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

DE-FE0031811 15th June 2021, 11:10 AM

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

Outline

- Background and Objectives
- Last Stage Bucket Project Update and Accomplishments
- Wye-Block Project Update and Accomplishments
- Changes and/or Problems Encountered to Date
- Future Work and Schedule
- Questions

Background and Objectives

- L-0 Last Stage Bucket (Turbine Blade) Water Droplet Erosion is a somewhat common, and very severe issue facing steam turbine operators
  - Can failures be predicted from operational data and inspection findings?

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

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)

Background and Objectives

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

Last Stage Bucket Leading Edge Erosion

- Recent inspection of GE D11 unit with 20 years of service revealed severe erosion.
- Similar findings on coal unit LSBs with 30+ years of service.

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

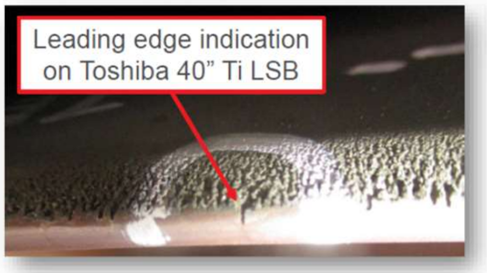
Failure Mechanism of Interest:
Cracks emanating from erosion pits

Background and Objectives

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

Industry Importance- Coal fleet challenges related to LSB erosion:

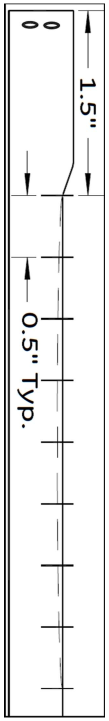
- Low load operation and frequent cycling
- LSB failure could result in retirement of older coal unit
    - Must reduce risk of failure
- Budget impact
    - Monitor/predict LSB life to prevent catastrophic failure OR preemptive replacement

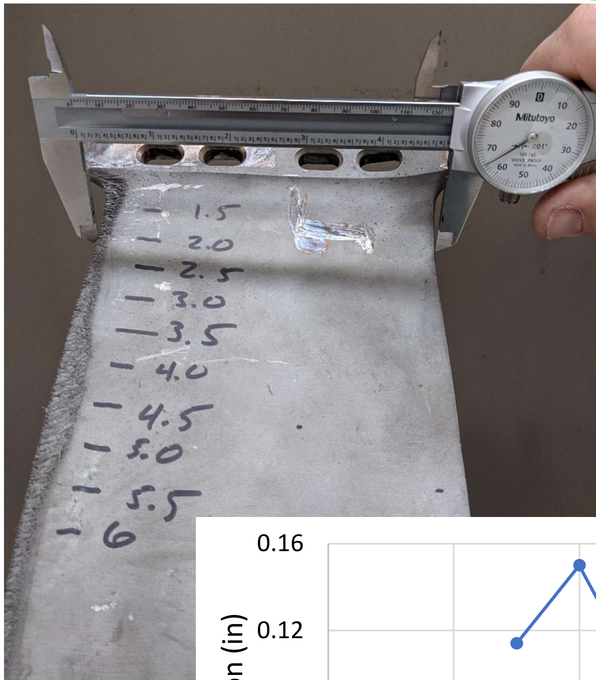


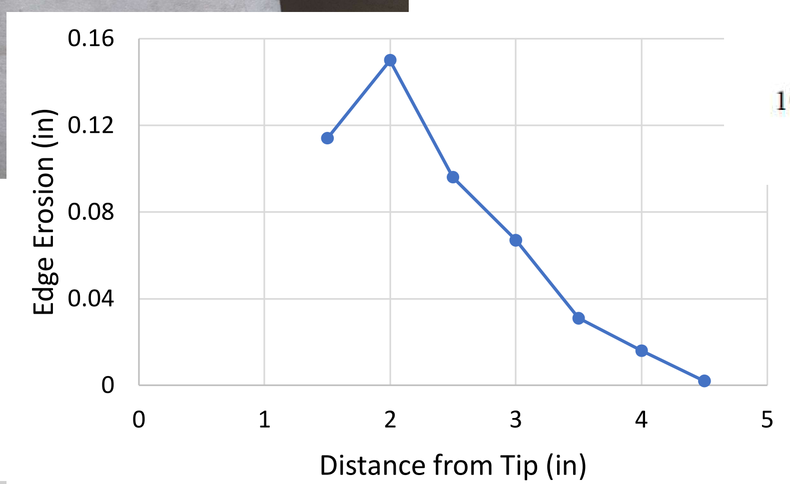
- Many GE coal steam turbines are equipped with 30” or 33.5” Jethete LSBs.

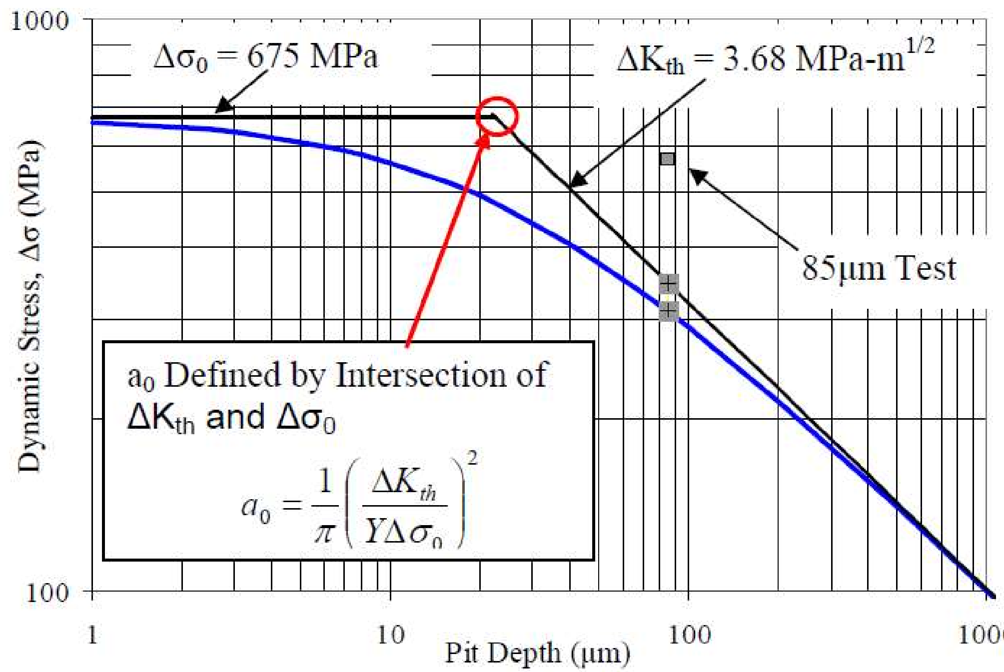
- Southern Company likely has 33.5” GE self-shielded LSBs on-hand that can be used for this research.
    - Covid has prevented the replacement of these buckets.

Background and Objectives



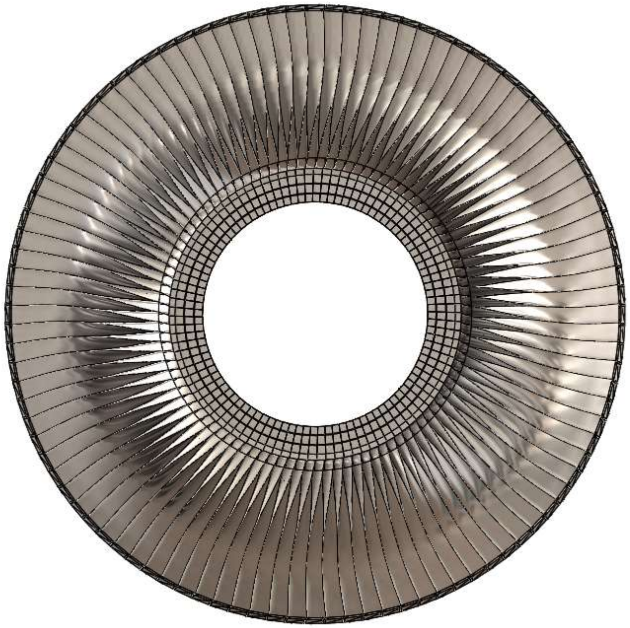


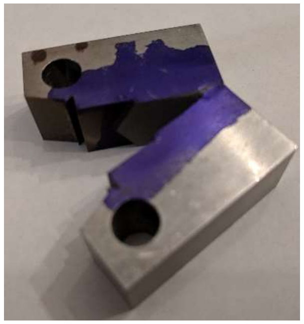




LSB Updates and Accomplishments

- Solid model of Last Stage Bucket (LSB or L0) created by use of 3-D scanning of Southern Company supplied blade
  - Local stress state quantified along length of LSB
- Analyzed operations and inspection data
  - Determined temperatures of interest
  - Characterized operational “cycles”
- Materials characterization testing ~80% complete
- Life modelling architecture (Kitagawa Diagram) initialized

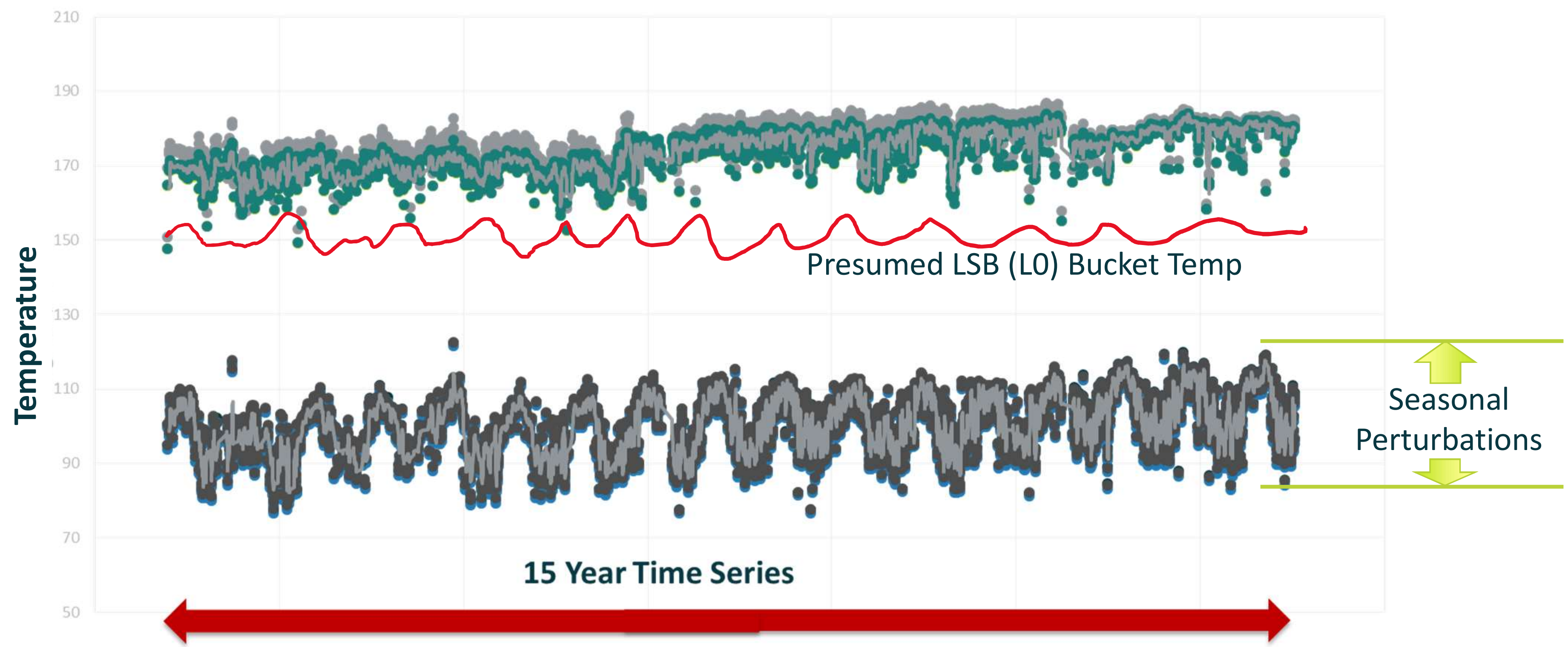




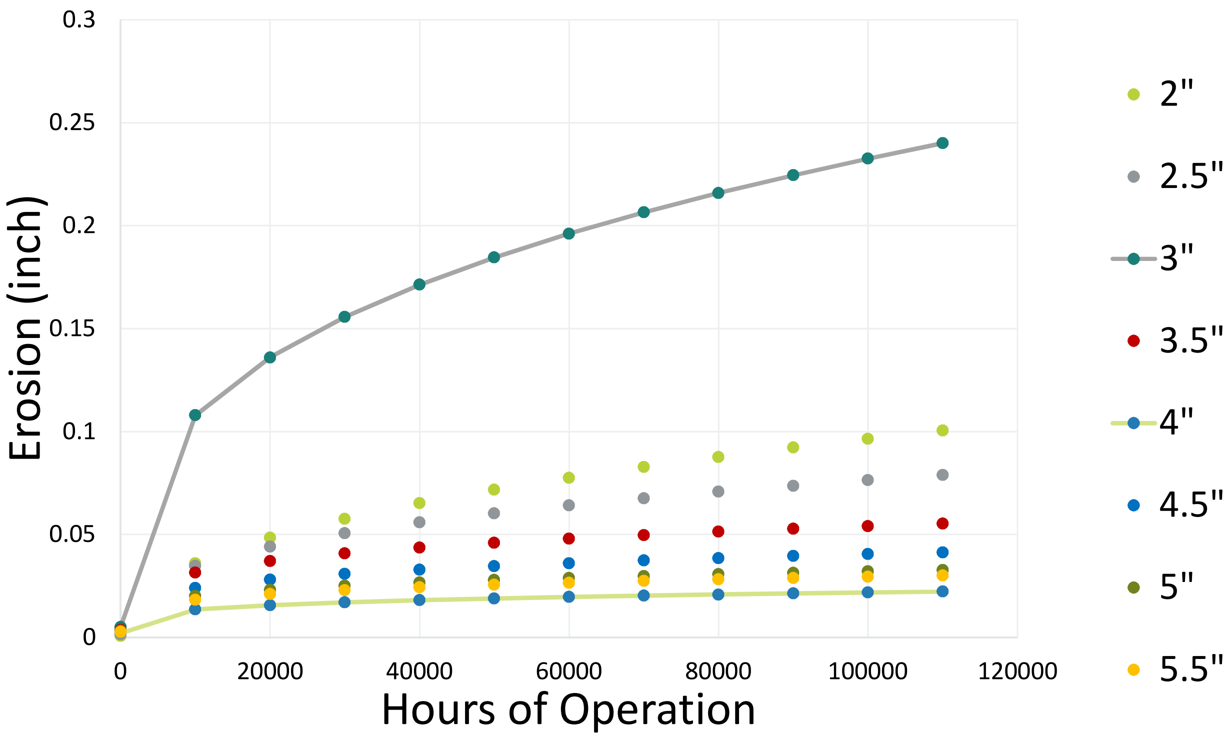
LSB Updates and Accomplishments

LSB operational temperature above 150°F

Characterization to be performed at 200°F



LSB Updates and Accomplishments

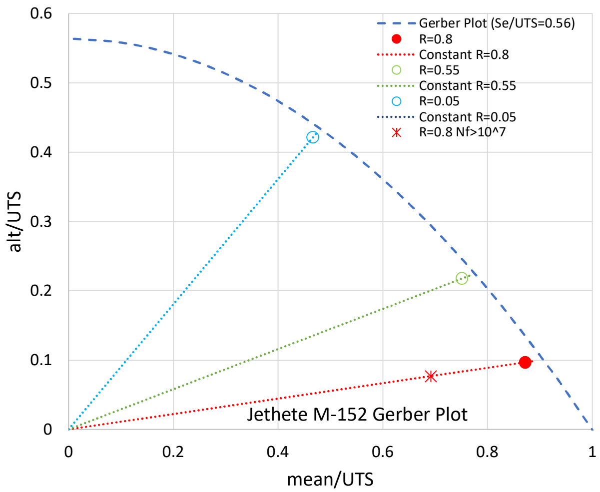


Analysis of 18 years of erosion inspection data for four facilities indicates:

- There are **no** clear correlations between turbine "starts" or hours of operation and erosion rate for **most** locations measured.
- However, there **are** correlations between hours of operation and erosion rate and turbine "starts" and erosion rate at 3" location.

- **There is a single location of greatest interest** for future inspection/monitoring.
  - Inspection of the L0 Buckets at 3" location (down from tip) is critical, as this region exhibits highest erosion rates

LSB Updates and Accomplishments



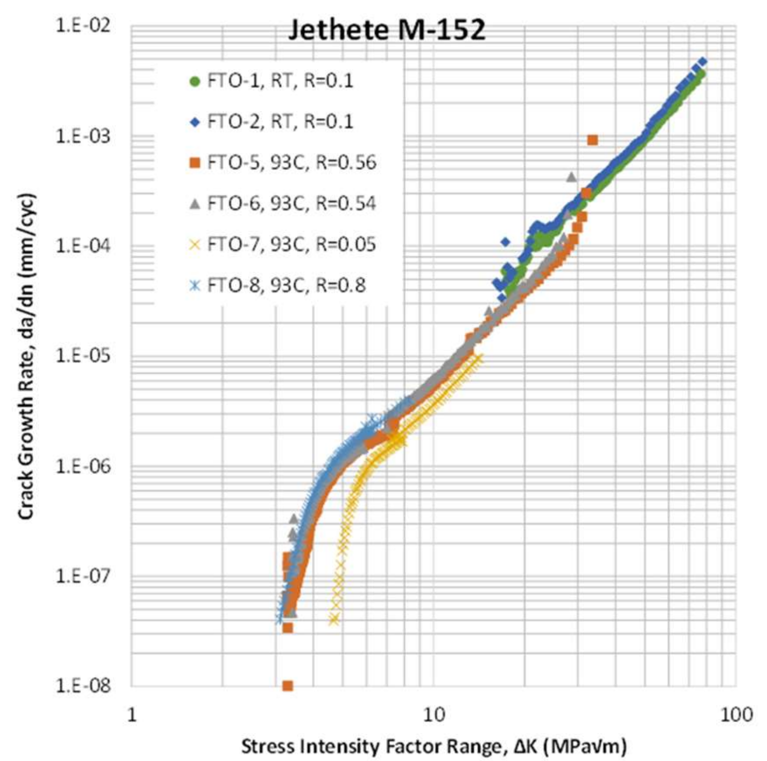
LSB FCG and FCG threshold testing complete

- FCGR and FCG_{th} insensitive to Temp between 27C and 100C
- FCGR insensitive to load ratio (R)
- FCG_{th} exhibits R-sensitivity at low R

Stress-Life testing (S-N) underway

- Data matches lit quite well

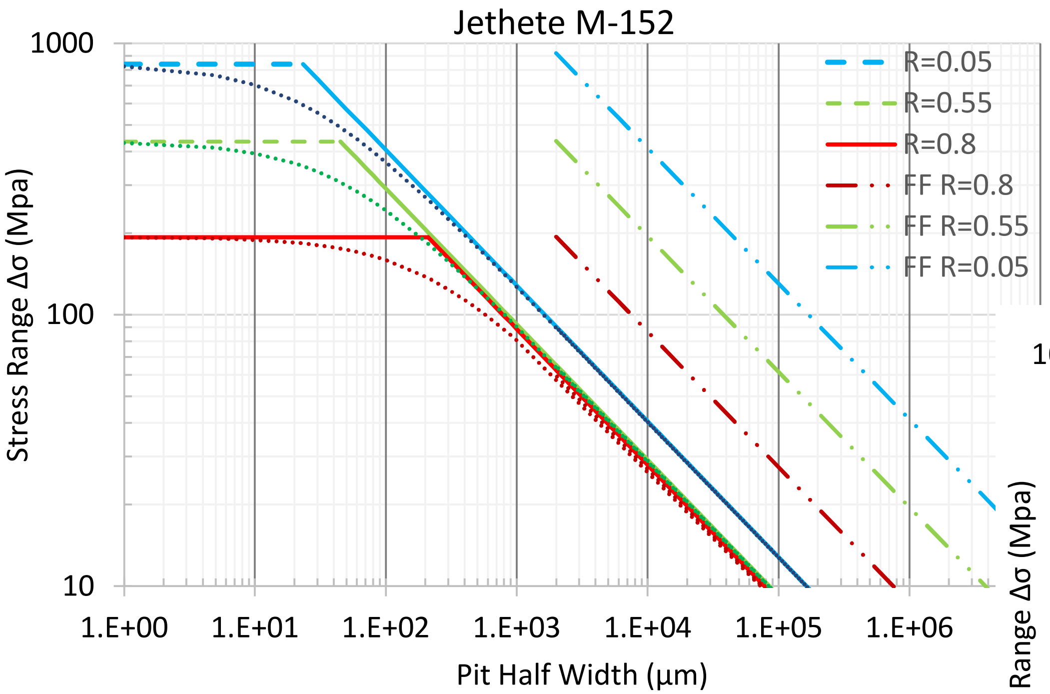
Specimn	Temp	Test	R	C	m
(#)	(deg C)	Control	(-)		
FTO-5	93	Load- increasing ΔK	0.56	1.11×10^{-8}	2.73
FTO-6	93	Load- increasing ΔK	0.54	1.21×10^{-8}	2.73
FTO-7	93	Load- increasing ΔK	0.05	8.89×10^{-9}	2.62
FTO-8	93	Load- increasing ΔK	0.8	N/A	N/A
FTO-1	27	Load- increasing ΔK	0.1	1.44×10^{-8}	2.84
FTO-2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

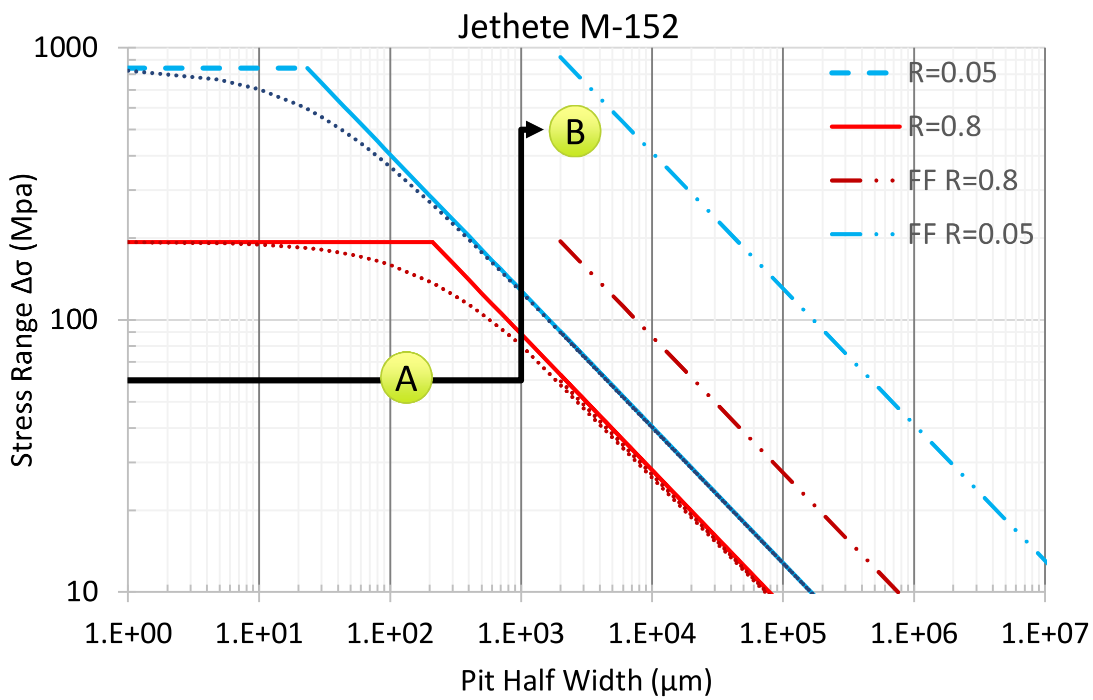
Specimen	Temp	Mean	Alt	Min	Max	Max/UTS	$\Delta\sigma_0$	R	Nf
(#)	(deg C)	(Mpa)	(Mpa)	(Mpa)	(Mpa)	(%)	(Mpa)	(-)	(10^6 cycles)
JH01L	93	676.5	75.0	601.5	751.5	77%	150.0	0.80	>10
JHC2L	93	852.6	94.7	757.8	947.3	97%	189.5	0.80	>2.5
*N/A**	*93*	*734.2*	*213.1*	*521.0*	*947.3*	*97%*	*426.3*	*0.55*	*N/A*
*N/A**	*93*	*455.9*	*412.5*	*43.4*	*868.4*	*89%*	*824.9*	*0.05*	*N/A*

LSB Updates and Accomplishments



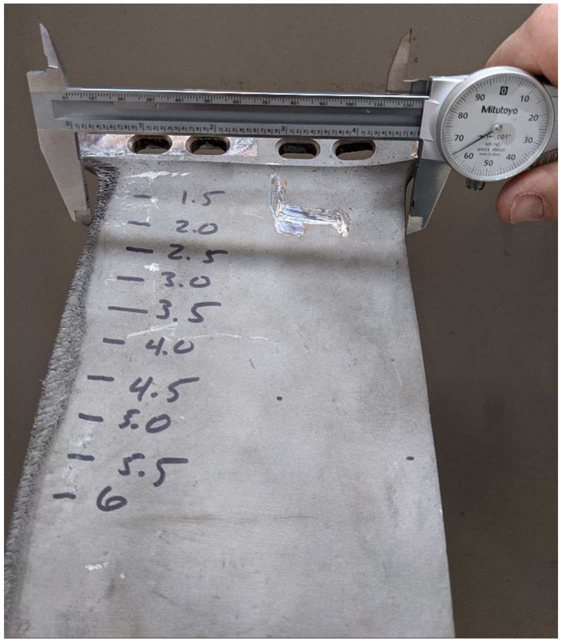
Kitagowa life diagrams preliminarily calibrated for Jethete blade material at 100C.

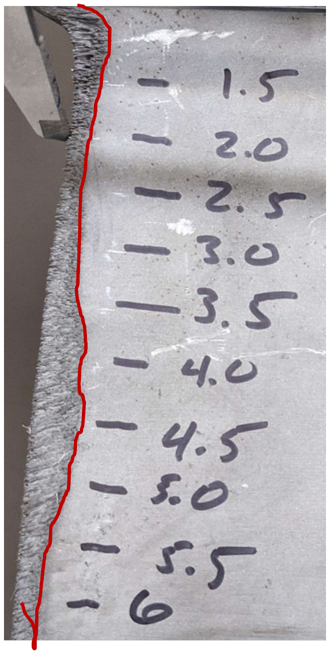
- LSB operates at R=0.8 during steady state (A)
- LSB experiences R~0.05 during startup and shutdown (B)

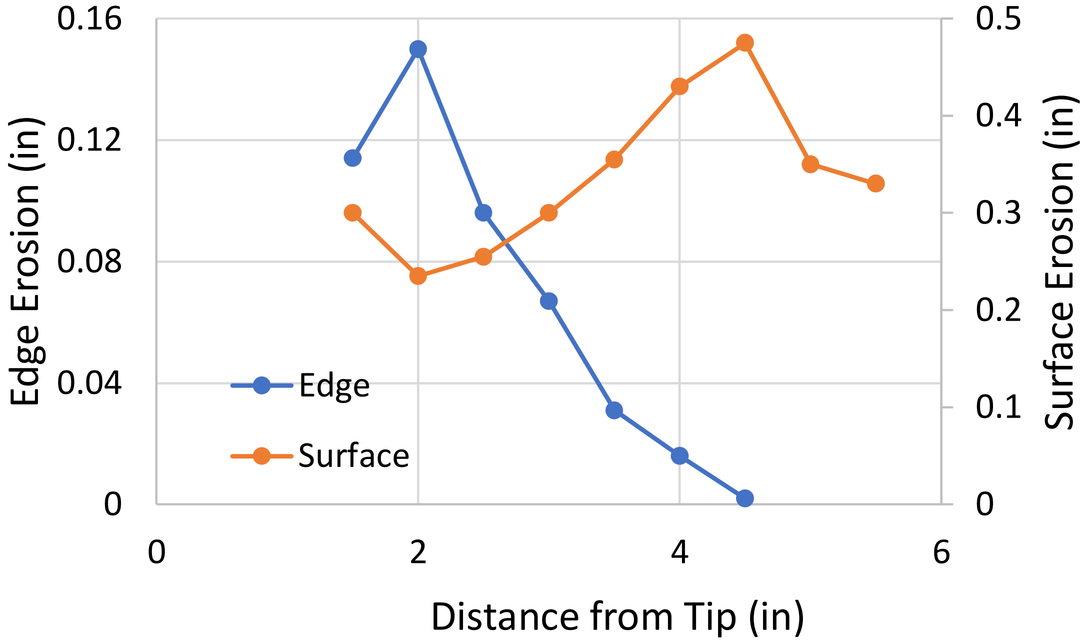


R	Δσ0	ΔK_{th}
(-)	(Mpa)	MPa-√m
0.05	824.9*	4.7
0.55	426.3*	3.4
0.80	189.5	3.2

LSB Updates and Accomplishments





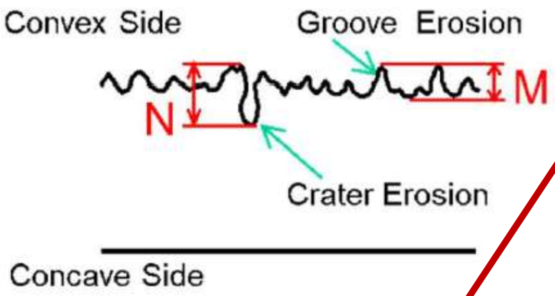


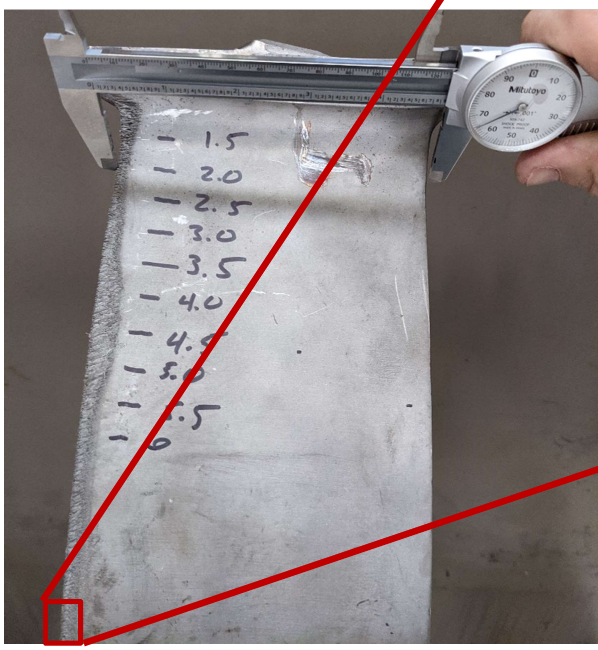
Field measurements taken during inspection performed by use of caliper

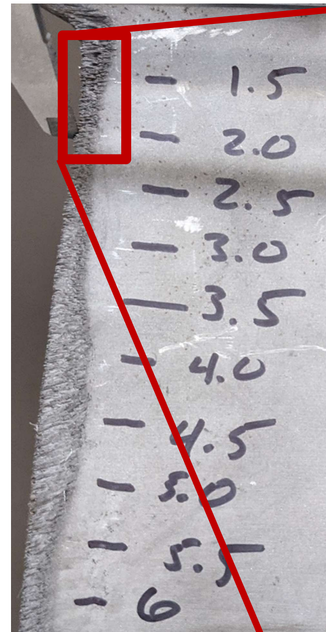
- Caliper measurements (“Edge” Data) of representative in-service blade shown in blue (note difference from 18-YR data)
- Surface erosion data (“Surface) of representative in-service blade shown in orange

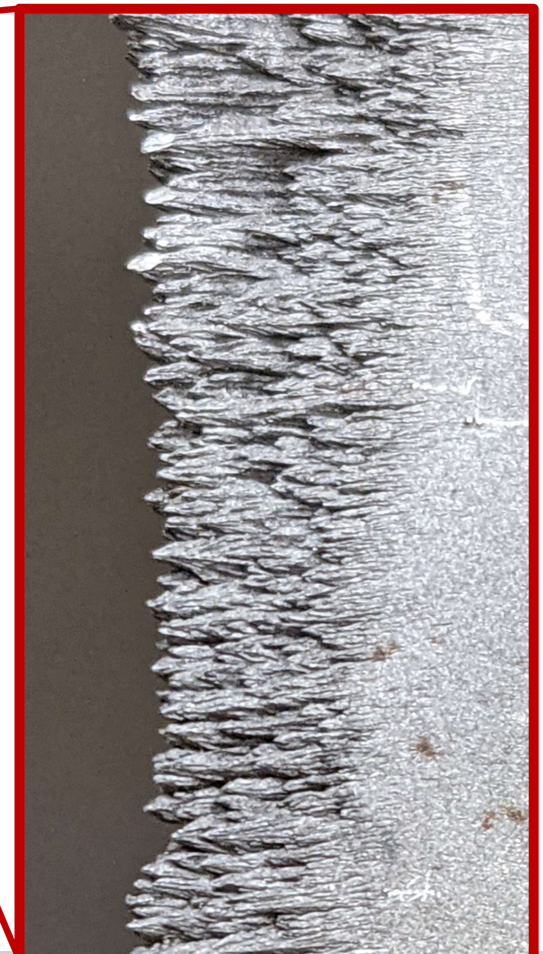
Neither measurement technique results in data that can be used to determine “crack” or “pit” size

LSB Updates and Accomplishments









- “Pitting” clearly present far from LSB tip. This is not primary location of failures.
- Pitting→”feathering” or crack present near LSB tip.

Must correlate THIS damage to Kitagowa Model

LSB Future Work

<u>JETHETE L0/LSB PROJECT</u>

1. Virgin material characterization (90% complete)
2. Analyze plant inspection data in an attempt to correlate life to inspection data (60% complete)
3. Corelate inspectable characteristics to “crack” on Kitagowa Diagram
4. Create Kitagowa Diagram (operations, maintenance, and life estimation tool) (50% complete)
5. Verification (testing and plant data)
6. Creation of model application GUI and user manual

		Quarter Start Date								
	JETHETE PROJECT	Oct-20	Jan-21	Apr-21	Jul-21	Oct-21	Jan-22	Apr-22	Jul-22	Oct-22
1	Virgin Material Characterization									
2	Plant Inspection Data- Corelate life to inspection data									
3	Corelate Inspectable characteristics to "crack" on Kitagowa Diagram									
3.a.	Testing of specimens pulled from service blades									
4	Kitagowa Diagram									
5	Verification (testing and plant data)									
5.a.	Random inspection-life verifiaction									
5.b	Random application to a series of service blade specimens									
6	Creation of Model Application GUI and User Manual									

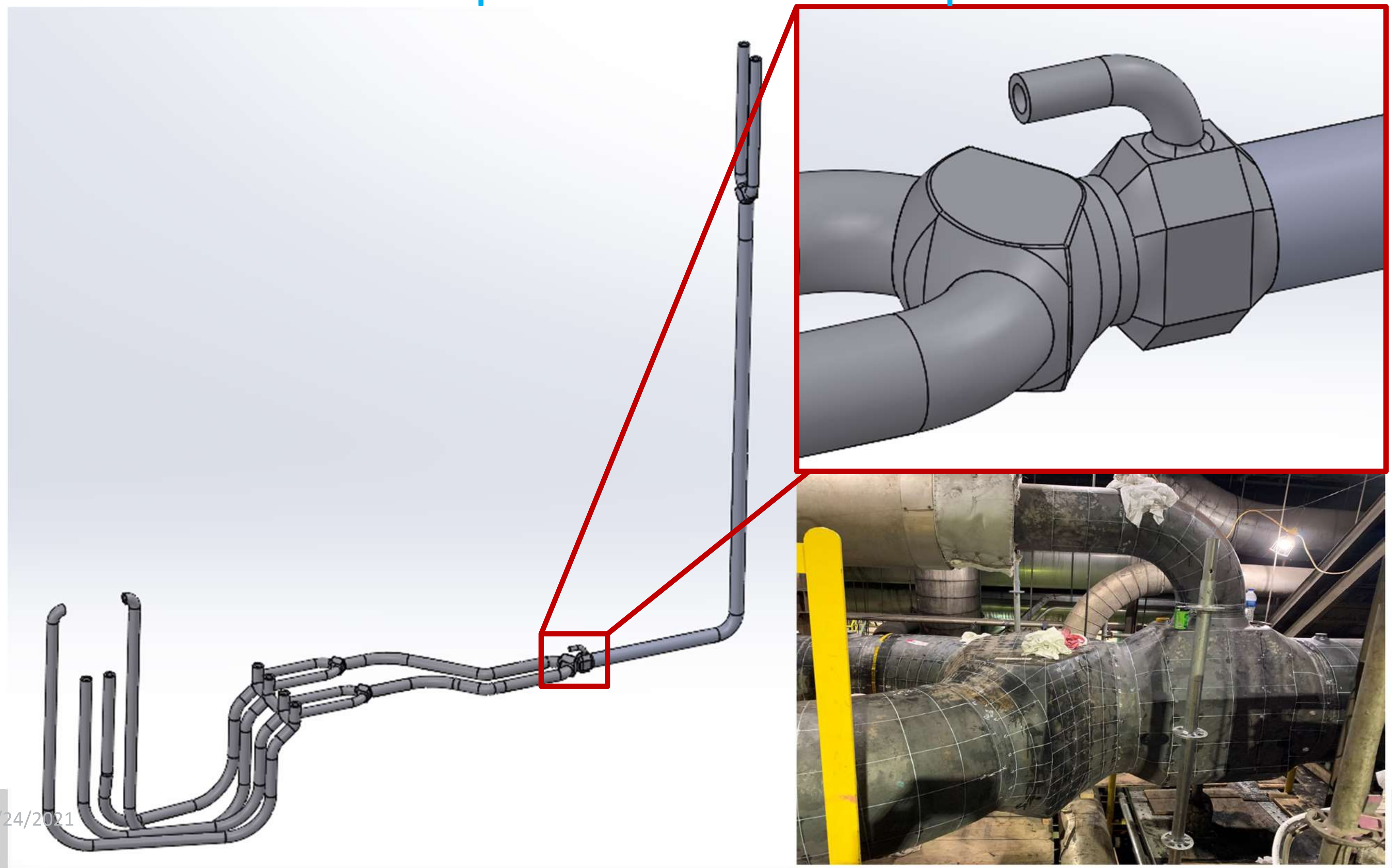
Background and Objectives

- Main Steam Wye-Block Life Modelling
  - Can the remaining life to crack initiation be predicted by use of past, present, and future operational conditions coupled with non-destructive evaluation data?
- **Create life prediction and M&O scheduling models to enhance the performance and cost-effectiveness of coal-based power generation in the U.S.**

Background and Objectives

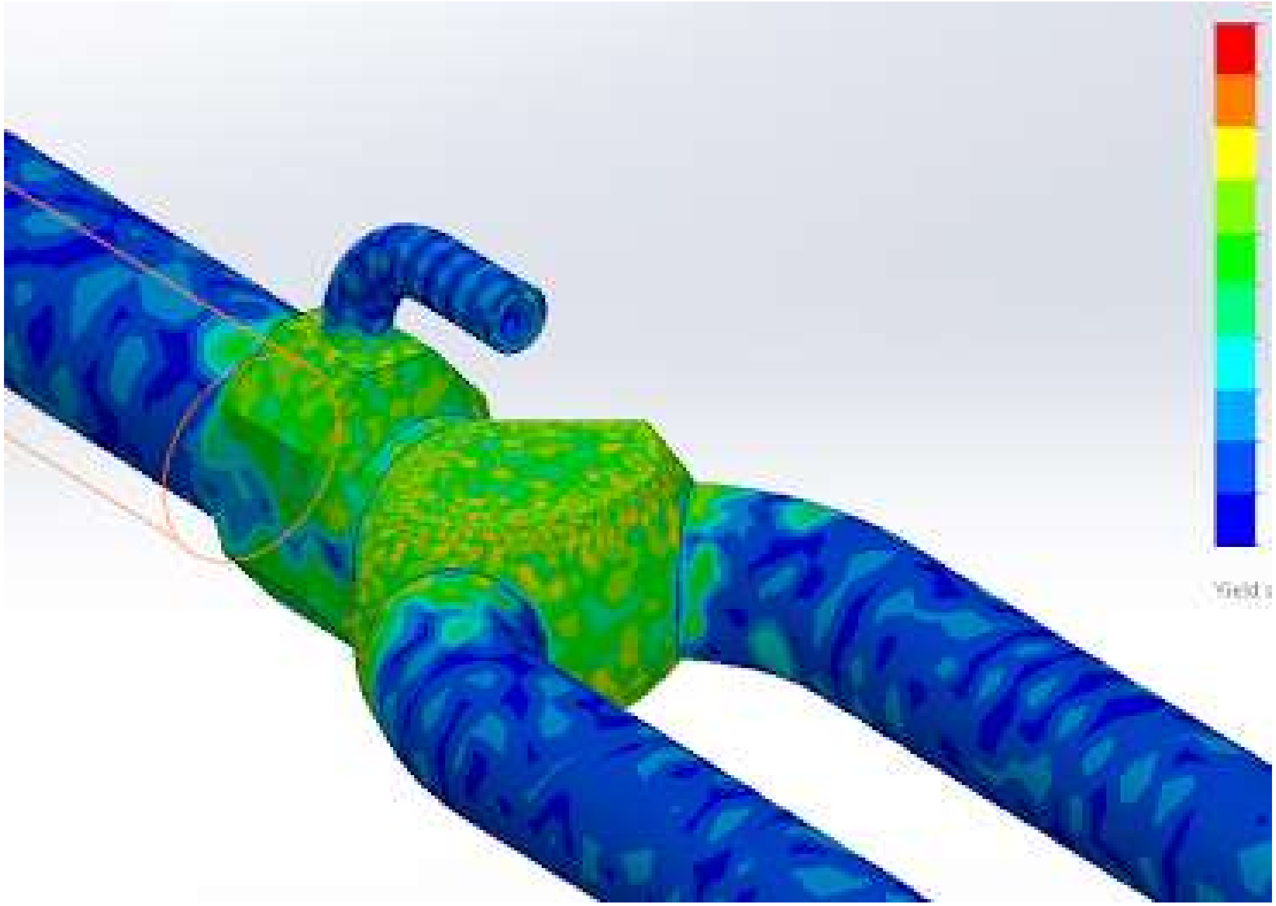
- Main Steam Wye-Block Life Modelling
  - Create a life prediction model for P22 welds experiencing creep and/or fatigue-creep by use of:
    - Operational Data from “Unit A” over an 18-year period
    - Inspection Data from “Unit A” over same 18-year period
    - Drawings and schematics of main steam 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 Updates and Accomplishments



WYE-Block Updates and Accomplishments

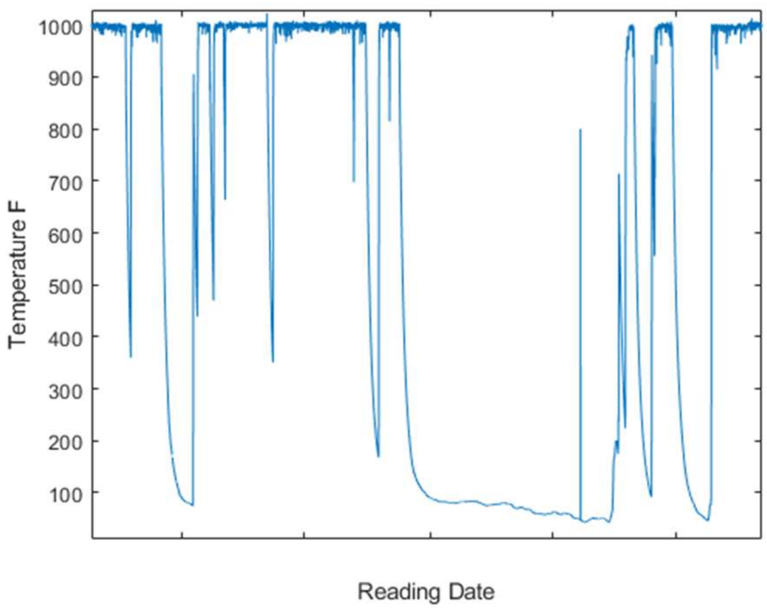
- BC's:
  - Vertical fixity at top-most pipe header
  - Full fixity at turbine connections
- LC's
  - 3500 psi internal
  - 1000°F saturated
- Constitutive Model
  - P22 BM with temperature-dependent yield stress



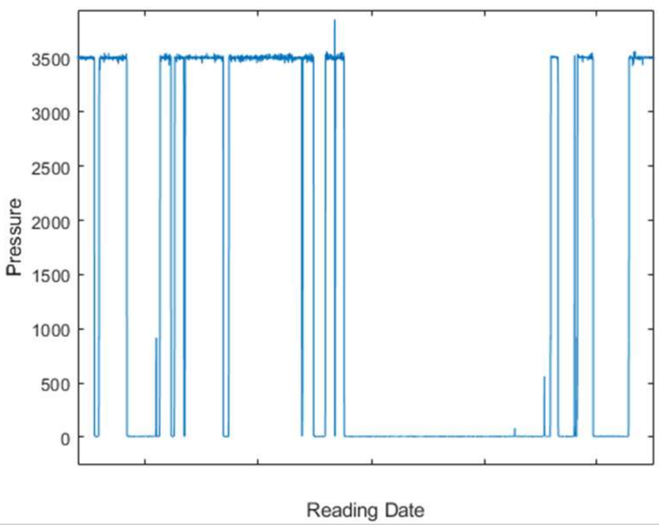
WYE-Block Updates and Accomplishments

Current Analysis of Plant Data for "Unit A" Over 18-Year Period

Temperature

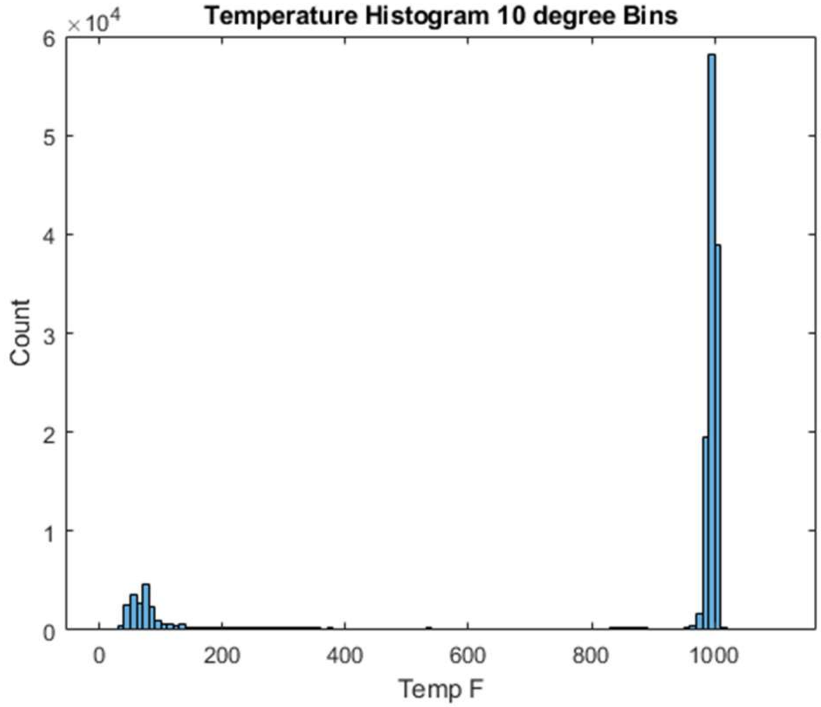


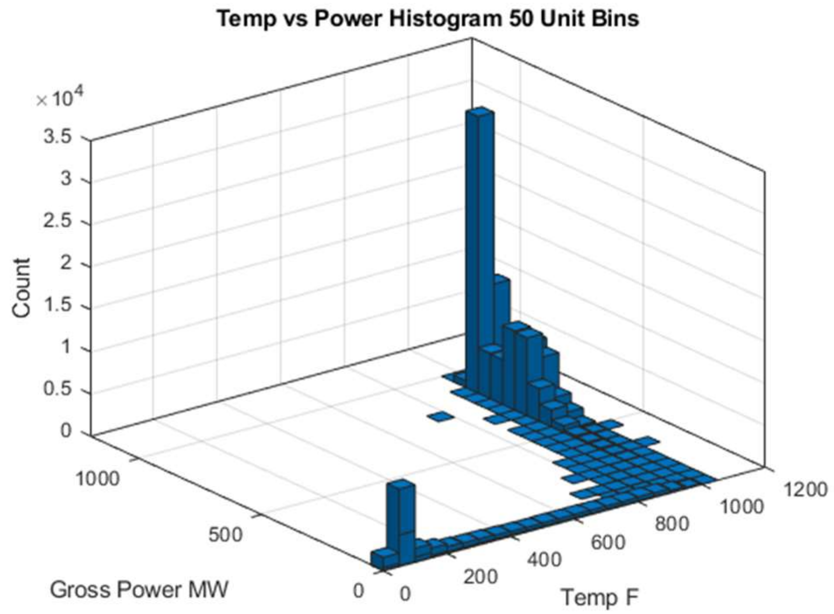
Pressure (combination of two data sets)



WYE-Block Updates and Accomplishments

Current Analysis of Plant Data for “Unit A” Over 18-Year Period

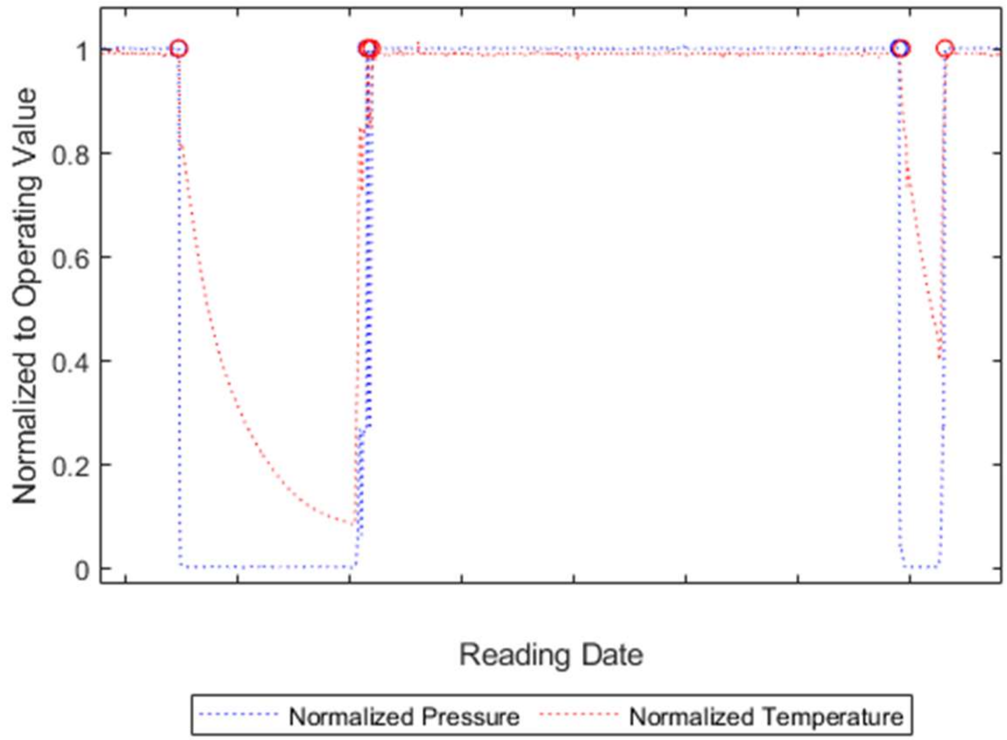




WYE-Block Updates and Accomplishments

Current Analysis of Plant Data for “Unit A” Over 18-Year Period

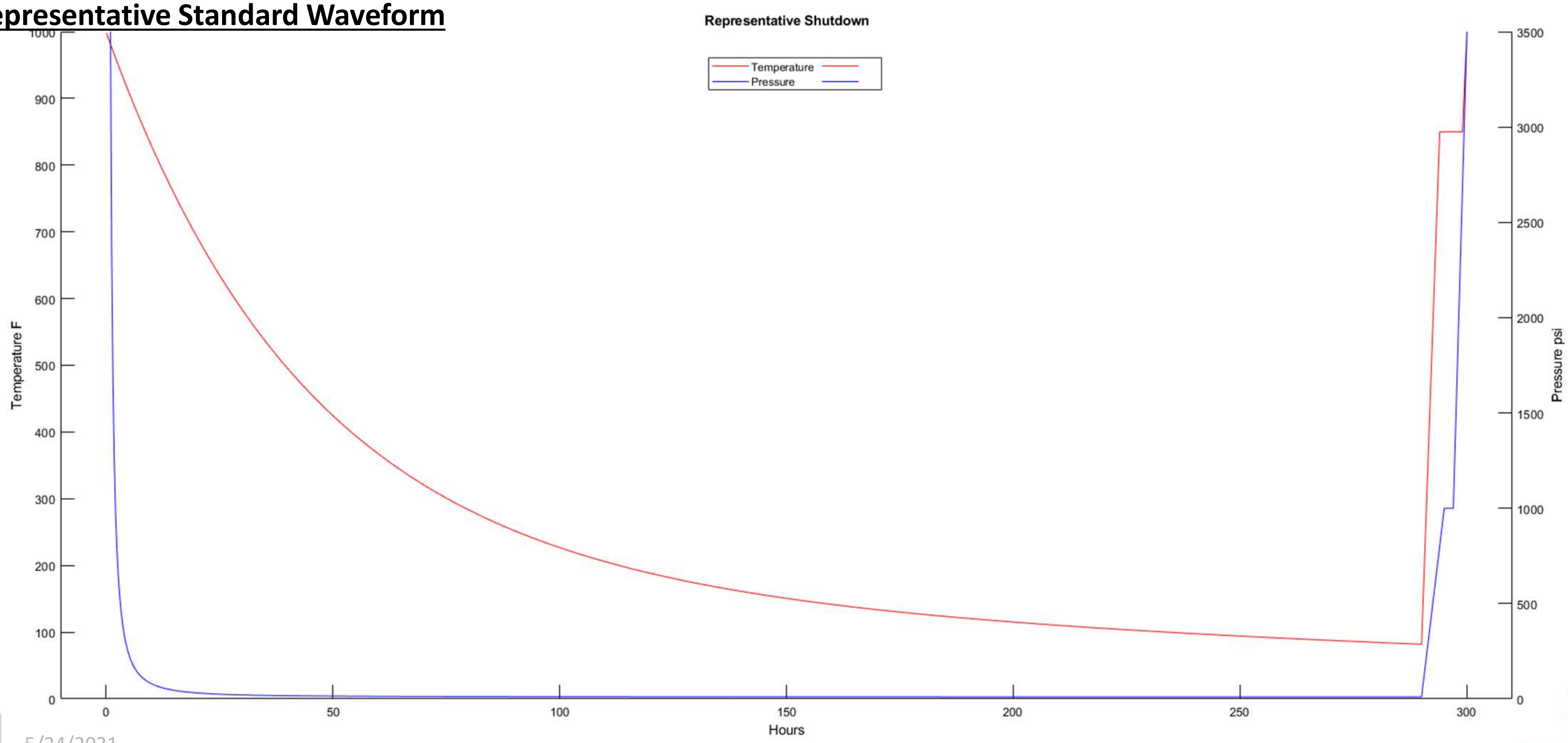
Cycle starts when temp greater than 900F & pressure greater than 3400psig
Cycle ends when temp falls below 900F & pressure falls below 3400psig



WYE-Block Updates and Accomplishments

Current Analysis of Plant Data for “Unit A” Over 18-Year Period

Representative Standard Waveform

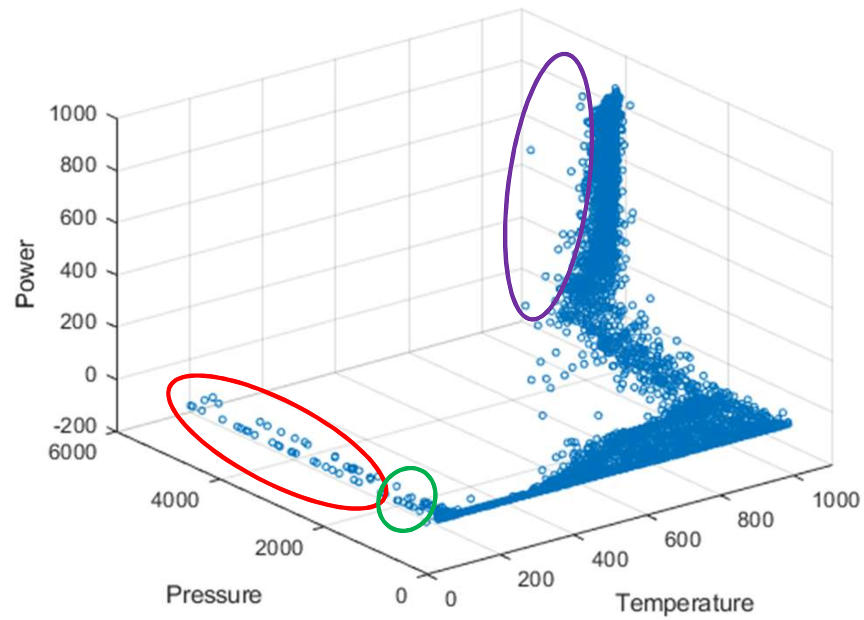


WYE-Block Updates and Accomplishments

Current Analysis of Plant Data for "Unit A" Over 18-Year Period

Excursions in Operating Conditions

- **Prior Concerns**
  - Excursions on Both Temperature and Pressure
  - Many occur at low temp high pressure
- **Current understanding**
  - Most events attributed to sensor errors and maintenance activities
    - SoCo event logs, correlation to other sensor values, known pressure relief valve settings etc.
  - **Low temp moderate pressure (RT/2000psi) real**
    - Result of specific maintenance procedure "hydro"
    - 1 event/2 years
  - **High temp high pressure (Operating Temp/3900psi)**
    - Typically result in "trip" and shutdown
    - 1 event/year



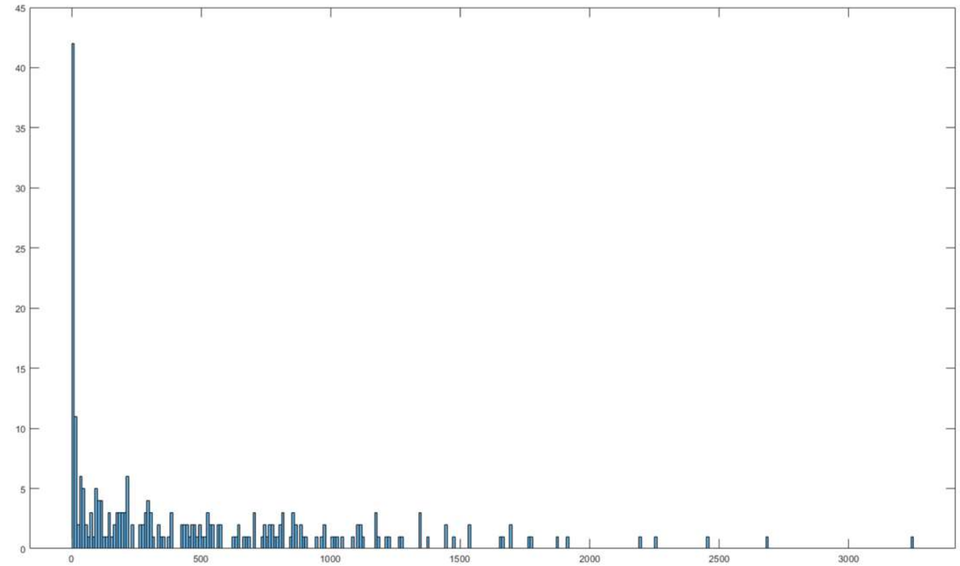
WYE-Block Updates and Accomplishments

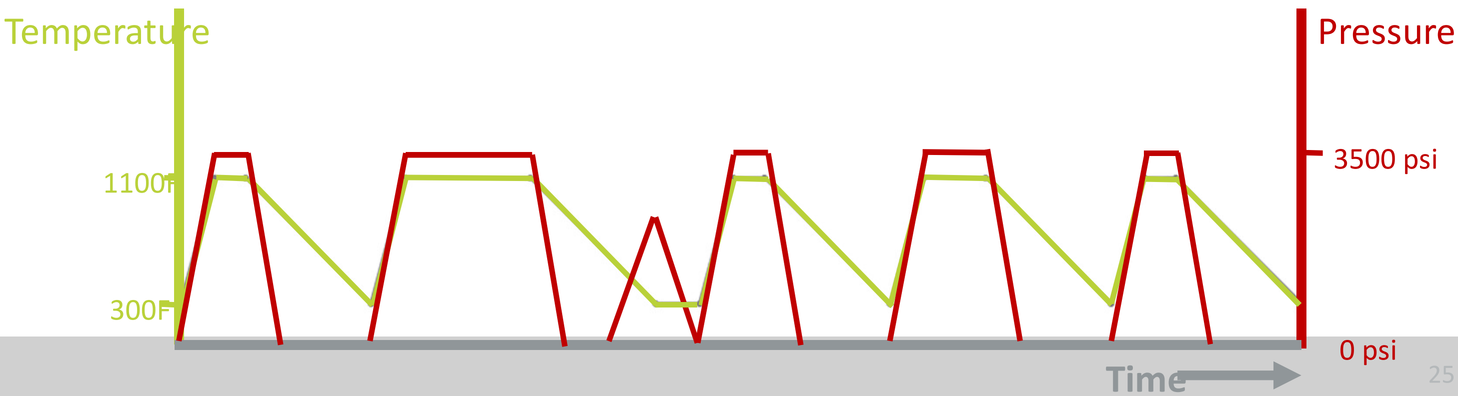
Current Analysis of Plant Data for “Unit A” Over 18-Year Period

<u>Testing Waveform</u>

- Important Parameters
  - Hold times at operating temperature
  - Frequency of hold times
  - Frequency of excursions
  - Location of excursions within spectrum

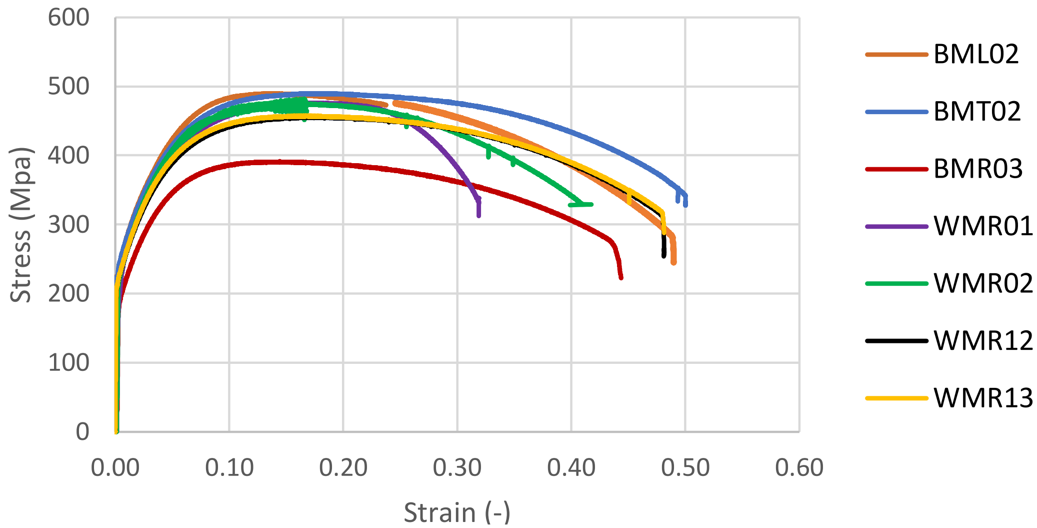
```
min(onhours)
ans = 1
max(onhours)
ans = 3247
mean(onhours)
ans = 492.0494
median(onhours)
ans = 293
mode(onhours)
ans = 2
```





WYE-Block Updates and Accomplishments

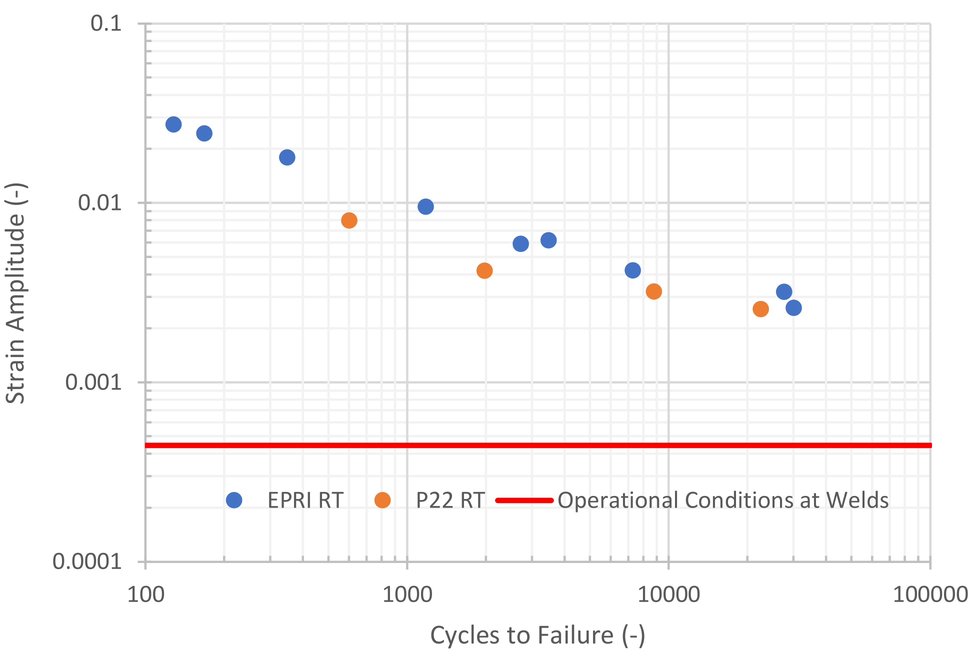
Specimen	Material	Location	Orientation	E (Gpa)	Sig_Y (Mpa)	UTS (Mpa)	E_f (-)
BML02	P22	Base Metal	Longitudinal	204.6	239.0	489.5	48.9
BMT02	P22	Base Metal	Transverse	199.2	241.0	489.8	50.0
BMR03	P22	Base Metal	Radial/Out	170.4	194.0	391.2	43.8
WMR01	P22	Weld HAZ	Radial/Out	200.0	188.0	476.1	32.0
WMR02	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 behaves as annealed).
- BM is exhibiting transversely isotropic monotonic response (Radial orientation weaker).
- WM exhibiting considerable scatter in elongation to failure.

WYE-Block Updates and Accomplishments

- RT LCF



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

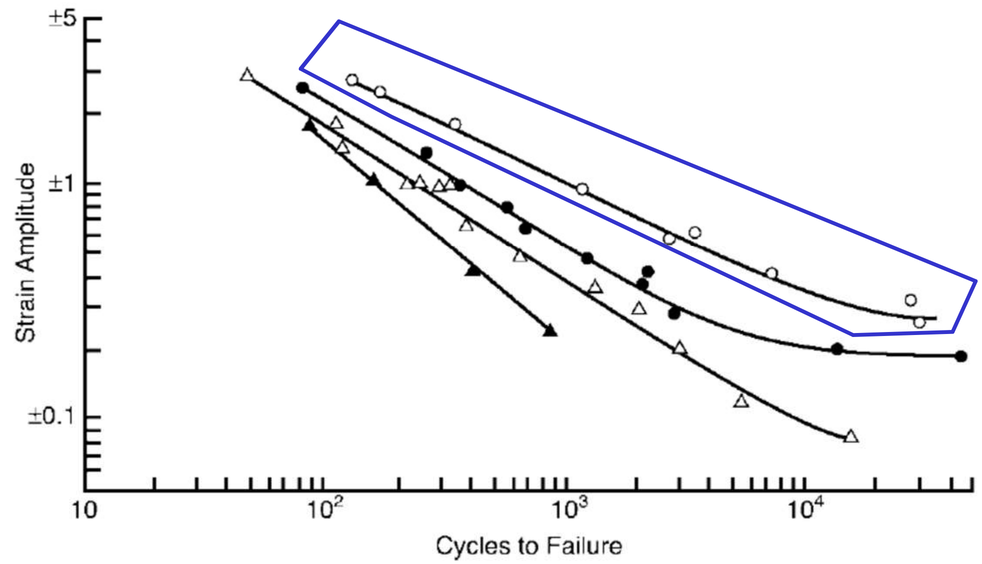


Figure 5-18
Test Results for 2-1/4Cr-1Mo Steel Showing That Holding at High Temperature Significantly Reduced the Number of Cycles to Failure [18]

WYE-Block Updates and Accomplishments

- Elevated temp LCF with hold times

Symbol	Temperature °C	Temperature °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

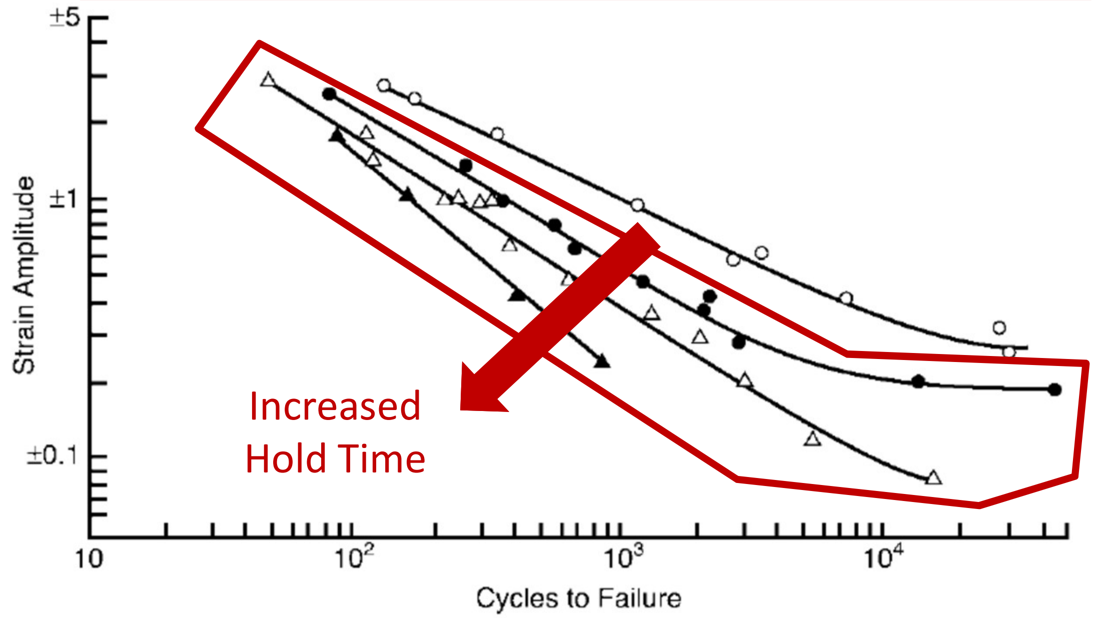
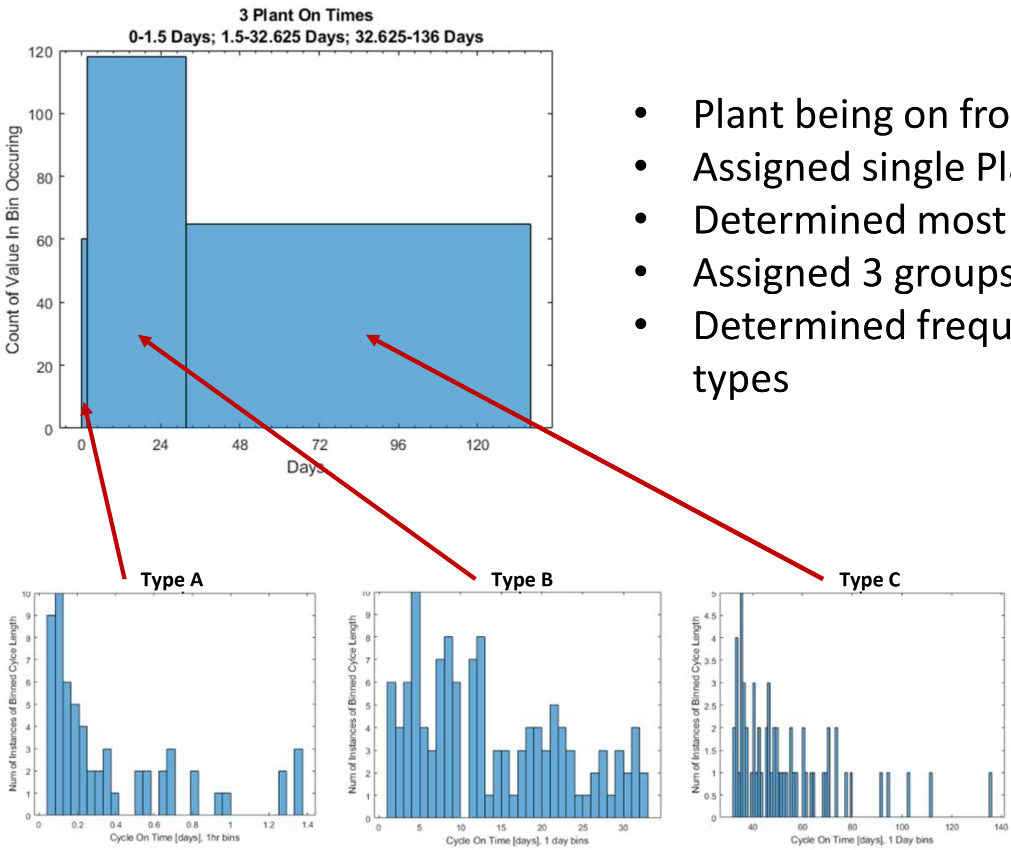
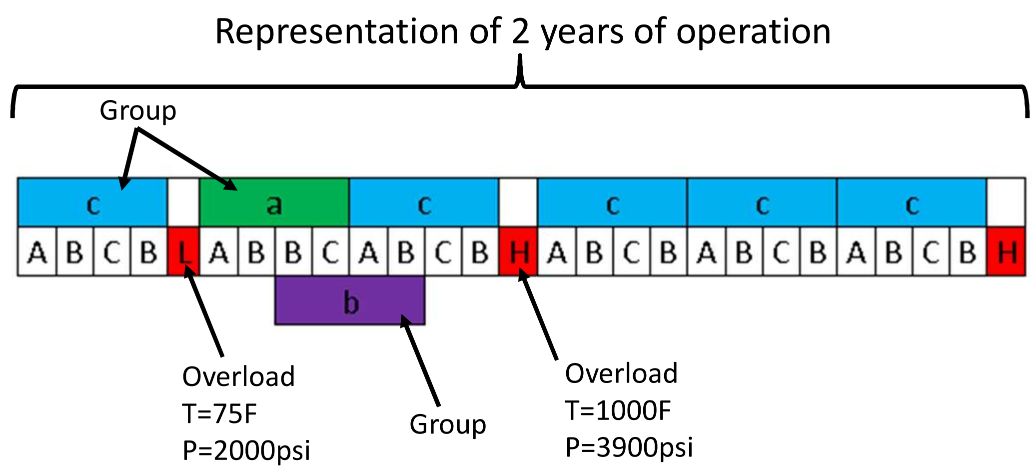


Figure 5-18
Test Results for 2-1/4Cr-1Mo Steel Showing That Holding at High Temperature Significantly Reduced the Number of Cycles to Failure [18]

WYE-Block Updates and Accomplishments

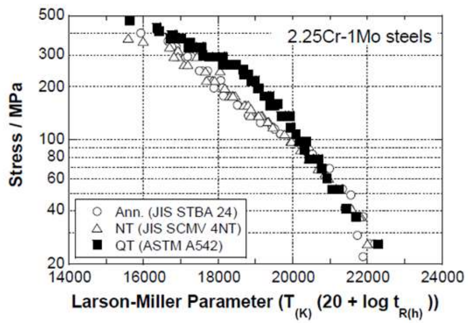


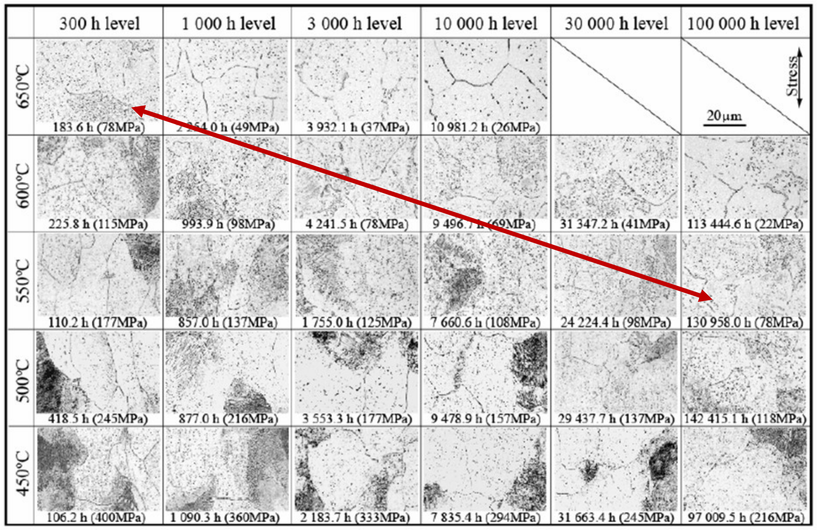
- Plant being on from 1.5-32.625 days is 2x as frequent as shorter or longer
- Assigned single Plant On Time representative of each type
- Determined most common ordering of these three types (group)
- Assigned 3 groups to represent type sequences
- Determined frequency of overload events positioning within grouping types



WYE-Block Updates and Accomplishments

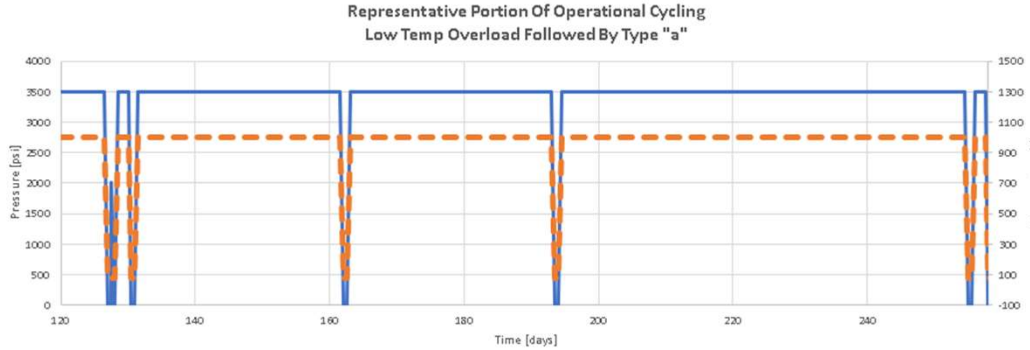
Representative 2 year period captured by approximately 5 hour test period

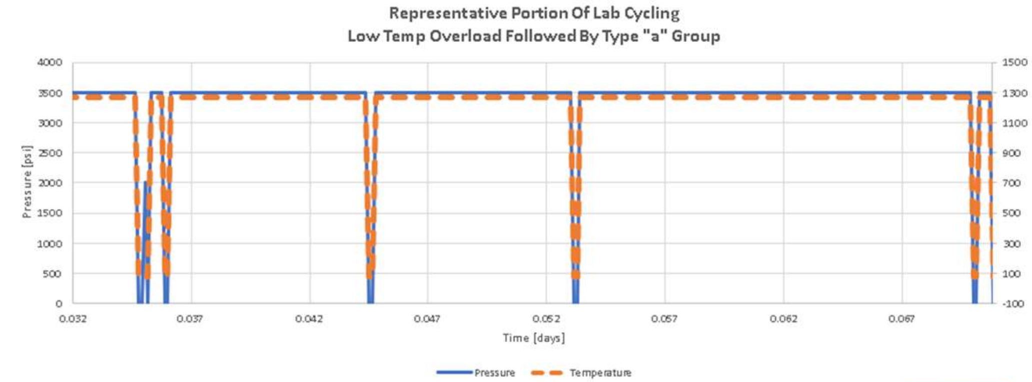




Kushima et al Metallographic Atlas for 2.25Cr-1Mo… 2005

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	1000	1270	1.09
B	30	710			.03
C	60	1420			.27





SR

Future Work

<u>WYE BLOCK PROJECT</u>

1. Monotonic Testing (30% complete)
2. Strain-controlled testing of individual microstructures (Started and ongoing)
3. Strain-Controlled testing of cross-weld assembly at 1000F
4. Microstructural Evolution of Material
5. Microscopy of Weld (30% complete)
6. Microscopy of Tested Specimens (Started and ongoing)
7. Determination of dominant damage mechanisms (80% complete)
8. Calibration of Finite Element Plasticity Models (Started and ongoing)
9. Calibration of Existing Damage Accumulation/Life Models to be used to predict creep and fatigue-creep crack initiation and inspection intervals (Started and ongoing)
10. Create Life Model Variable in Finite Element Package
11. Validation and Verification of Life Models
12. Creation of Life Model Application and User Manual

Future Work

	WYE BLOCK PROJECT	Quarter Start Date							
		Oct-20	Jan-21	Apr-21	Jul-21	Oct-21	Jan-22	Apr-22	Jul-22
1	Determination of Realistice LCs/BCs			*					
a	Analyze SoCo oeprational data			*					
b	Determine appropriate test waveforms			*					
2	Creation of Facility Solid Model (confirm displacements)			*					
a	Modification of Wye-block geometry			*					
b	Verification of units			*					
c	Application of LCs/BCs			*					
3	Specimen Prep								
a	Creation of specimen blanks								
b	specimen machining								
4	Monotonic Testing All								
5	Strain-Controlled Testing All								
6	Strain-Controlled Testing of cross-weld assembly 1000F								
7	Characterize Microstructural Evolution of Material								
a	Aging studies (reduced time)								
b	Effects of quenching								
8	Microscopy of Weld								
a	Spatial chemical composition (EDAX, SEM)								
b	Microhardness map								
c	Optical (grain size/morphology and micro. Constituents)								
9	Microscopy of Tested Spedcimens								
a	Monotonic fracture surfaces (optical)								
b	Strain-control RT fracture surfaces (optical)								
c	Strain-control 1000F fracture surfaces (optical)								
d	strain-control 1000F longitudinal section (optical+SEM)								
e	Microstructural evolution (RT and 1000F grain size/morphology, chemical composition, micro.constituents)								
10	Determination of Dominant Damage Mechanisms								
11	Calibration of ABAQUS Plasticity Models								
a	BM air								
b	BM 1000F								
c	Weld fusion zone 1000F								
d	HAZ 1000F								
12	Calibration of Existing Damage Accumulation/Life Models								
a	FIP?								
b	Pineau (Not Mine 2- Fournier)								
13	Implement Life Model Variable in ABAQUS								
14	Verification and Validation of Life Models								
a	Comparrison to operations and maintenance schedules								
15	Creation of Life Model Application and User Manual								

Questions?

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