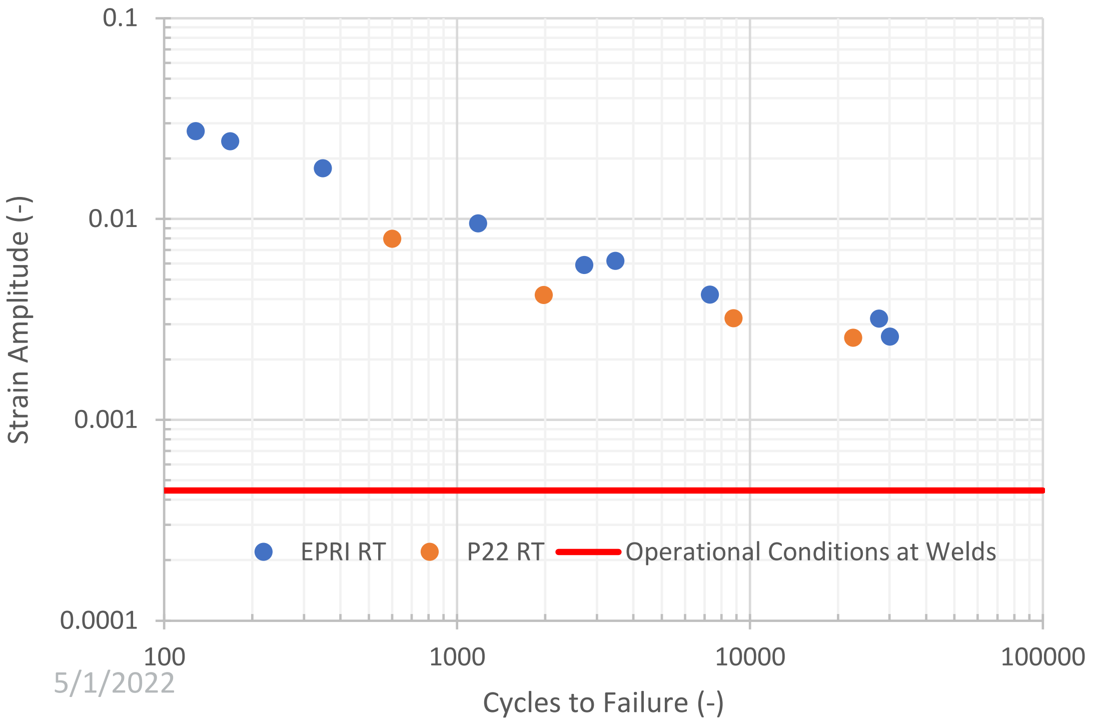


- RT monotonic testing complete
- Base Material (BM) and Weld Material (WM) exceptionally ductile (material removed from service is overaged (behaves as annealed)).
- BM is exhibiting transversely isotropic monotonic response (Radial orientation weaker).
- WM exhibiting considerable scatter in elongation to failure.

WYE-Block LCF Experimental Data

- RT LCF testing complete
  - Fully reversed testing (R = -1) found to be problematic due to (extreme) material ductility
  - Fully reversed test data typically required to create constitutive model which incorporates material evolution

Symbol	Temperature °C	°F	Cycling Rate (cpm)	Hold Time in Maximum Strain Position (minutes)	Elapsed Time (minutes)
○	RT	RT	1	0	1
●	600	1100	1	0	1
△	600	1100	1	30	31
▲	600	1100	1	300	30t



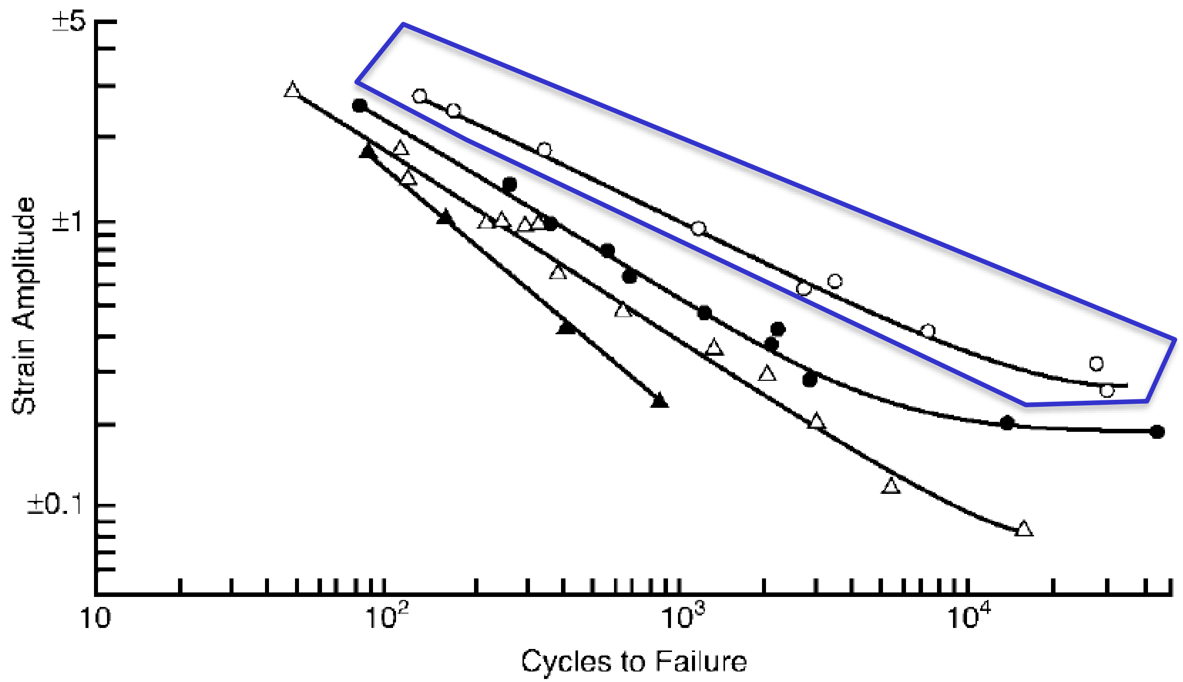
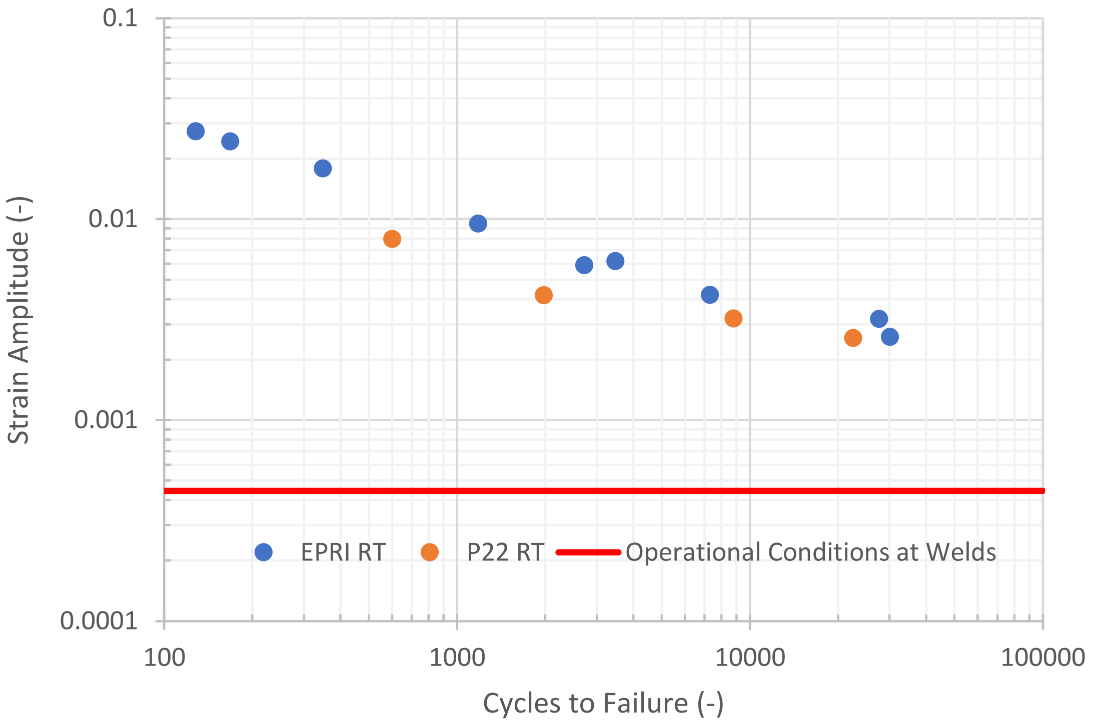


Figure 5-18
Test Results for 2-1/4Cr-1Mo Steel Showing That Holding at High Temperature Significantly Reduced the Number of Cycles to Failure [18]

WYE-Block LCF Experimental Data

- HT LCF testing notes
  - HT LCF testing is required for calibration of cyclic constitutive model which captures history-dependent material evolution
  - Difficulty collecting RT data indicated that HT testing not possible at R = -1



Symbol	Temperature °C	°F	Cycling Rate (cpm)	Hold Time in Maximum Strain Position (minutes)	Elapsed Time (minutes)
○	RT	RT	1	0	1
●	600	1100	1	0	1
△	600	1100	1	30	31
▲	600	1100	1	300	30t

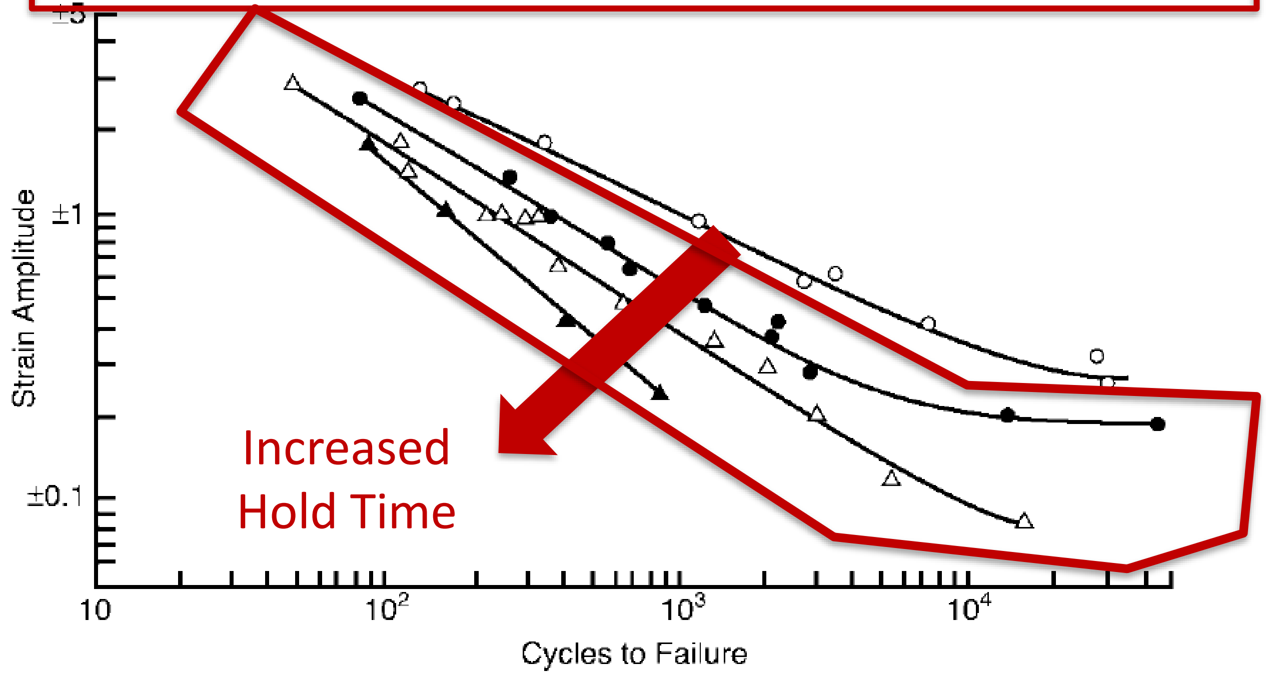
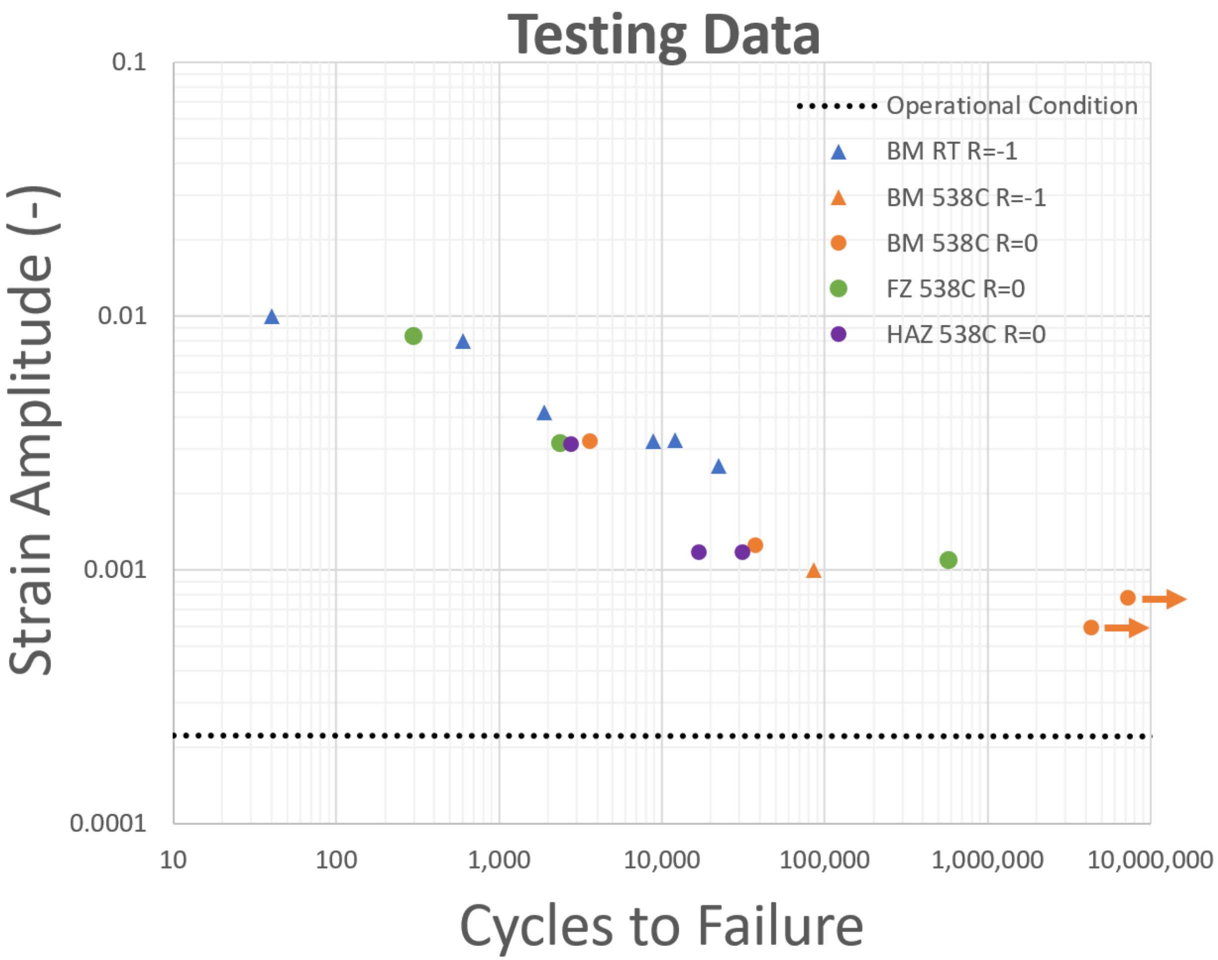
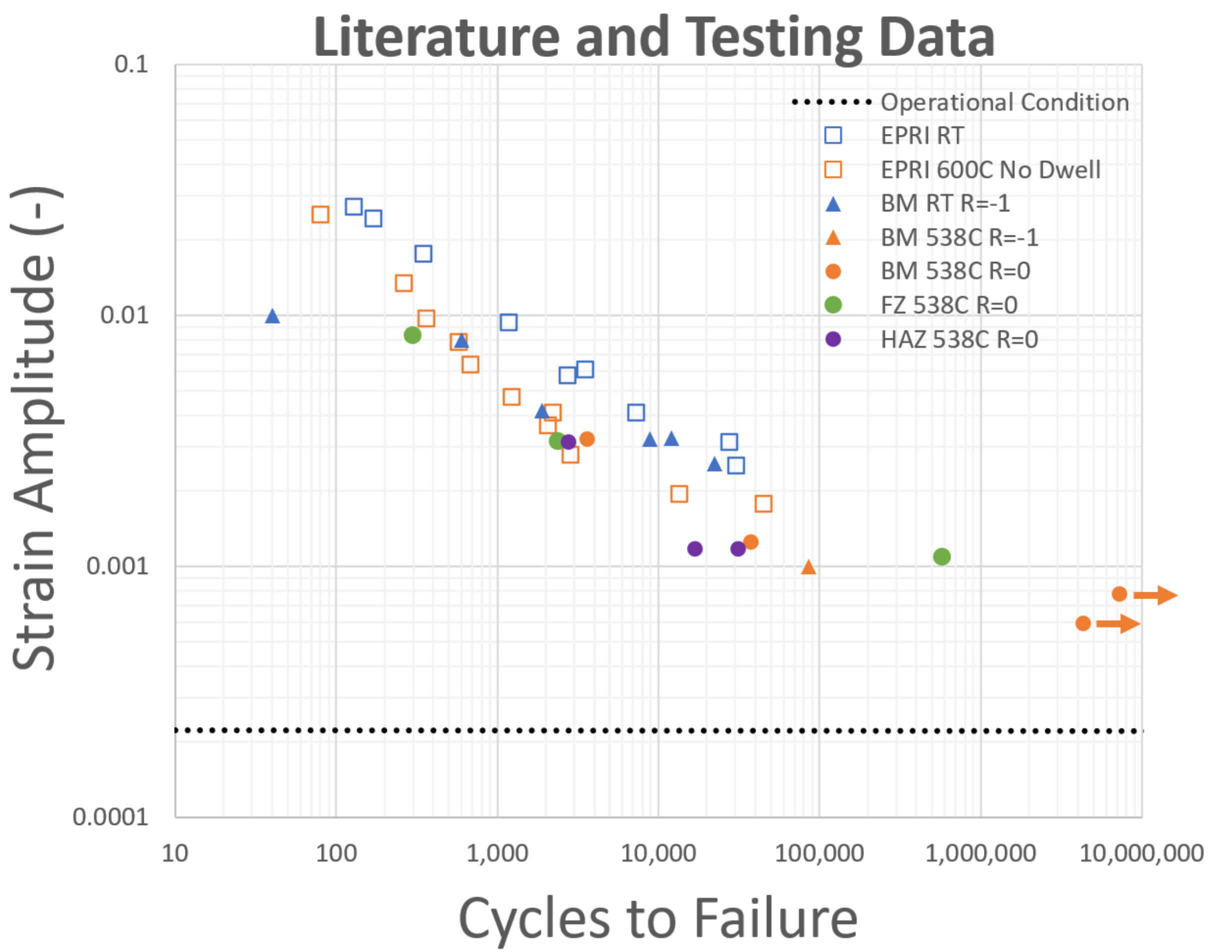


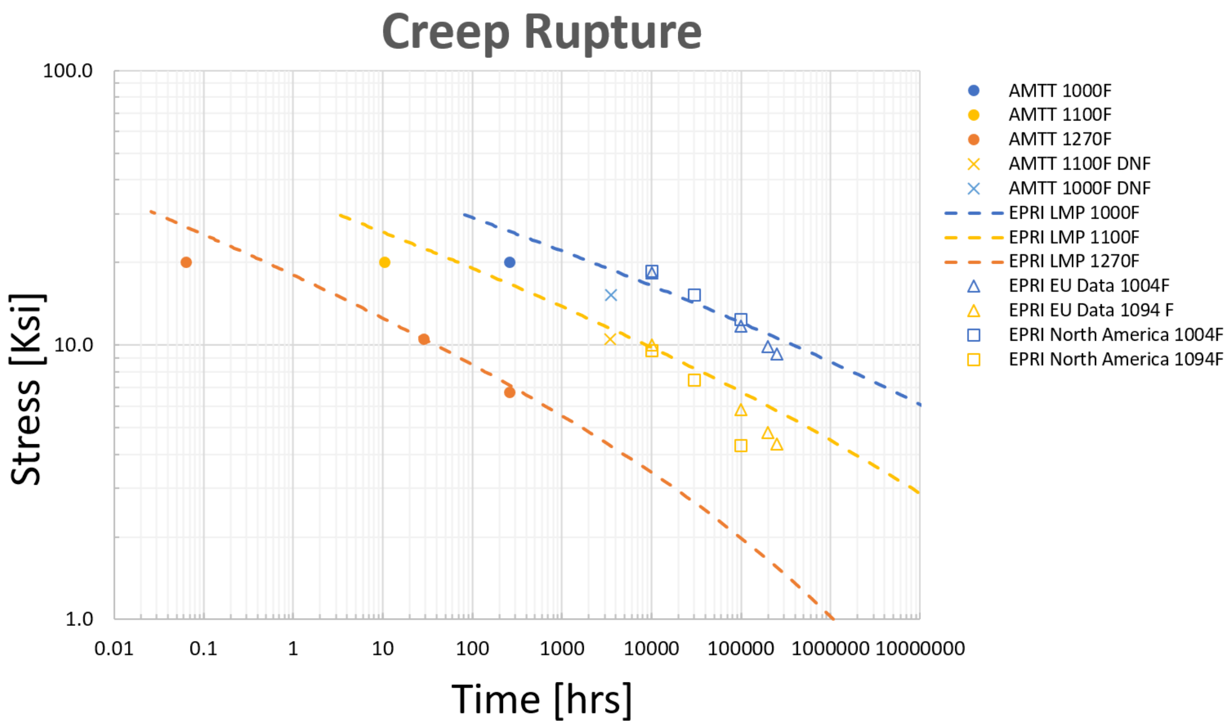
Figure 5-18
Test Results for 2-1/4Cr-1Mo Steel Showing That Holding at High Temperature Significantly Reduced the Number of Cycles to Failure [18]

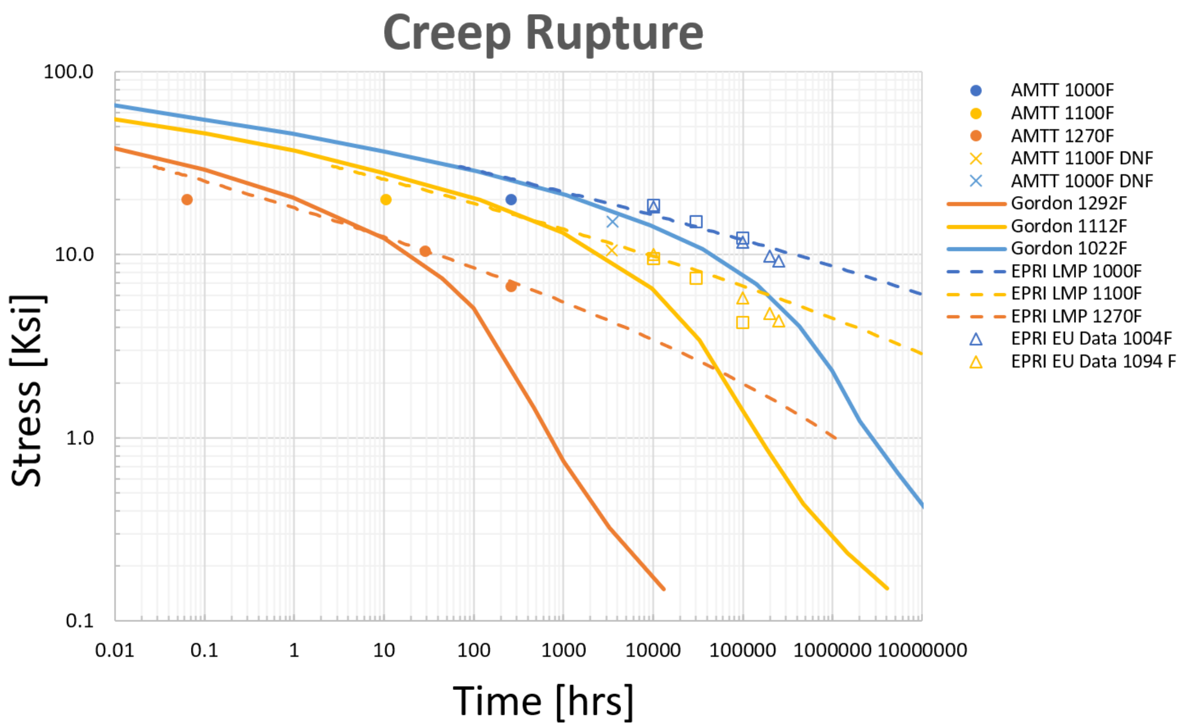
WYE-Block LCF Experimental Data





WYE-Block Creep Experimental Data





WYE Block Future Work and Program Impact

Future work:

- Creep testing 75%+ complete relative to test matrix, 50% complete relative to testing hours. Experimental data collected to date has indicated that creep testing is more valuable that certain LCF tests that were planned. Creep testing to continue throughout 2022
- HT LCF testing of base material, weld material, and heat affected zone complete. Cross-weld testing to begin in May 2022
- Calibrate material constitutive model
- Calibrate life model
- Verify and Validate combined life model

Outcomes:

- Calibrated life prediction model which accurately predicts creep-fatigue crack initiation in P22 and its welds as a function of operating conditions

Impacts:

- Reduction in the M&O costs as a result of
  - data-driven inspection and repair scheduling and
  - “retirement for a cause” replacement protocol
- Extension of the useful life of coal-fueled power plants

Questions

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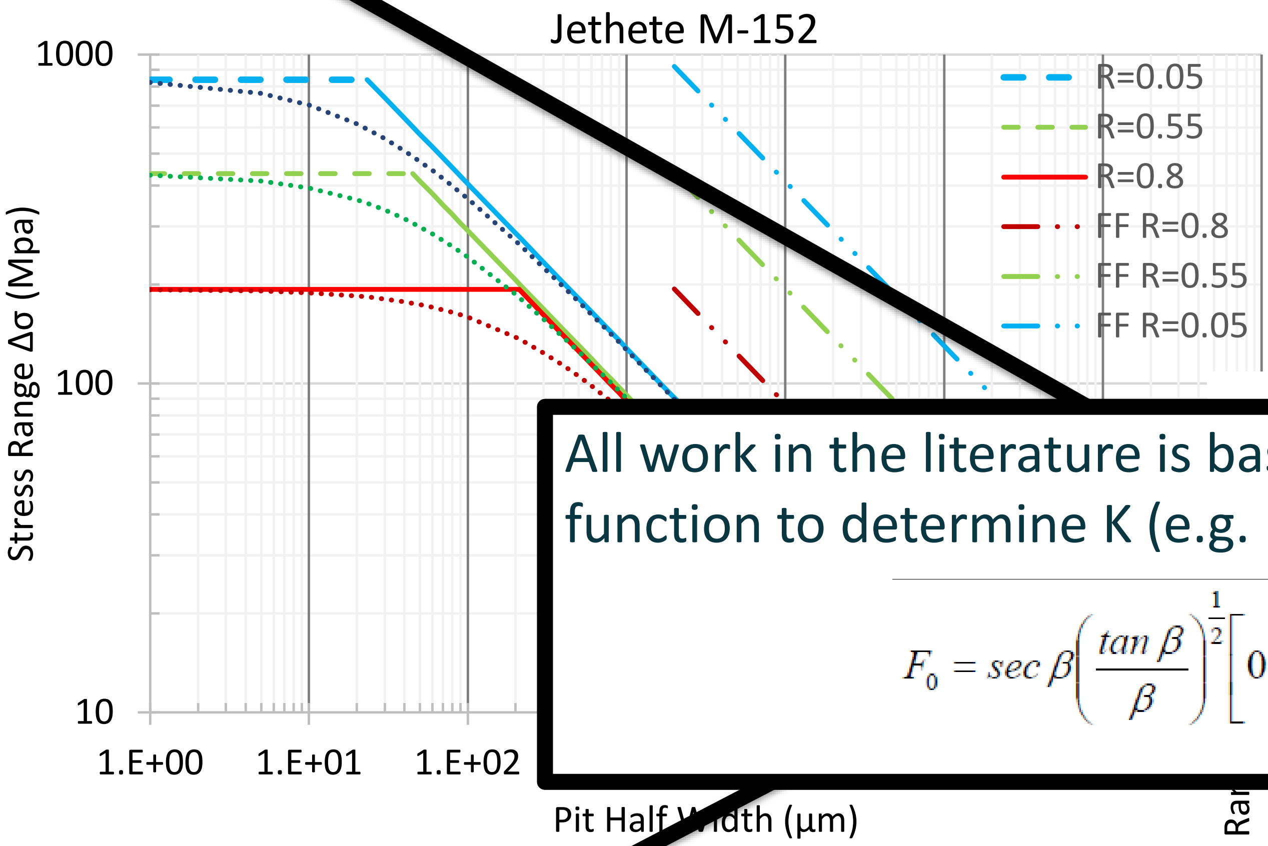
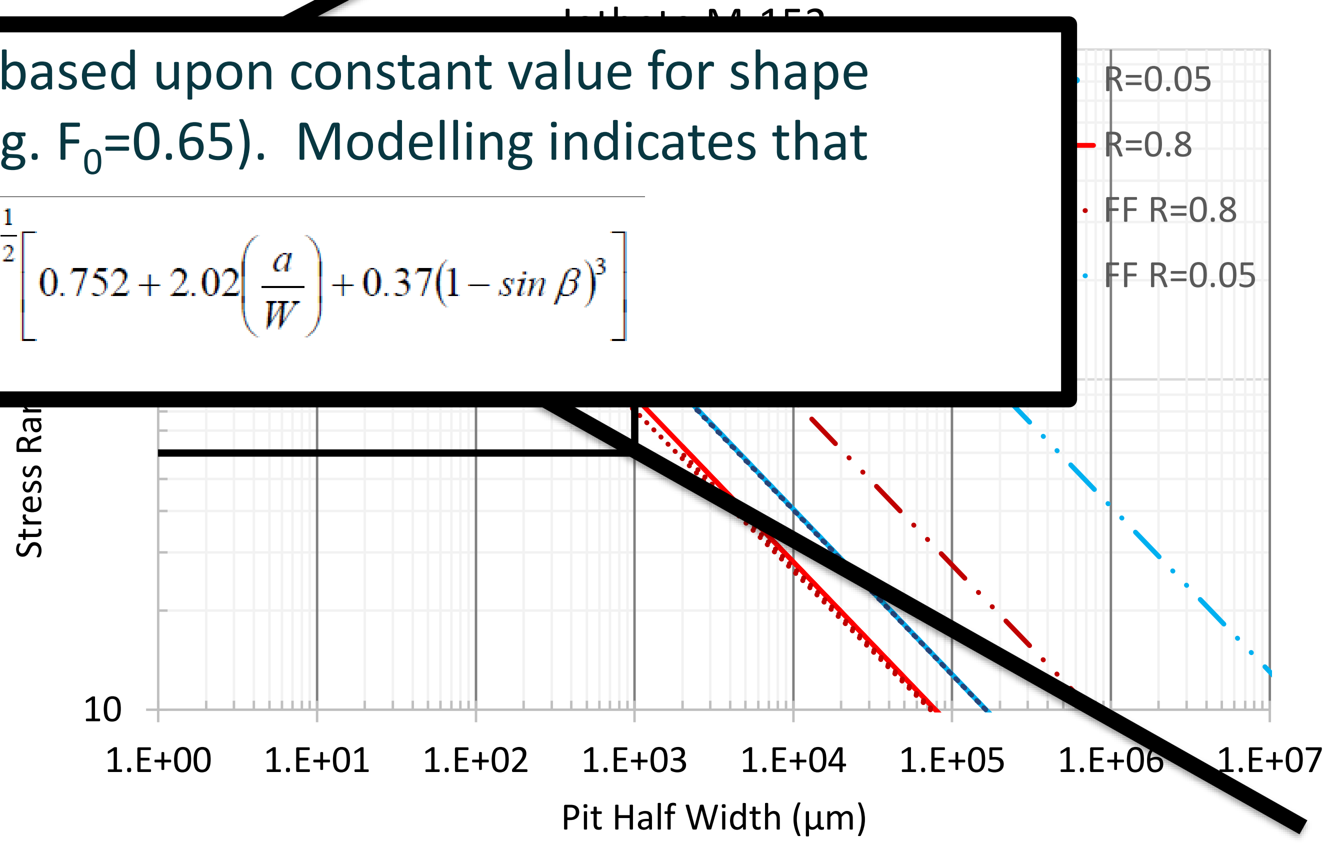
This material is based upon work supported by the Department of Energy Award Number DE-FE0031811

LSB Experimental Data



All work in the literature is based upon constant value for shape function to determine K (e.g. F_0=0.65). Modelling indicates that

$$F_0 = \sec\beta\left(\frac{\tan\beta}{\beta}\right)^{\frac{1}{2}}\left[0.752 + 2.02\left(\frac{a}{W}\right) + 0.37(1-\sin\beta)^3\right]$$

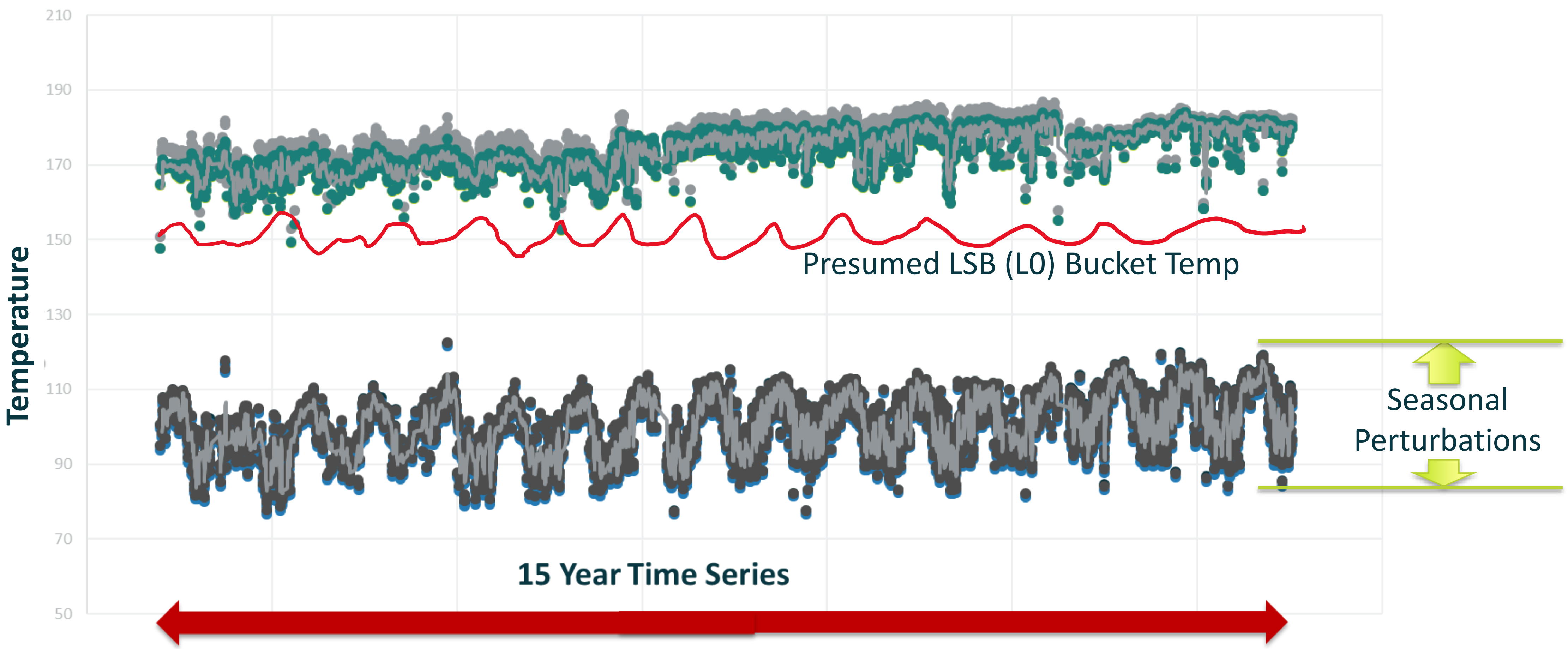


R	Δσ0	ΔK_{th}
(-)	(Mpa)	MPa√m
0.05	824.9*	4.7
0.55	426.3*	3.4
0.80	189.5	3.2

LSB Updates and Accomplishments

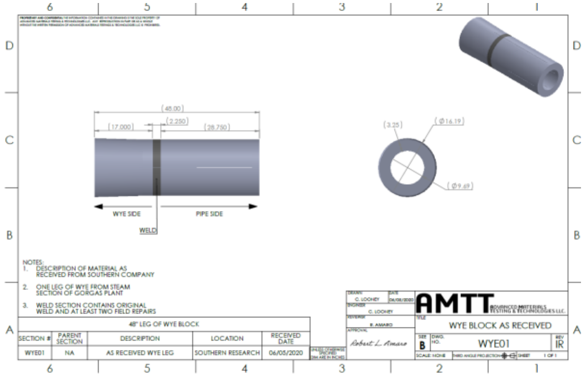
LSB operational temperature above 150°F

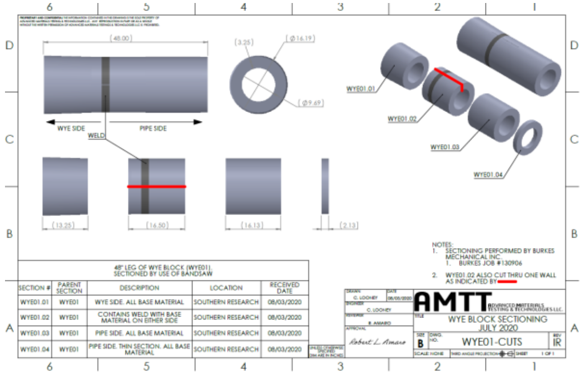
Characterization to be performed at 200°F

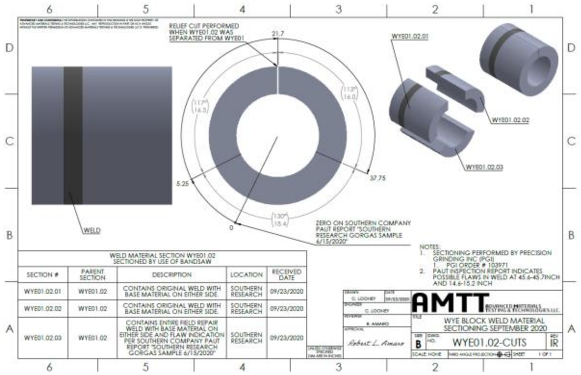


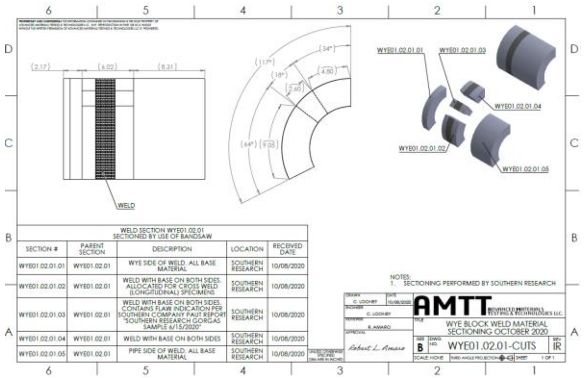
WYE-Block Material Tracking

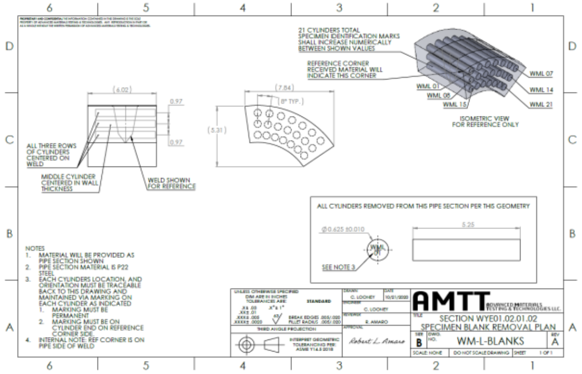
Specimen Sectioning

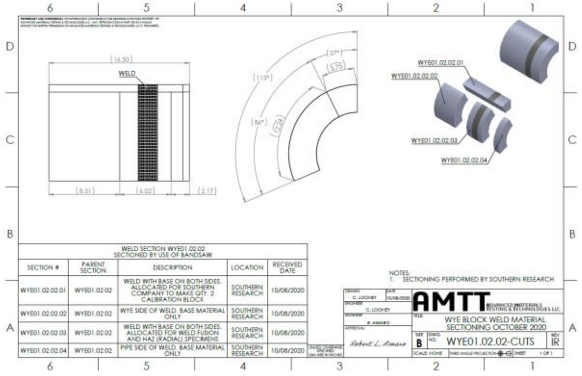


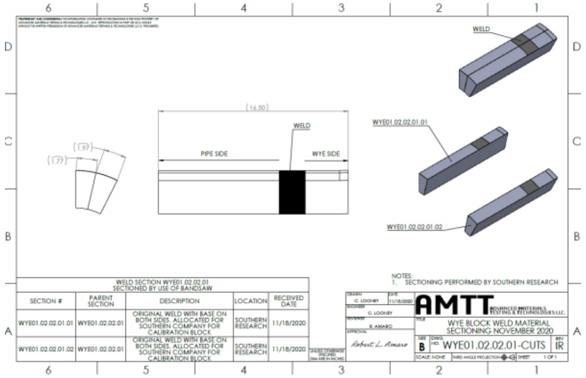


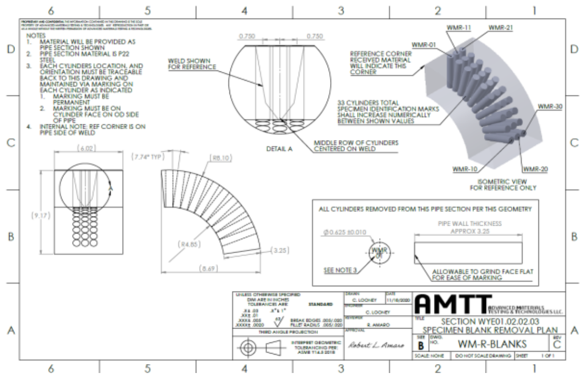


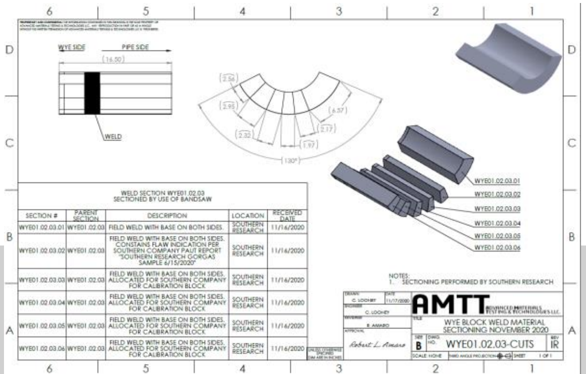


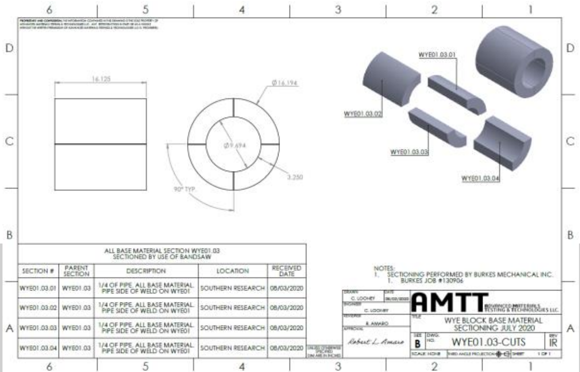


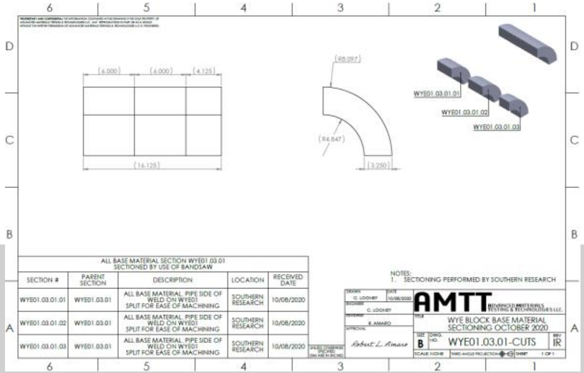


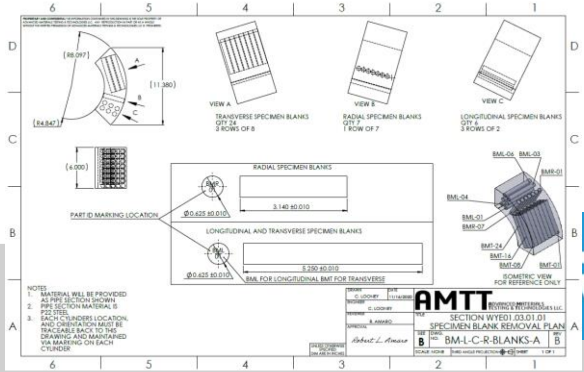






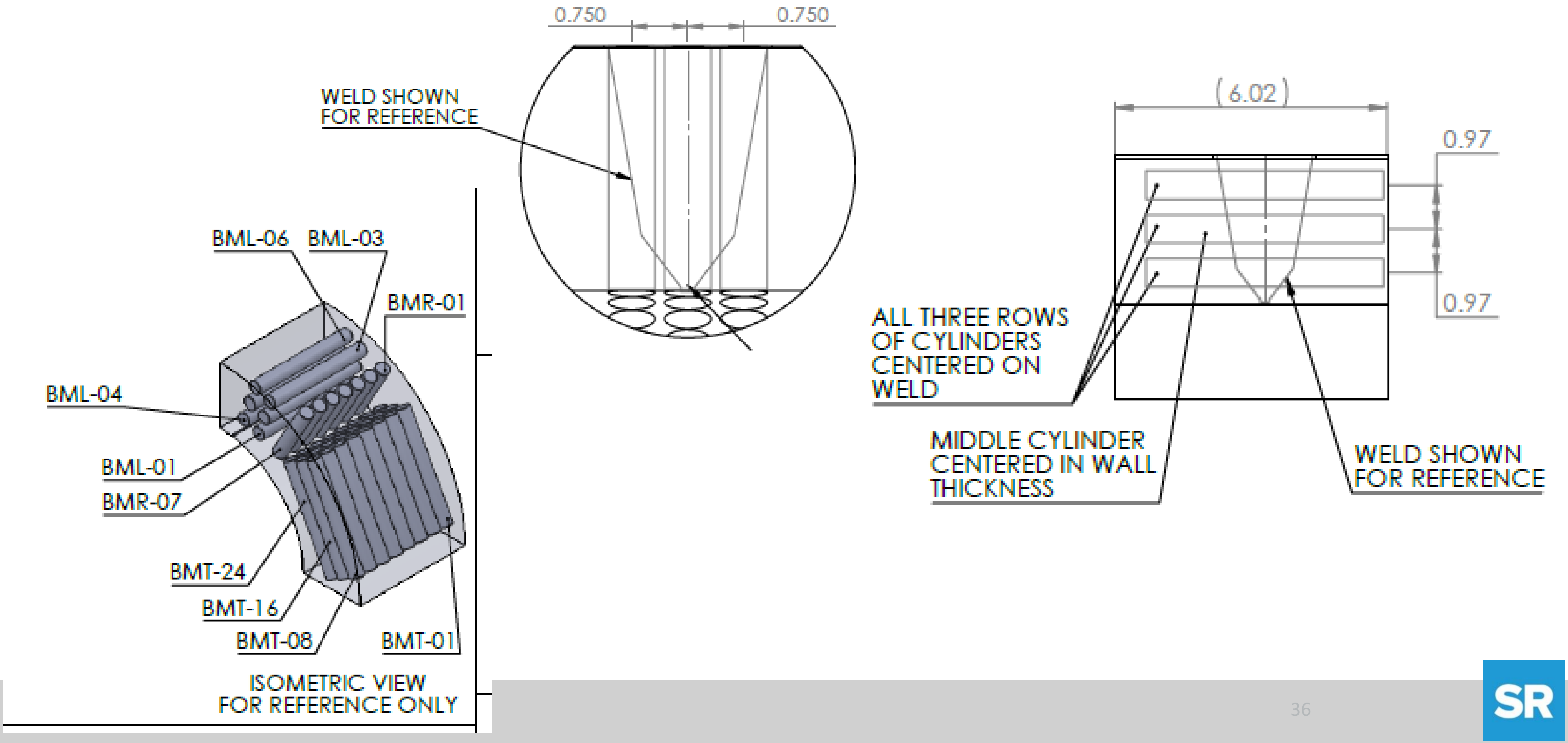






WYE-Block Weld Specimen Details

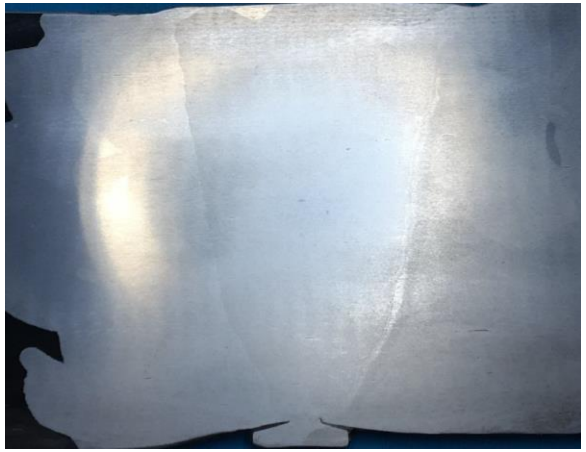
Specimen Sectioning

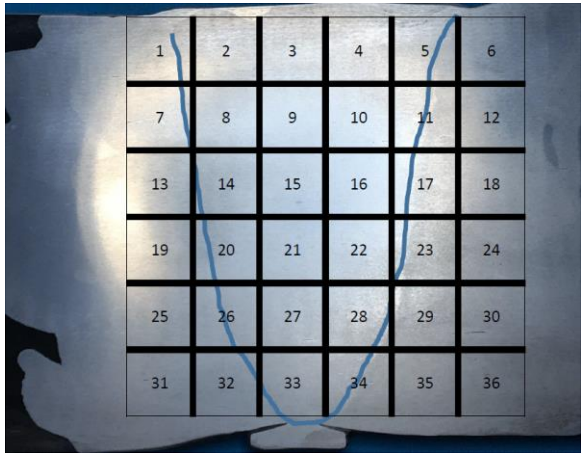


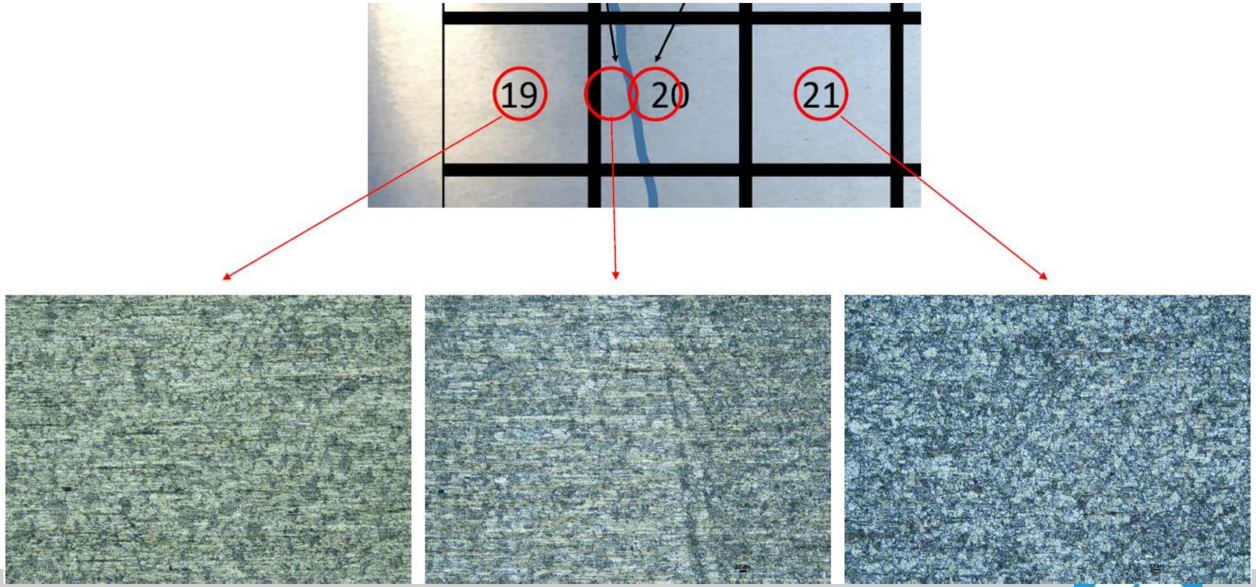
WYE-Block Updates and Accomplishments

Qualified Weld Procedure and Weld Microscopy

Reconstructed WPS					Wye Block	
Welding Processes:		GTAW/SAW			Types:	Manual/Machine
Joints						
Joint Design:	Double Angle V (Compound V) Single Groove					
Root Spacing:	0.1875"					
Backing:	YES					
Backing Material:	Backing Ring					
	Metal					
Base Metal						
	ASTM A355 Low-Alloy Steel GR P22 (UNS K91560)					
	to					
	ASTM A355 Low-Alloy Steel GR P22 (UNS K91560)					
Thickness Range:	Base metal:		3.375"			
Maximum Pass Thickness < 0.500":			YES			
Filler Metals						
		Root (GTAW)			Fill (SAW)	
Spec. No.:		Arcos (brand) Chromenar 521			EB3	SFA 5.23
AWS No.:		sim. To ER90S-B3				AWS A5.23
F-No.:						
Gas						
				% Composition		
		Gas(es)		Mixtures	Flow Rates	
Shielding:						
Trailing:						
Backing:						
Other						
Preheat						
Preheat Temperature, Minimum:			500F			
Interpass Temperature, Maximum						
Preheat Maintenance						
Other:			Rate of heating not to exceed 600F per hour			
PostWeld Heat Treatment						
Temperature Range:			1325F +/-25F			
Time Range:			7 hours			
Other:			Rate of heating not to exceed 600F per hour.			
			Cooling rate shall be controlled at a rate of 200F per hour			
			until a temperature of 600F is reached.			







WYE-Block Testing

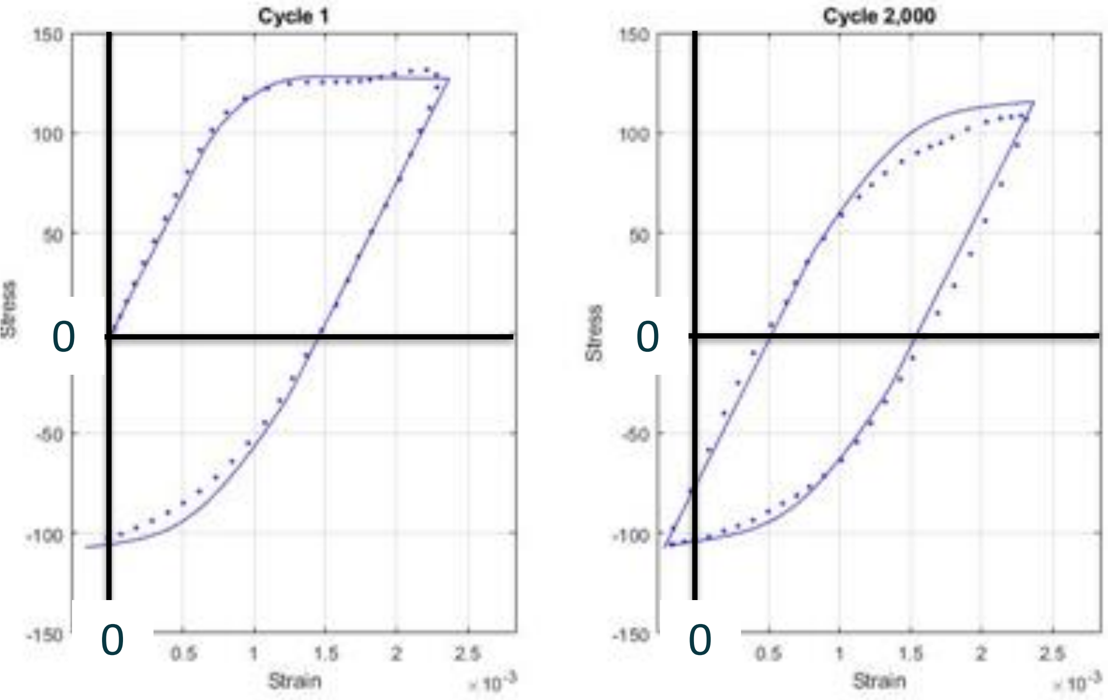
Test Matrices

		Total Specimen Counts		Specimens Per Test												
		Total Blanks	Total Machined	Monotonic RT	Monotonic HT	LCF RT	LCF 1000F (A)	LCF 1000F R=0.5	CF 1000F Long dwell (B)	CF 1270F long dwell (B)	CF 1270F med dwell (B)	CF 1270F Short dwell (C)	CR 1000F (A)	CR 1100F (A)	CR 1270 (A)	IS waveform
Base Matl.	Longitudinal (OD)	4	2		*		1			0	0		1			
	Longitudinal (Mid)	4	4	1	*	1 (2ND LONG	1							1	1	
	Longitudinal (ID)	4	2		*		1	1				0				1
	Transverse (OD)	10	6	1	*	5										
	Transverse (Mid)	10	6		*							0	1	1	2	1
	Transverse (ID)	10	5		*		1		1	1	1					
	Radial	14	4	1	*				1	1	1					1
Primary Weld	Longitudinal OD (Cross Weld)	7	7		*											
	Longitudinal Mid (Cross Weld)	7	7		*											
	Longitudinal ID (Cross Weld)	7	7		*											
	Radial HAZ (Pipe Side)	10	10	2	*											
	Radial HAZ (Wye Side)	10	1		*											
	Radial Fusion	10	10	2	*											

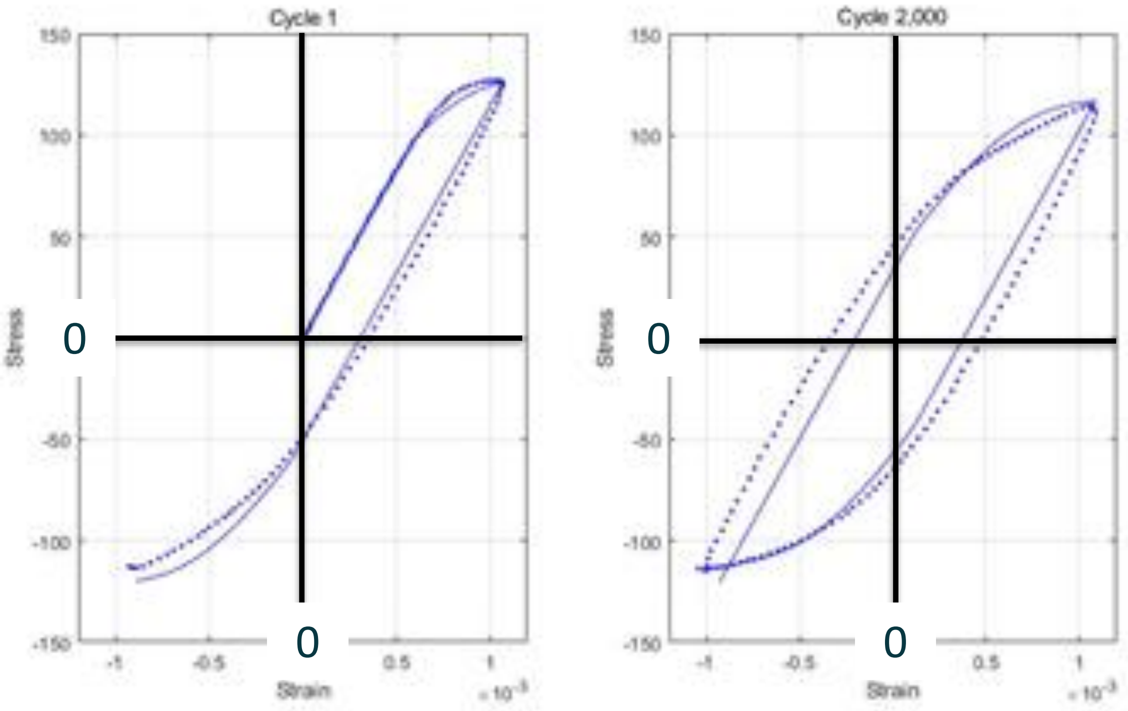
WYE-Block Modelling

HT LCF Modelling to enable testing at R = 0.05 (not fully reversed at R = -1)

- Modelling results indicate that calibration of an elevated temperature constitutive model for P22 steel by use of not-fully reversed experimental data is sufficiently able to capture elevated temperature material evolution at R=-1
- Program will reconfigure test matrices to perform HT testing at R=0.05 (specimens will never be loaded by use of negative mechanical strain)



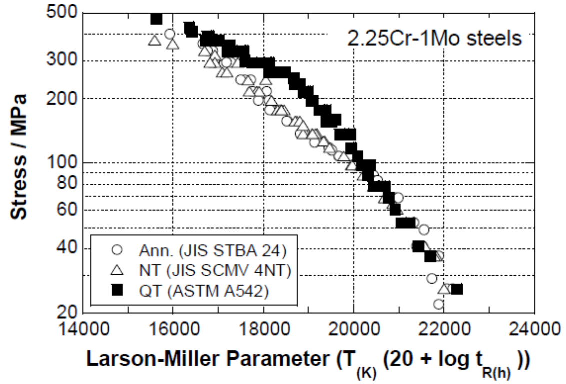
Constitutive model calibration for R=0.1 data, proof of efficacy

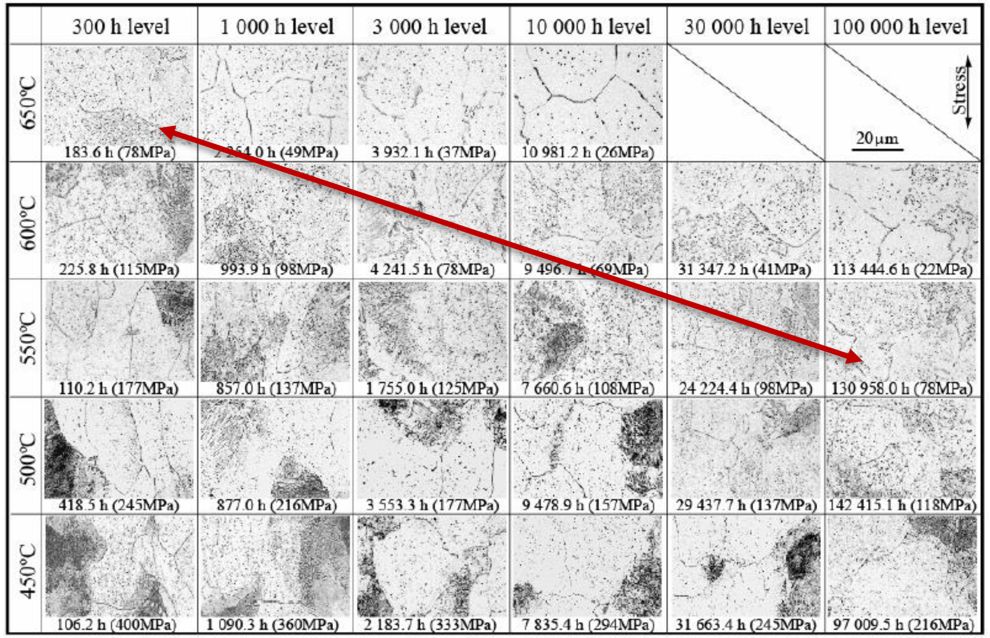


Constitutive model prediction for R=-1 data

WYE-Block Testing

Representative 2 year period captured by approximately 5 hour test "cycle"





Kushima et al Metallographic Atlas for 2.25Cr-1Mo… 2005

Type	Operational Plant On Time (days)	Test hold time at temperature (s)	Operational Max Temp (F)	Test Max Temp (F)	%Difference in Operational v. Test LMP
A	1.5	35.5			1.09
B	30	710	1000	1270	.03
C	60	1420			.27