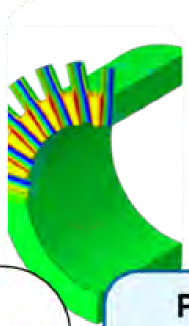
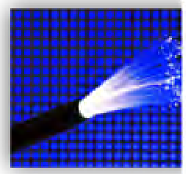
Integrated Boiler Management Through Advanced Condition Monitoring and Component Assessment

DE-FE0031683

Approach

- Real-time High-Temperature, Distributed Fiber Optic Sensing
- Integration of Existing Instrumentation
- Expanded Model for Creep & Fatigue Damage
- Enhanced Data Analysis





Challenge

- Flexible Operation
- Thermal Cycling and Transients
- Fatigue Damage to Critical Boiler Components
- Cumulative Creep Damage
- No on-line Condition Monitoring available for Critical Boiler Components

EPRI ELECTRIC POWER RESEARCH INSTITUTE

AEP AMERICAN ELECTRIC POWER

SENTEK INSTRUMENT LLC

Structural Integrity Associates, Inc.®

Project Outcomes

- Condition Monitoring System for All Boiler Types
- Prevention/Prediction of Component Failures
- Improved Creep & Fatigue Assessment
- Improved Thermal Management and Temperature Control

Project Plan

Design ➡ Build ➡ Verification Testing ➡ Full-Scale Plant Demonstration ➡ Analyze ➡ Transfer to Industry

Project Objectives and Status

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Project Objectives

- Develop, demonstrate, and support technology transfer of an integrated boiler management system to track accumulation of creep and fatigue damage
  - Includes development of high-temperature fiber-optic distributed sensing
  - Near real-time damage assessment
- Improved boiler operation in concert with existing plant data and processes

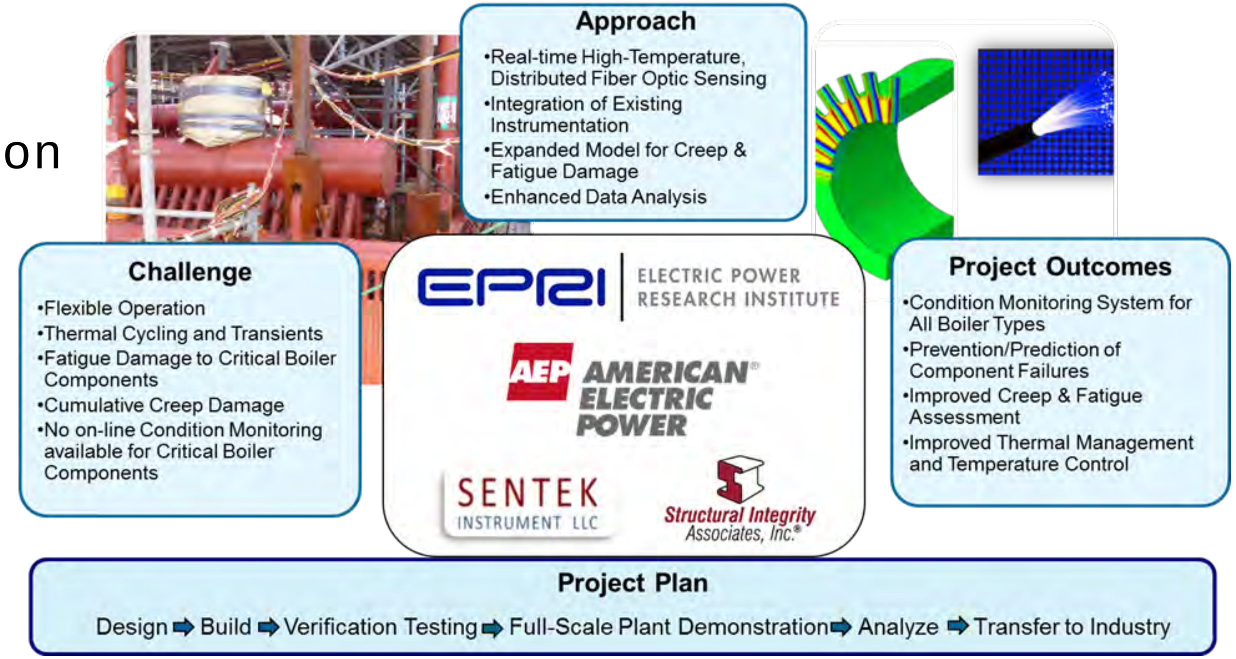
Current Status

- Development of integrated boiler management system complete
- Fiber-optic distributed sensing development continues
- Host-site demonstration of integrated boiler management system planned for 4Q 2020
- Demonstration of fiber-optic distributed sensors delayed until 2021

Project Partners

Project Partners and Responsibilities

- Project prime (EPRI)
  - Overall project management
  - Coordination of partner activities
  - Coordination with host site for demonstration
- High-temperature, distributed fiber-optic sensors (Sentek Instrument LLC)
- Creep-Fatigue Management System (Structural Integrity Associates)
  - Fiber-optic sensor output
  - Existing plant instrumentation
- Host-site demonstration (AEP)



Creep-Fatigue Management System

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Temperature Variability During Flex Ops

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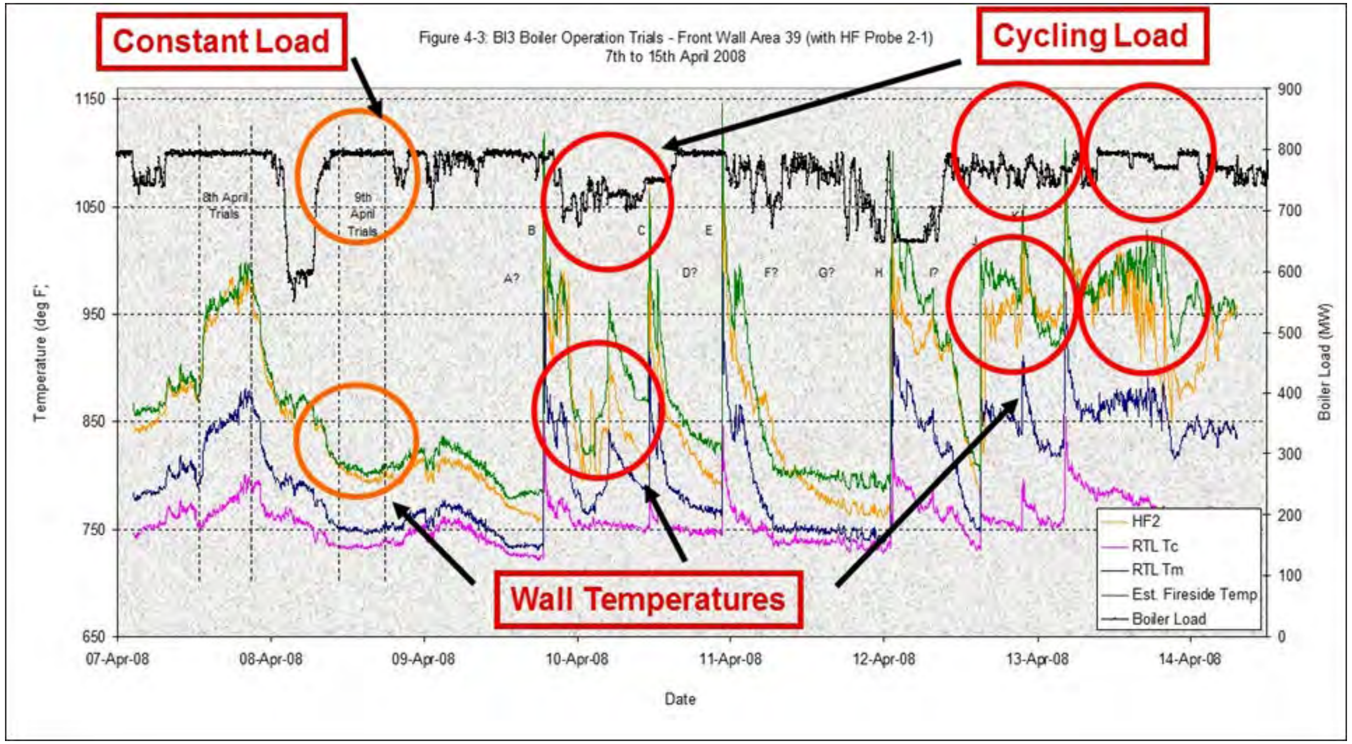
Fossil plants are increasingly required to operate in more flexible operating modes:

- More startups & shutdowns
- More partial load operation

Expected to cause accelerated fatigue- and creep-related damage

Increases significance of tracking equipment condition for:

- Minimizing failures
- Optimizing replacement schedules
- Optimizing inspection timing



Role of Integrated Life Management

Most relevant and up-to-date information can help reduce analysis uncertainty:

- Material properties
- Stress state
- Operating data/environment

Integrated approach

- Determination of material ‘condition’
  - Stress, strain, temperature, etc. (innovative sensor technologies)
  - Track damage accumulation in key components
- Life assessment tools needed - Advanced Condition Monitoring

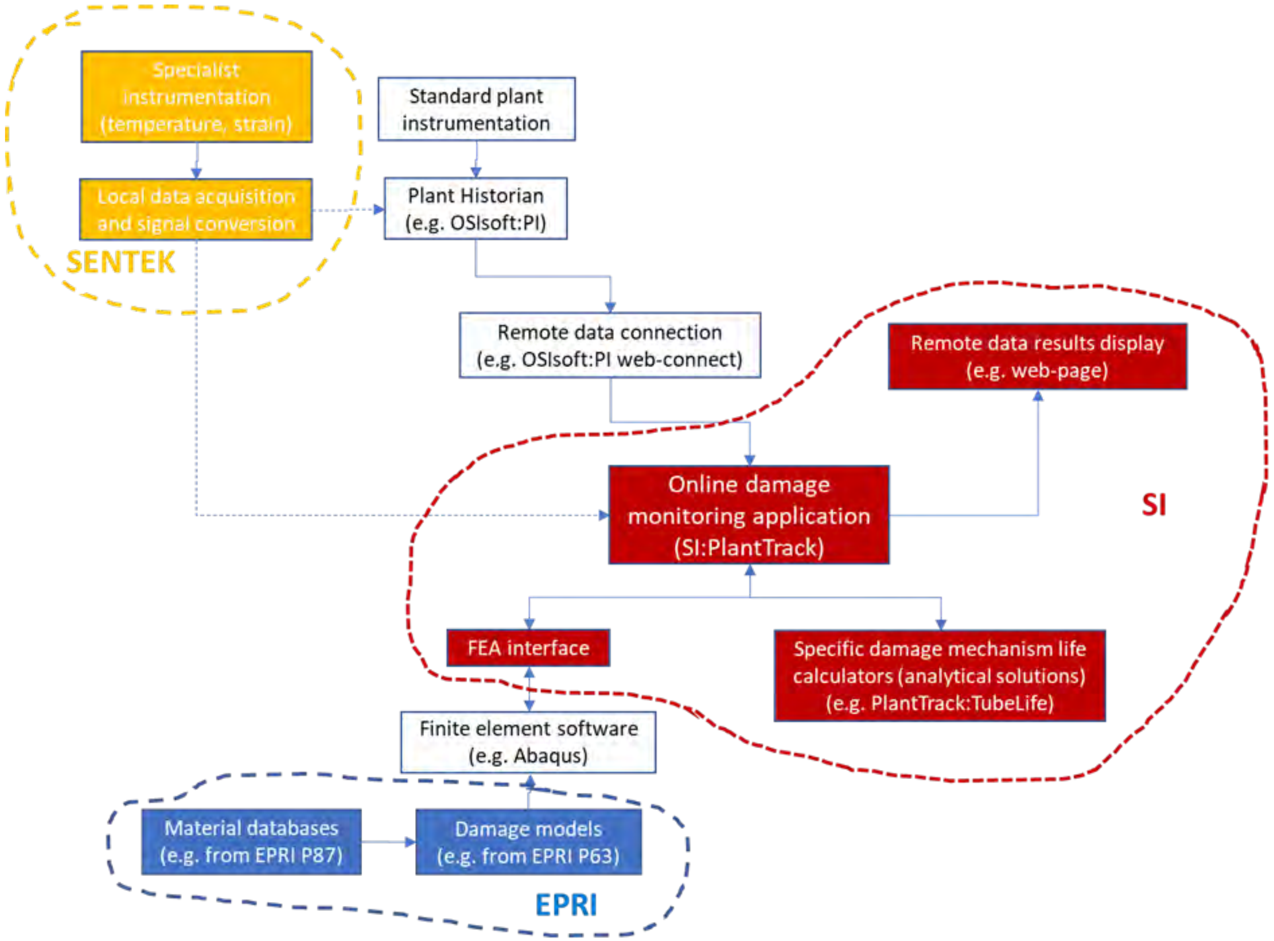
Online Damage Monitoring

Modular configuration to leverage existing technology

- Connection to plant historian (OSIsoft:PI)
- Finite element software (Abaqus)
- Damage constitutive models (EPRI)
- Web-based interface (PlantTrack)

Scalable system adaptable to any component or damage mechanism

- Python scripting in Abaqus
  - Automation of FE analysis and post-processing
- Connectivity between applications
  - Data exchange and display

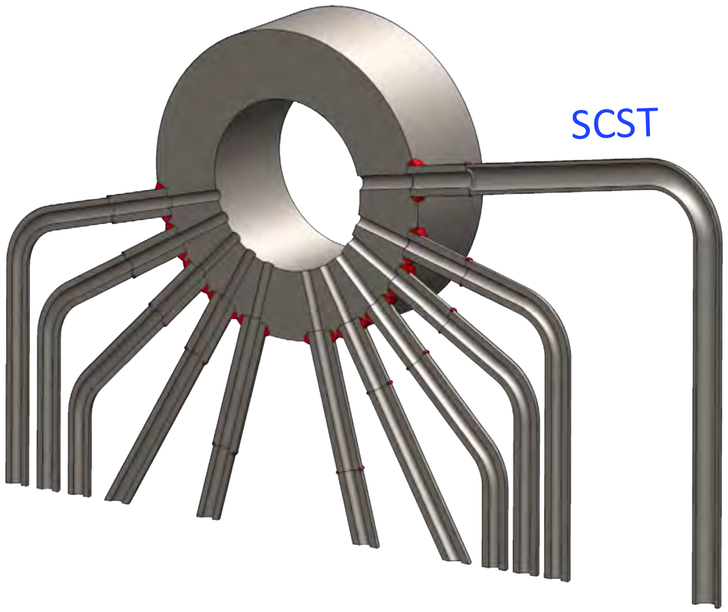


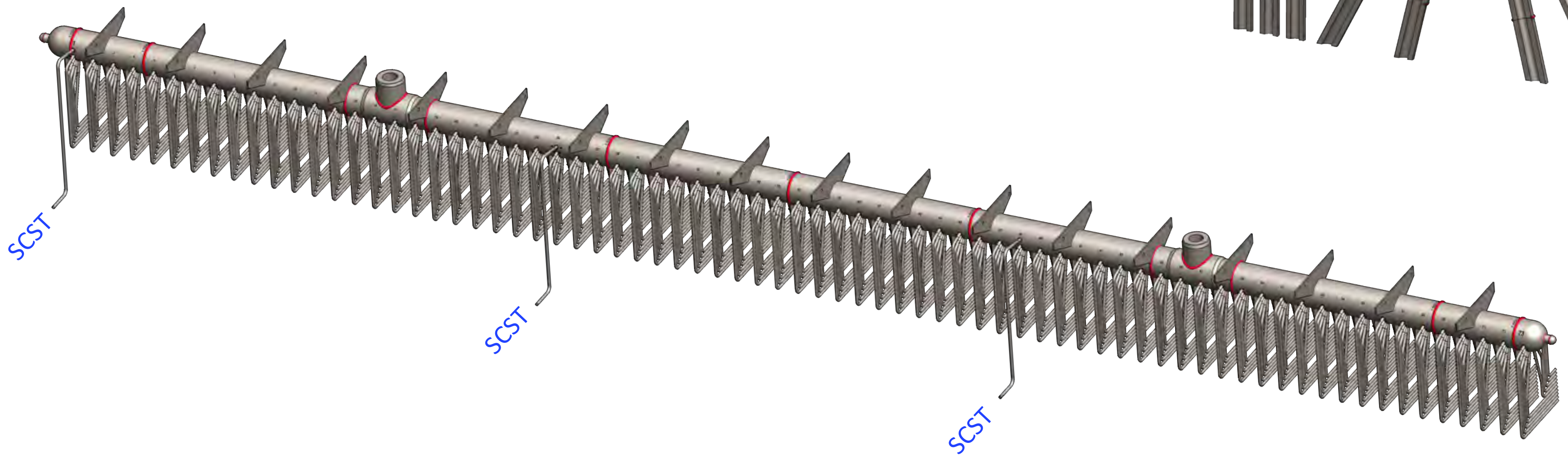
Secondary Superheat Outlet Headers

Demonstration site: AEP Amos Plant, Unit 3 (1973)

Overall view of the front secondary superheat outlet header (SSOH) and a cross-section through an assembly with a steam cooled spacer tube (SCST)

- 73 tube assemblies across the length of each header (two SSOH's).
- Each assembly has 10 tube penetrations.
- Three steam cooled spacer tubes (SCST) along the front header length and 1 SCST on the rear SSOH.



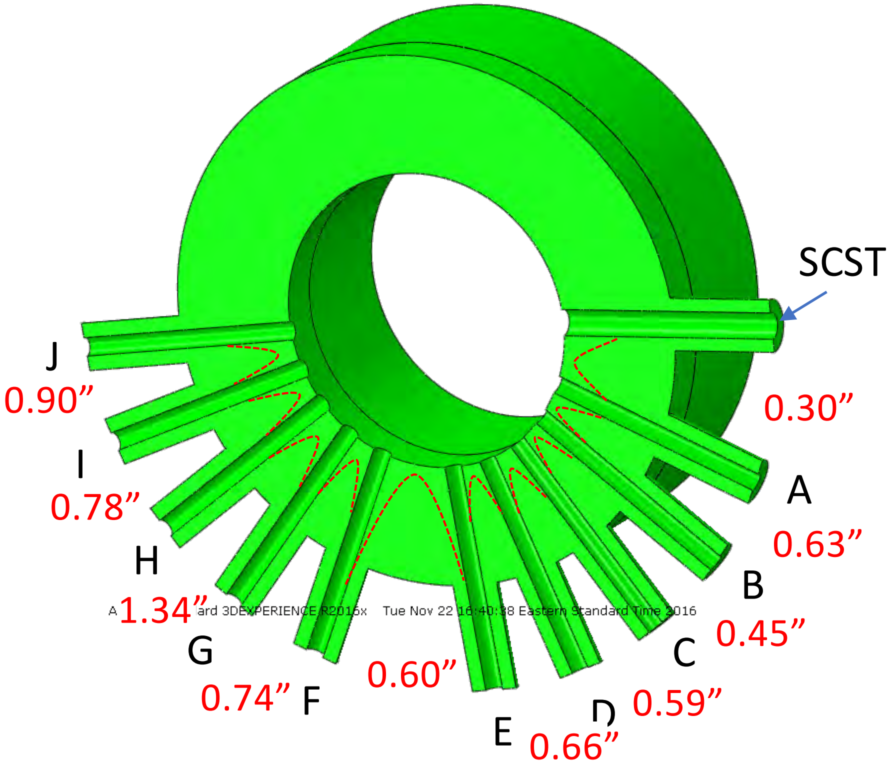


Borehole Ligament Crack Depths from ID

SSOH selected because of known history of ligament cracking, particularly the assemblies with SCSTs

Example cross-section shown from one of the assemblies with known ID connected cracking

Far right shows borescope image of ID ligament cracking



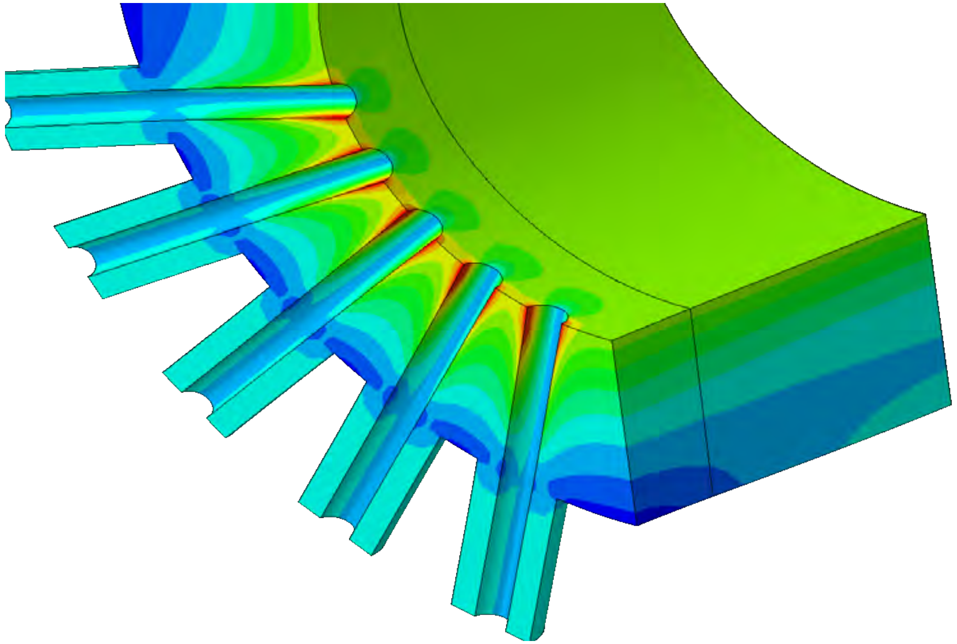
Maximum measured crack depths in the ligaments

3D Finite Element Analysis

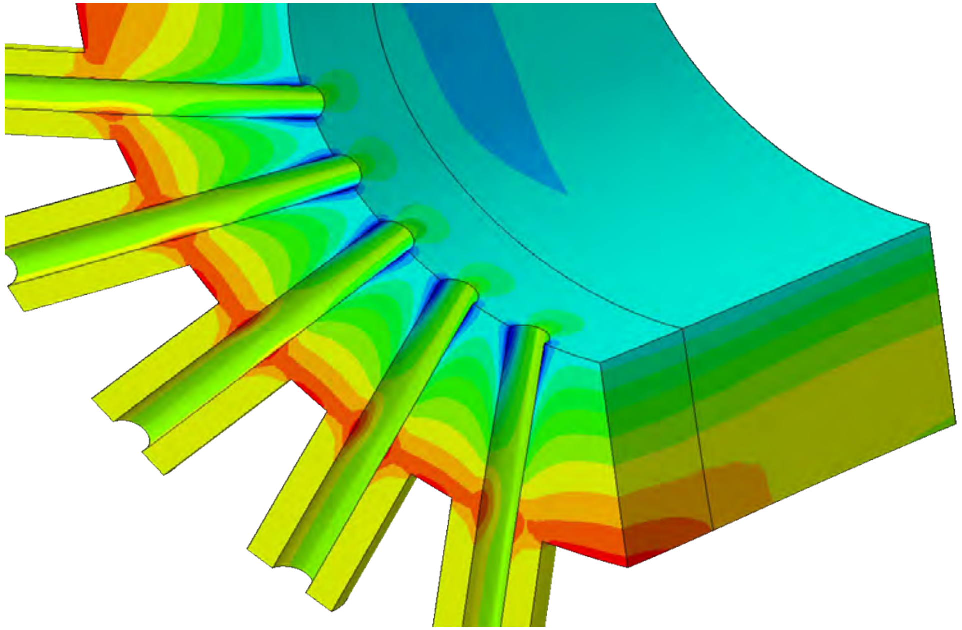
Stress contour plots generated from initial fitness-for-service (FFS) assessment

ID tube borehole edges experience high tensile and compressive stresses during cycling which leads to thermal fatigue damage and ligament cracking

- Caused by top-to-bottom temperature differentials which in turn causes constrained thermal stresses at tube borehole edges



Axial stress during forced cooldown



Axial stress during cold start-up

Conclusions of Initial FFS Assessment

Mechanism of damage and cracking shown to be thermal fatigue based on the pattern, location, and supporting FE analysis.

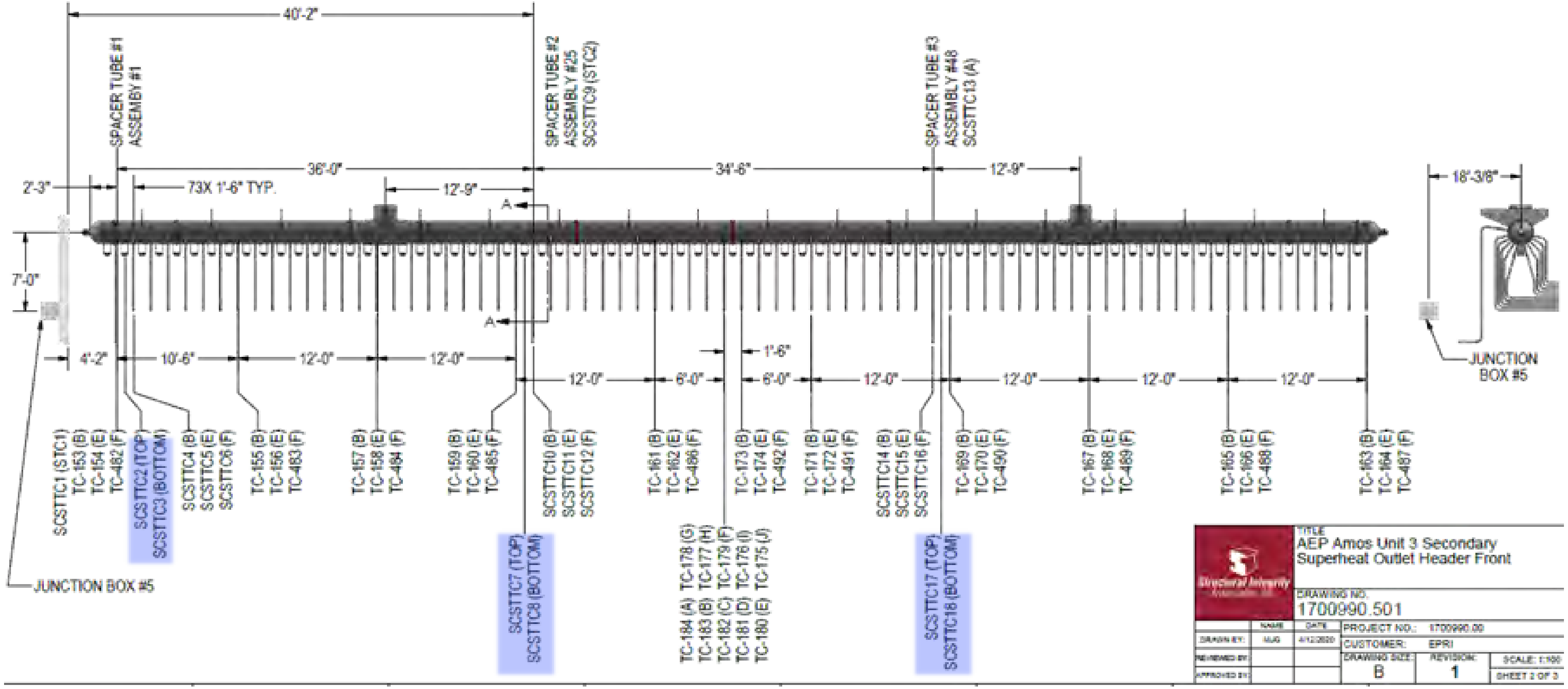
- Most significant cracking observed adjacent to SCST
- Typical start-up/shutdown cycles experienced by the header do not explain the damage.
  - Condensate entering from the SCST offered one plausible explanation as to why the damage would be localized to the SCST assemblies

Not sufficient local thermocouple data to assess the temperature response that may be leading to the damage

- Local temperature sensor thermocouples (TC’s) mounted on the steam cooled spacer tubes (SCST’s) to quantify frequency and magnitude of local transients
- Critical for tuning the FEA model to simulate operating (thermal) data

New Temperature Instrumentation

AEP installed new temperature sensors across the header concentrated around the SCST's



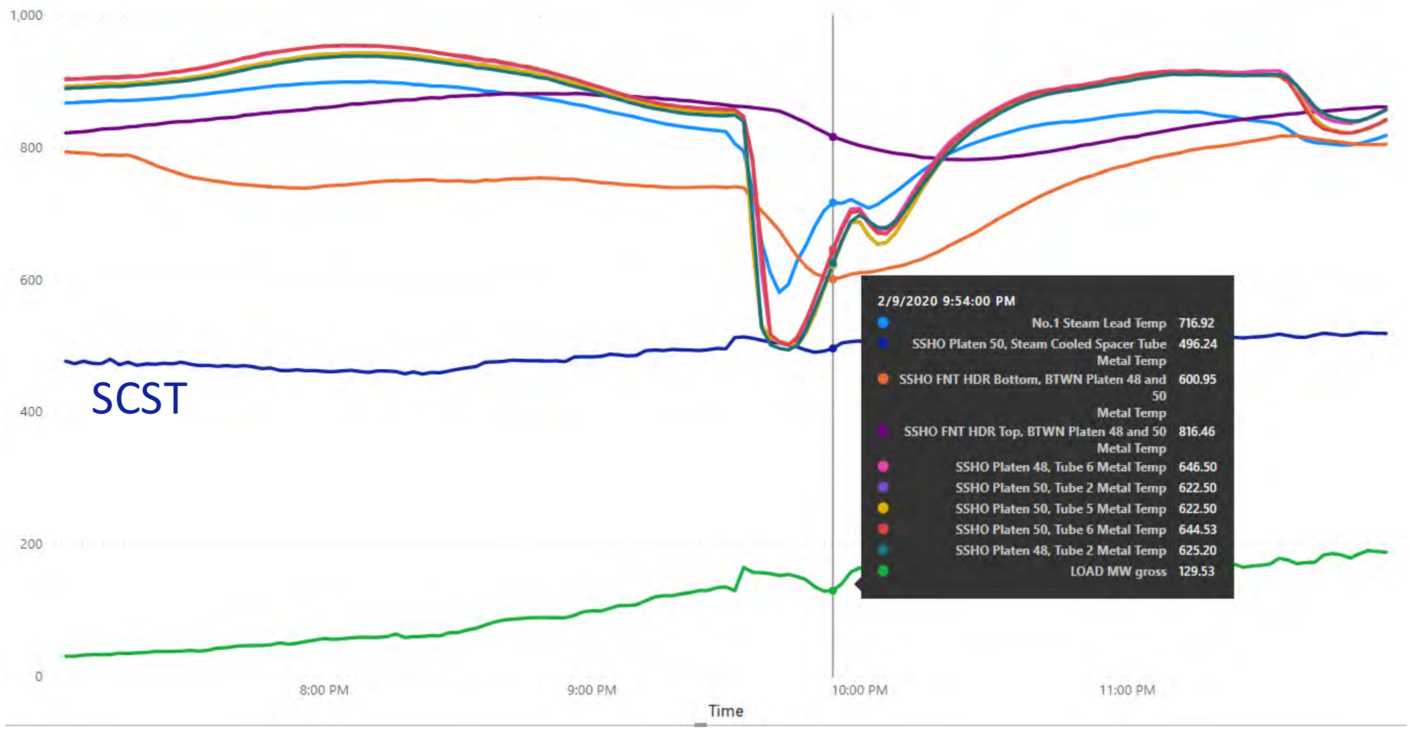
Example Thermal Shock During Startup

Snippet of temperature data from the thermocouples during unit startups

SCST much cooler temperature than the adjacent tubes

At approximately 9:30, the tubes experience a significant downshock to SCST Temp

Local Tubes Near SCST



Opportunity for Integrated Boiler Management System

Thermocouples provide frequency and magnitude of local transients, however additional FE analyses required quantify the stresses, strains, and damage from each

No way to quantify the relative significance that partial improvements have on damage accumulation rates

Opportunity to leverage existing FE model and configure a near real-time damage tracking solution that accounts for most recent operating data

- Tracking locations with known damage
- Tracking damage development in locations where wear-out failures are expected
- Especially relevant given the age of the fleet and the increasing demand toward flex-ops.

Increased accuracy possible through local strain gauges

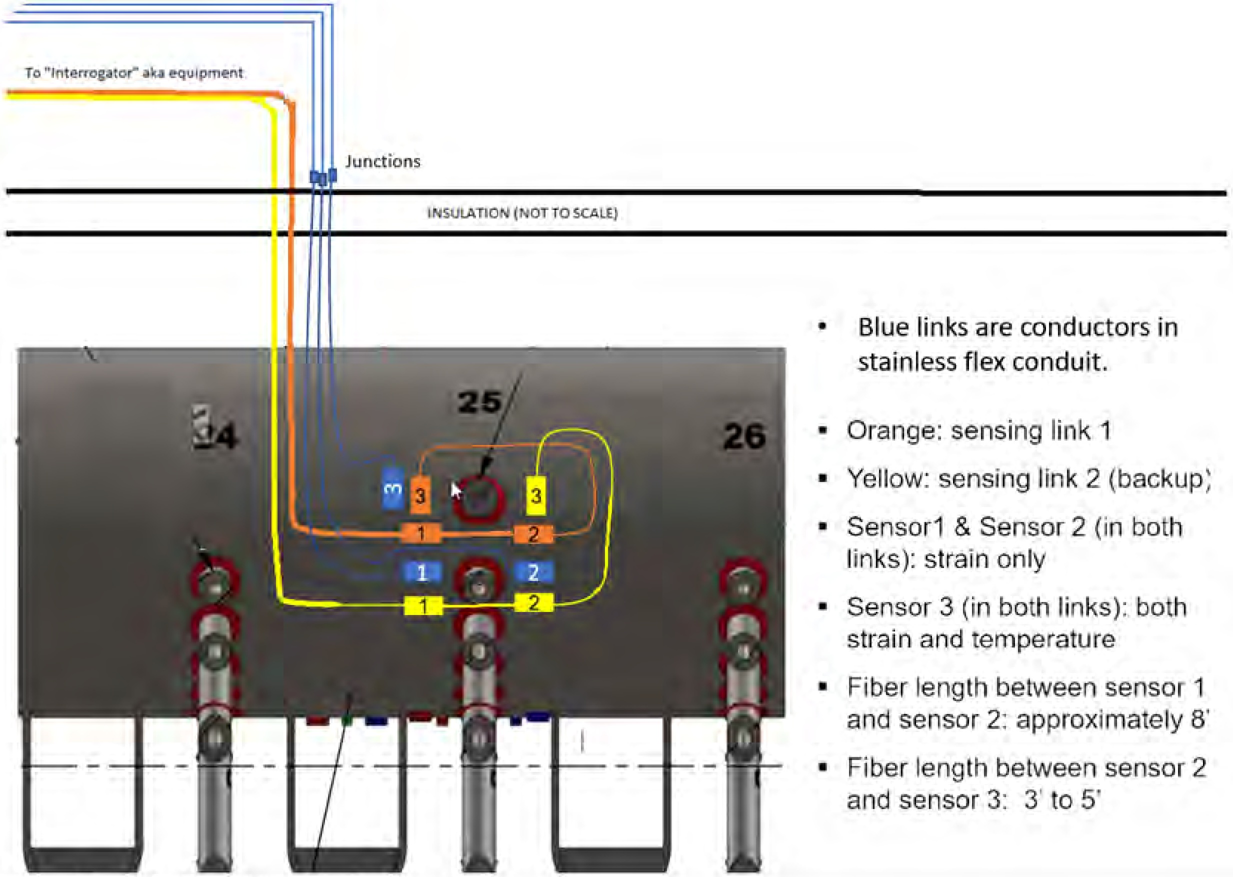
- Allow material properties to be fine-tuned

Strain Gauge Instrumentation

Local strain gauges planned to be installed during the upcoming outage

Results will not drive the FE model directly but will provide basis for modifications to FE material properties, and/or thermal boundary conditions

Figure shows additional instrumentation that EPRI will install to complement this project (supported outside this project)

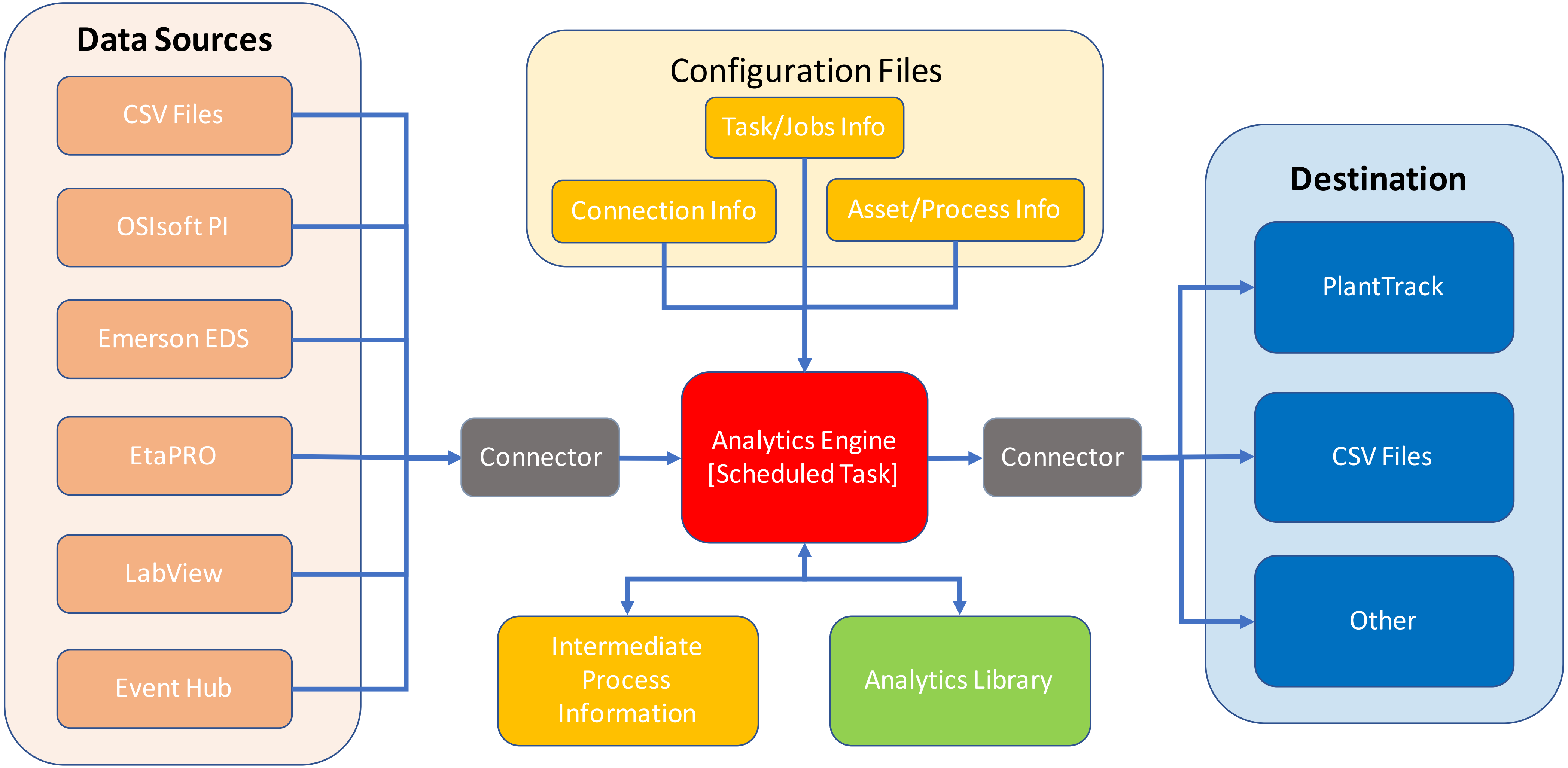


- Blue links are conductors in stainless flex conduit.
- Orange: sensing link 1
- Yellow: sensing link 2 (backup)
- Sensor1 & Sensor 2 (in both links): strain only
- Sensor 3 (in both links): both strain and temperature
- Fiber length between sensor 1 and sensor 2: approximately 8'
- Fiber length between sensor 2 and sensor 3: 3' to 5'

Orange – Sentek Sensing Link 1
Yellow – Sentek Sensing Link 2
Blue - Suprock Strain Gauges 1,2 and 3.

Condition Monitoring Software Architecture

Analytics Framework

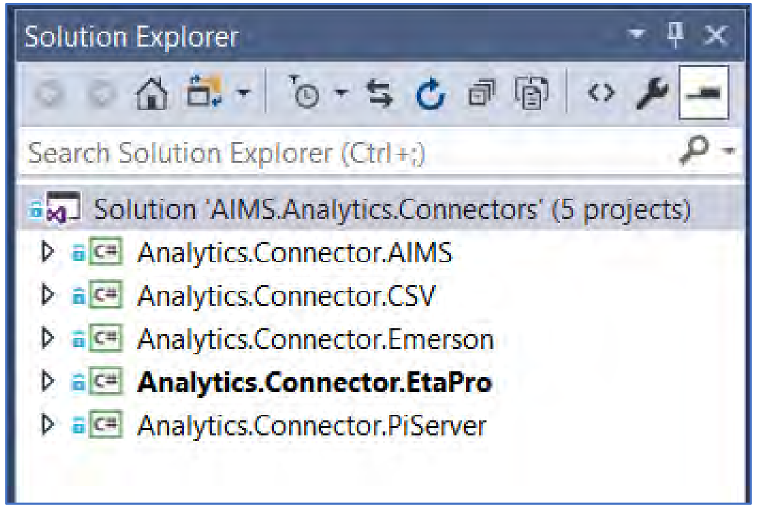


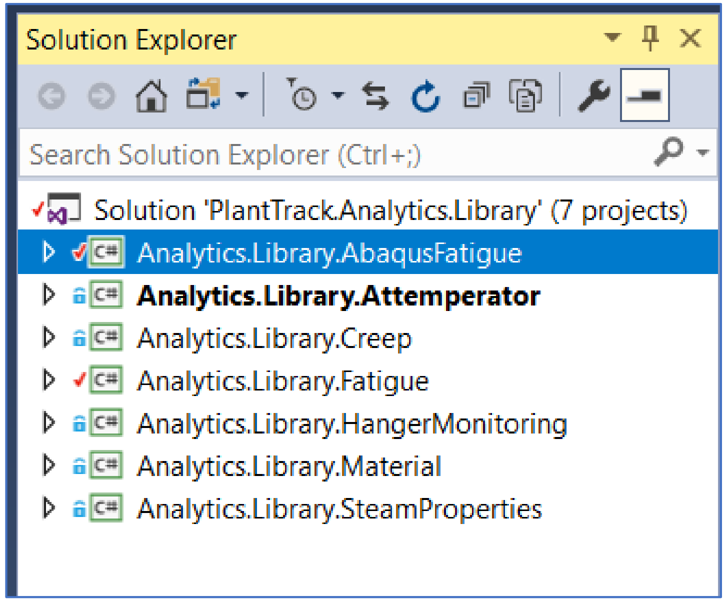
Key components of the Analytics

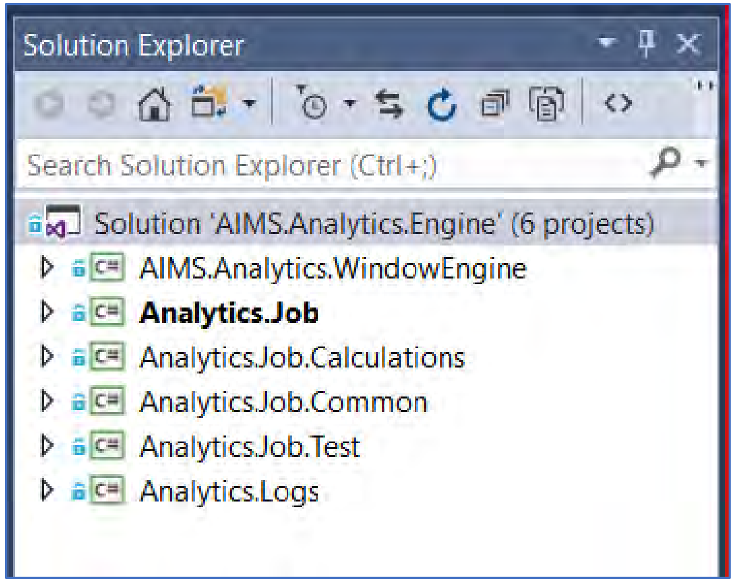
Connectors: Standard data connectors that can used to pull data from data historians. We continue adding to this as required for other data historians.

Analytics Library: We build the analytics in a way that they can be used from the analytics engine or web/desktop UI.

Analytics Engine: This engine is used to orchestrate getting the data from the source, executing the analytic and pushing the results to PlantTrack.



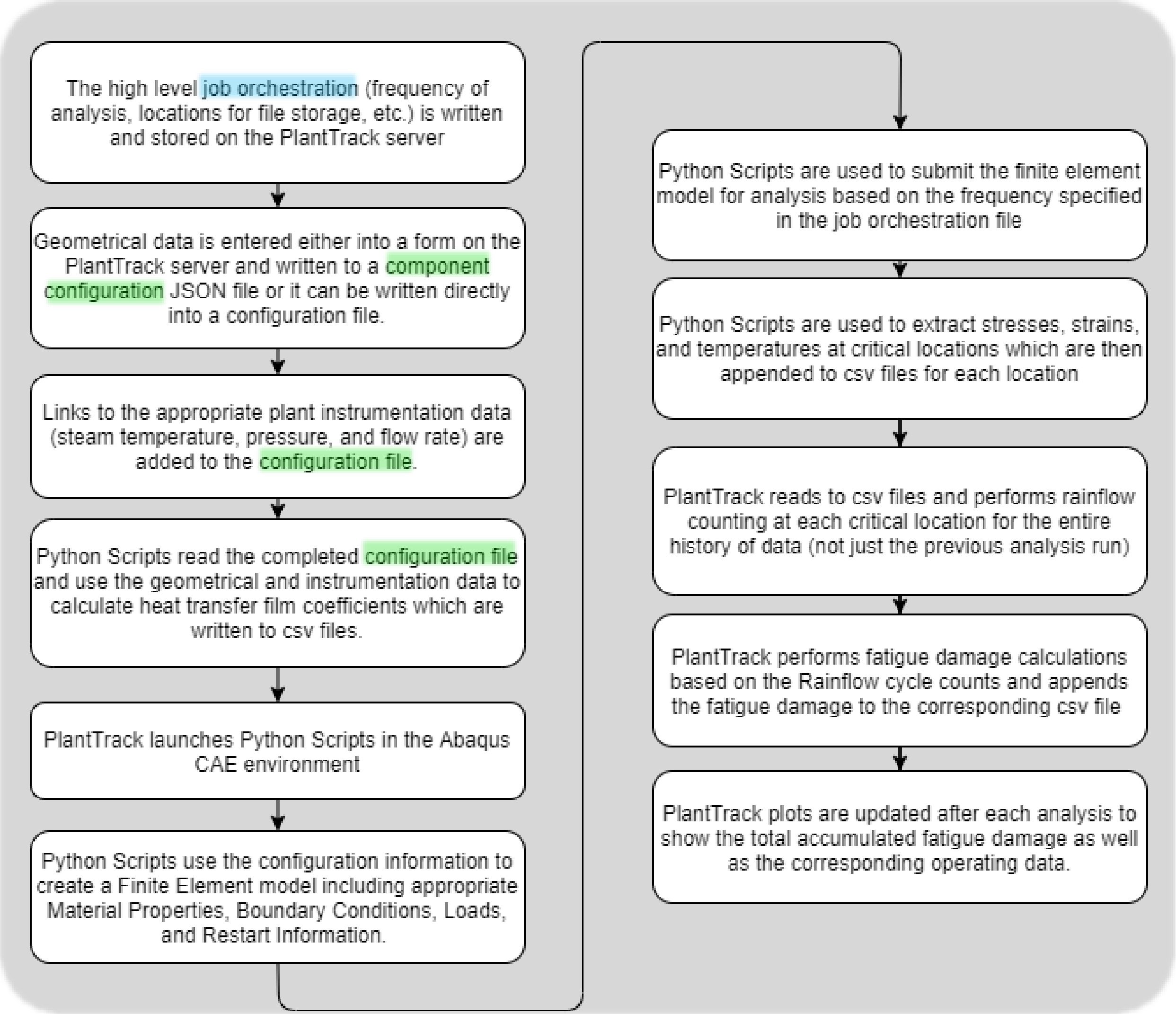




Flow Diagram of Real-Time Analysis

High-level view of analysis process

Following slides show snippets from the job orchestration and component configuration files



Job Orchestration


```
{
  "backgroundJobs": {
    "download": true,
    "process": true,
    "upload": true
  },
  "path": {
    "jobRootPath": "C:\\PlantTrack\\PlantTrackAnalyticsJob\\Demo\\",
    "inputFolderName": "Input",
    "workingFolderName": "Working",
    "outputFolderName": "Output",
    "inputArchiveFolderName": "Input Archive",
    "outputArchiveFolderName": "Output Archive",
    "componentConfigFolderName": "ComponentConfig"
  },
  "source": {
    "connectorType": "piserver",
    "serviceUrl": "http://155.109.19.244:8081/",
    "userName": "structI",
    "password": "******"
  },
  "schedule": {
    "scheduleType": "Frequency",
    "scheduleTime": "",
    "scheduleFrequencyHours": "24",
    "nextRunTime": "8/12/2020 2:00:00 AM"
  },
  "destination": {
    "connectorType": "Planttrack",
    "password": "******",
    "userName": "planttracksupport@structint.com",
    "serviceBaseUrl": "https://planttrack.structint.com/PlantTrackAPI/",
    "serviceName": "api/Data/SaveAnalyticsData",
    "subDomain": "Demo"
  }
}
```

Component Configuration

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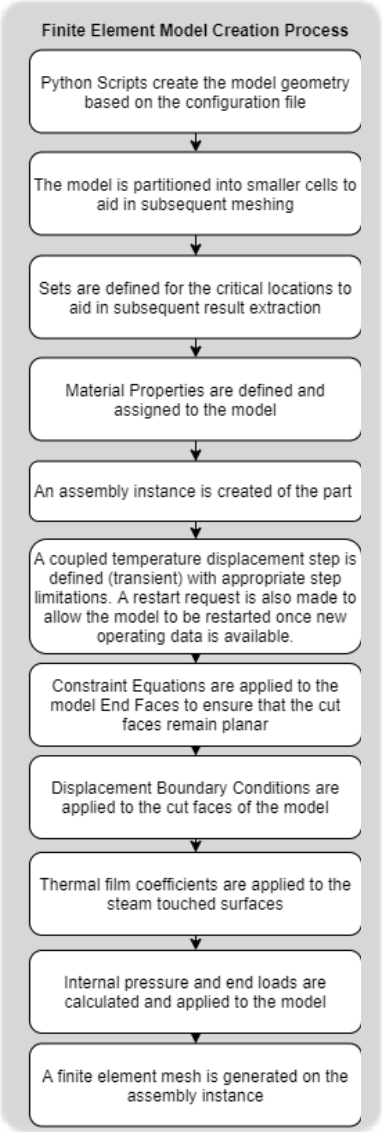
```
"Component_Type": "Header",
"Component_Name": "Superheat Outlet Header",
"Damage_Mechanism": "AbaqusFatigue",
"Material": "Gr 22",
"Operating_Data": {
  "Fields": [
    {
      "Field_Name": "Temperature",
      "Field_Tag": "3BAATE409",
      "Field_Unit": "C",
      "Field_Correction": 0,
      "Field_Correction_Unit": "C"
    },
    {
      "Field_Name": "Pressure",
      "Field_Tag": "3BAAPT416",
      "Field_Unit": "MPa"
    },
    {
      "Field_Name": "Flow_Rate",
      "Field_Tag": "HP1C-S006-MF",
      "Field_Unit": "kg/s"
    }
  ]
},
```

```
"Feature_Geometry": {
  "Outer_Diameter": 22.25,
  "Outer_Diameter_Unit": "in",
  "Wall_Thickness": 3.5,
  "Wall_Thickness_Unit": "in",
  "Tube_Outer_Diameter": 2.0,
  "Tube_Outer_Diameter_Unit": "in",
  "Tube_Wall_Thickness": 0.357,
  "Tube_Wall_Thickness_Unit": "in",
  "Tube_Axial_Pitch": 20,
  "Tube_Axial_Pitch_Unit": "in",
  "Tube_Angular_Distance": 28,
  "Tube_Angular_Distance_Unit": "in",
  "Number_of_Tubes": 4,
  "Angle_First_Tube_With_Y_Axis": 0.0,
  "Borehole_Diameter": 1.875,
  "Borehole_Diameter_Unit": "in"
}
```

Scripted Model Generation



The flow chart to the left shows the processes orchestrated by Python scripts (which drive the FE program)

Scripts were written to generate typical header geometries

- Not all atypical geometries are accounted for by scripts
- Modular nature allows a user to manually modify a geometry generated by the scripts or utilize existing FE model

Following slides provide figures of specific stages in this process

FE Model Monitoring Locations

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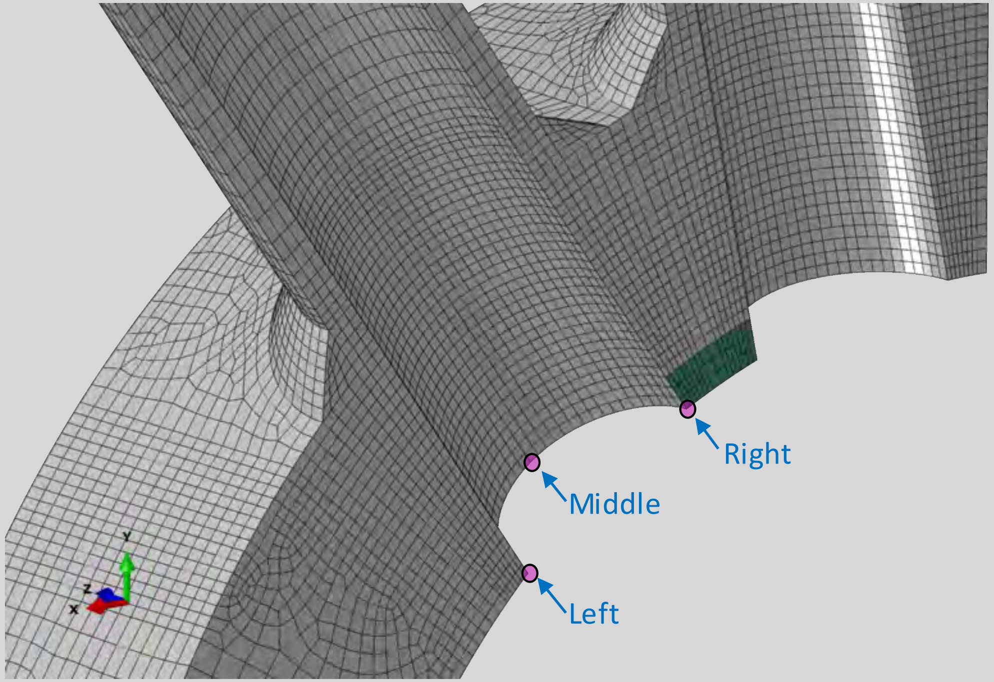
Finite Element Model Creation Process

1. Python Scripts create the model geometry based on the configuration file
2. The model is partitioned into smaller cells to aid in subsequent meshing
3. Sets are defined for the critical locations to aid in subsequent result extraction
4. Material Properties are defined and assigned to the model
5. An assembly instance is created of the part
6. A coupled temperature displacement step is defined (transient) with appropriate step limitations. A restart request is also made to allow the model to be restarted once new operating data is available.
7. Constraint Equations are applied to the model End Faces to ensure that the cut faces remain planar
8. Displacement Boundary Conditions are applied to the cut faces of the model
9. Thermal film coefficients are applied to the steam touched surfaces
10. Internal pressure and end loads are calculated and applied to the model
11. A finite element mesh is generated on the assembly instance



For monitoring damage and crack development on the axial and circumferential ligaments, stresses are extracted at three locations around each tube borehole (Left, Middle, Right)

FE Model Displacement Boundary Conditions

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Finite Element Model Creation Process

Python Scripts create the model geometry based on the configuration file

↓

The model is partitioned into smaller cells to aid in subsequent meshing

↓

Sets are defined for the critical locations to aid in subsequent result extraction

↓

Material Properties are defined and assigned to the model

↓

An assembly instance is created of the part

↓

A coupled temperature displacement step is defined (transient) with appropriate step limitations. A restart request is also made to allow the model to be restarted once new operating data is available.

↓

Constraint Equations are applied to the model End Faces to ensure that the cut faces remain planar

↓

Displacement Boundary Conditions are applied to the cut faces of the model

↓

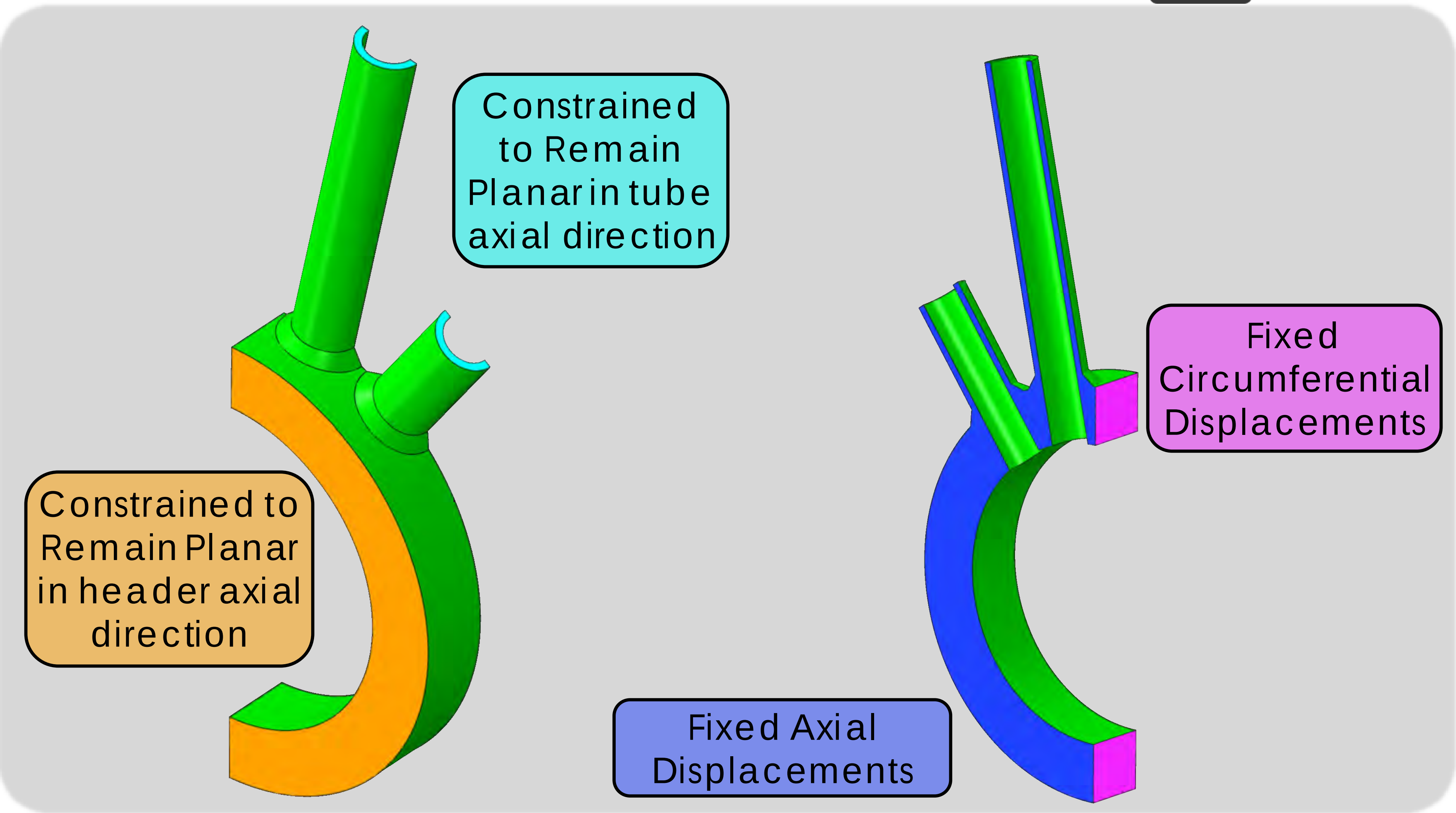
Thermal film coefficients are applied to the steam touched surfaces

↓

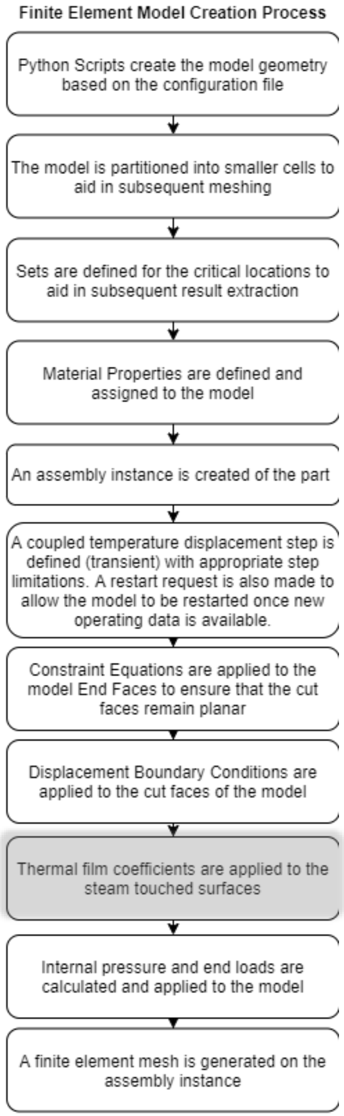
Internal pressure and end loads are calculated and applied to the model

↓

A finite element mesh is generated on the assembly instance



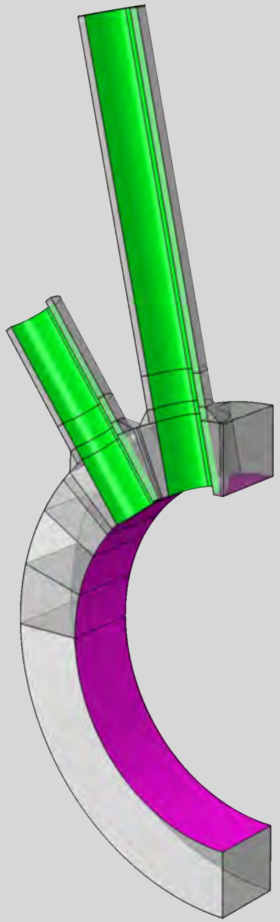
FE Model Thermal Boundary Conditions



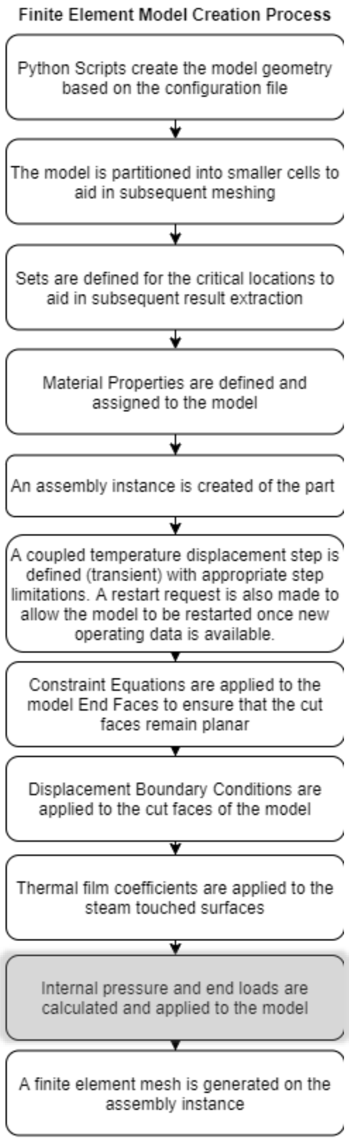
Surface film boundary conditions are applied to the ID surfaces for thermal transients

Surface film boundary conditions require:

- **Sink temperature**
  - Measured steam temperature or a local tube temperature (with adjustments)
- **Heat Transfer Film Coefficient**
  - Calculated based on the provided steam temperature, pressure, and steam flow rate.
  - Dependent on the size of the flow path and flow

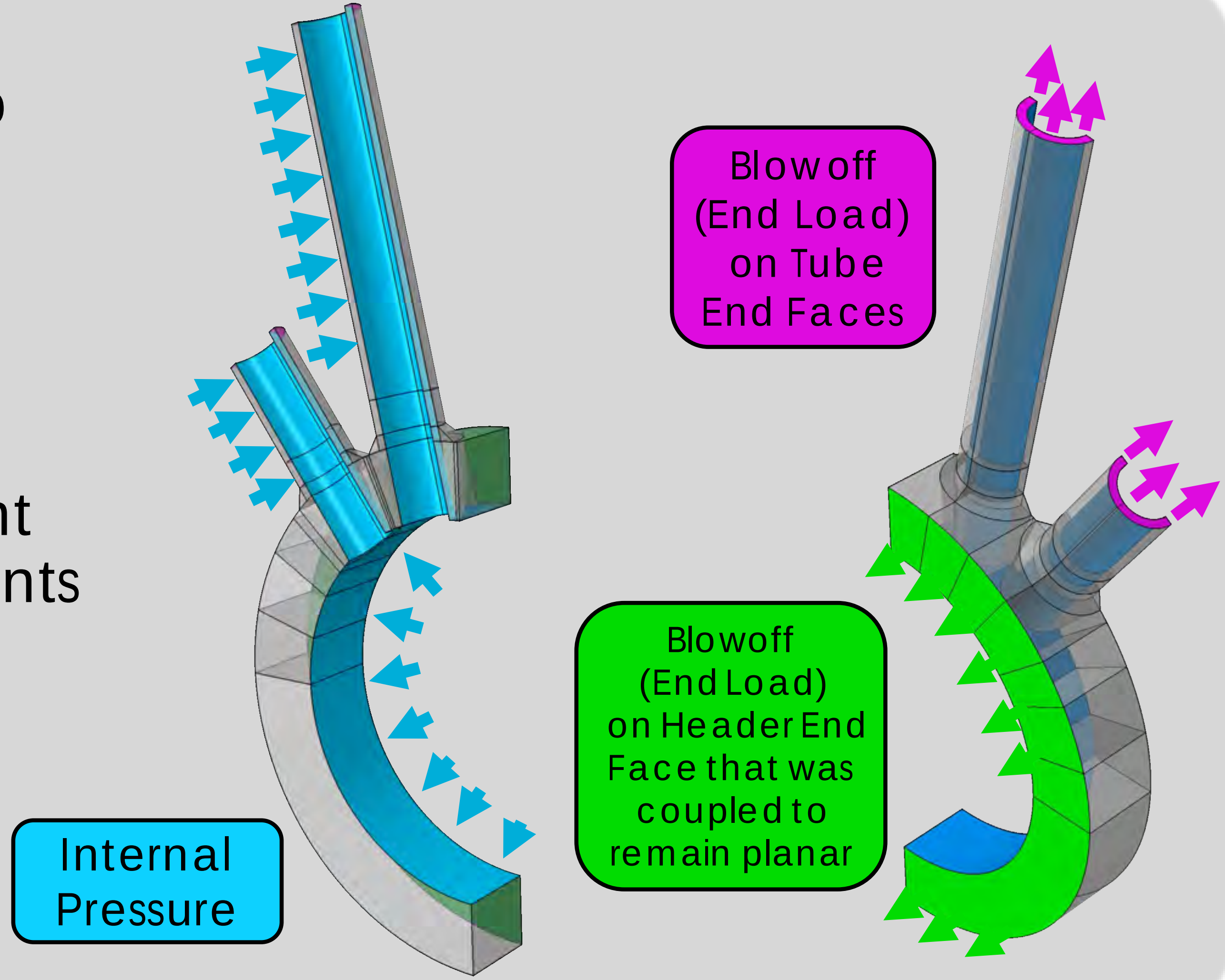


FE Model Pressure Loading



Internal pressure loading applied to the ID surfaces

End loads are also applied to the cut faces that don't have displacement boundary constraints to balance the internal pressure



FE Model Mesh

Finite Element Model Creation Process

- Python Scripts create the model geometry based on the configuration file
- ↓ The model is partitioned into smaller cells to aid in subsequent meshing
- ↓ Sets are defined for the critical locations to aid in subsequent result extraction
- ↓ Material Properties are defined and assigned to the model
- ↓ An assembly instance is created of the part
- ↓ A coupled temperature displacement step is defined (transient) with appropriate step limitations. A restart request is also made to allow the model to be restarted once new operating data is available.
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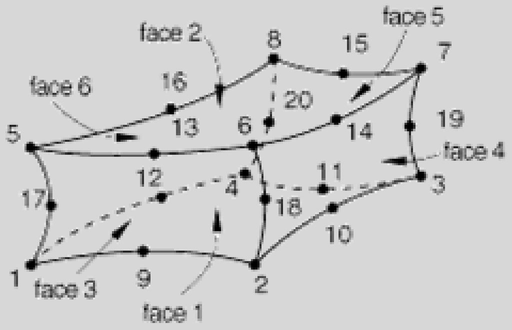
- ↓ Thermal film coefficients are applied to the steam touched surfaces
- ↓ Internal pressure and end loads are calculated and applied to the model
- ↓ A finite element mesh is generated on the assembly instance

Multiple options in configuration for desired mesh refinement

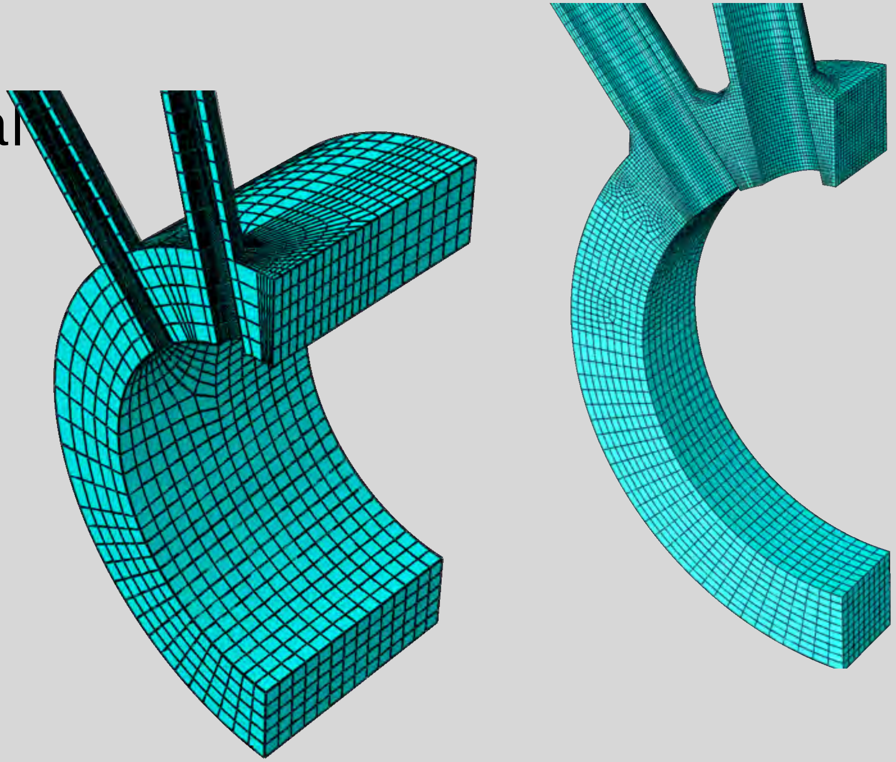
Coarse mesh typically used for initial validation

Fine mesh is typically used for final analysis and continual results trending

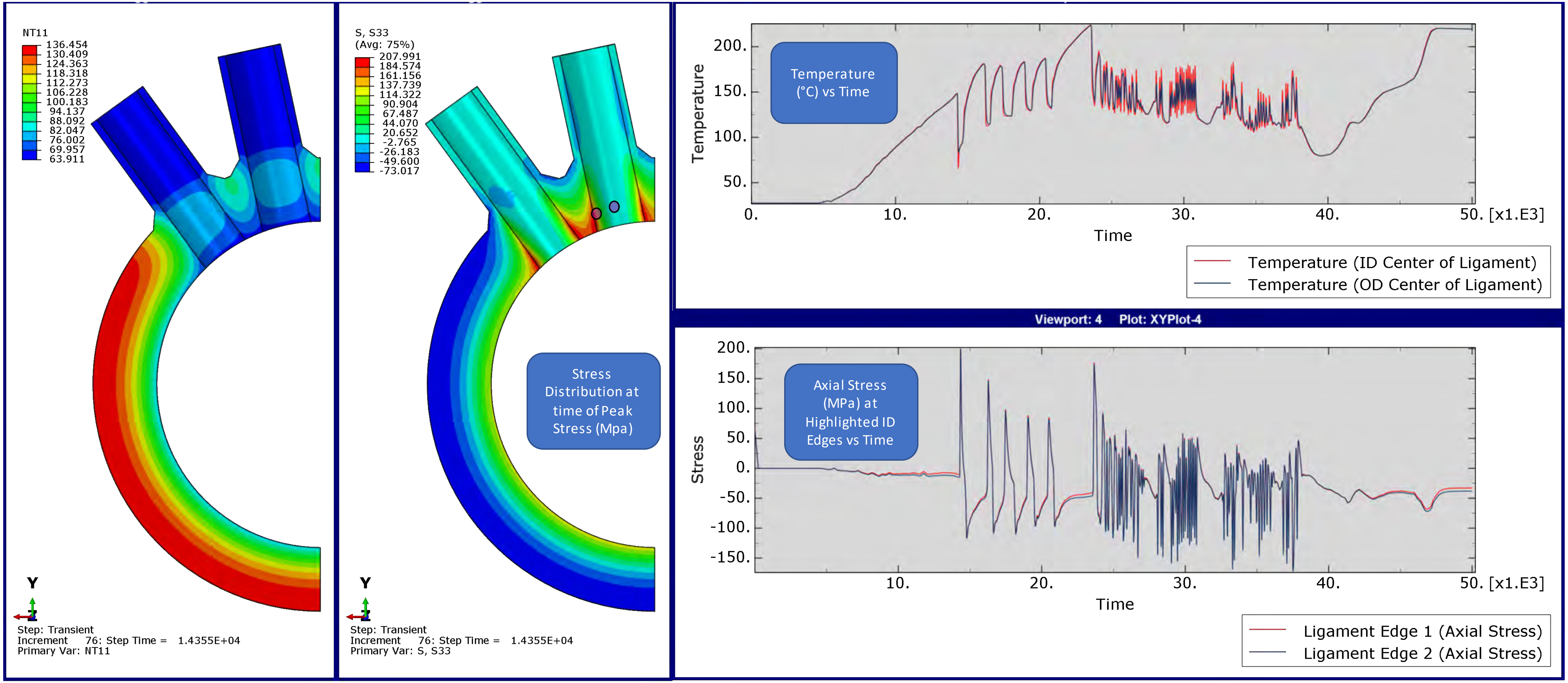
Meshed with quadratic reduced integration brick elements



20 - node element



Screenshot of example analysis



Crack Modeling

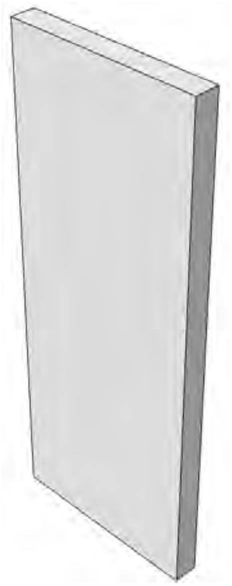
Crack Modeling – XFEM Method

Possibility of using extended finite elements (XFEM) was investigated

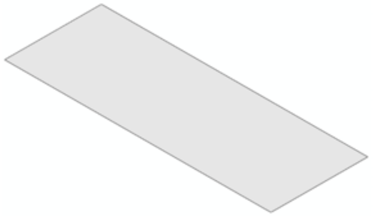
Allows cracks to be modeled without requiring a specific crack tip mesh

- Doesn't require remeshing with crack growth
- Allows more natural crack shapes

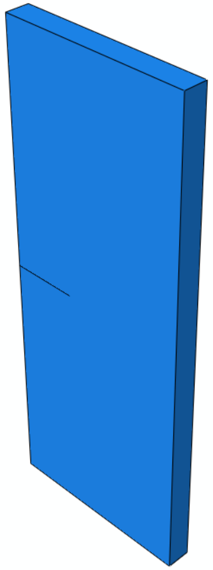
Only mechanism for growth in current implementation is fatigue, does not support creep crack tip parameter measurement, Ct



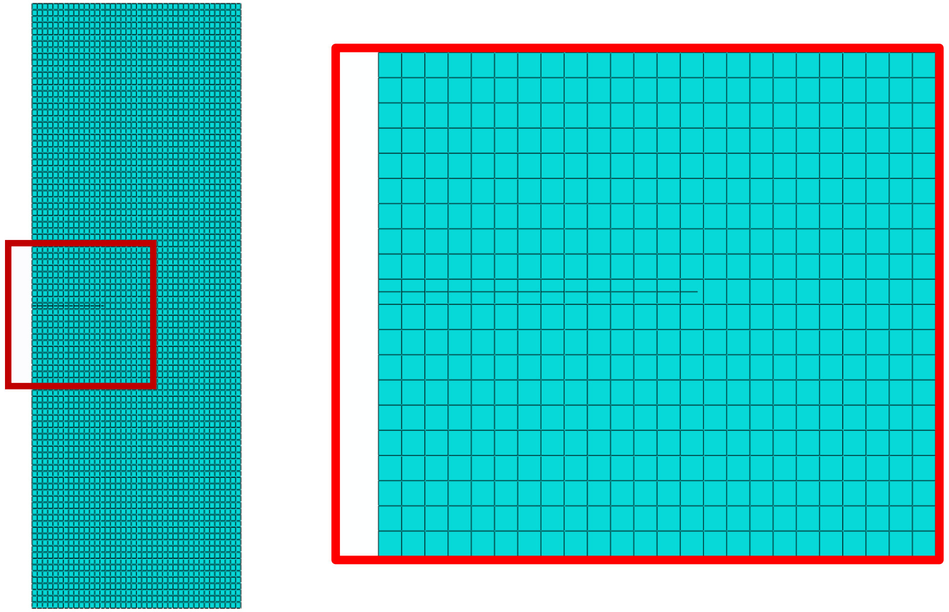
Cracked body



Crack surface



Assembled cracked body and crack surface



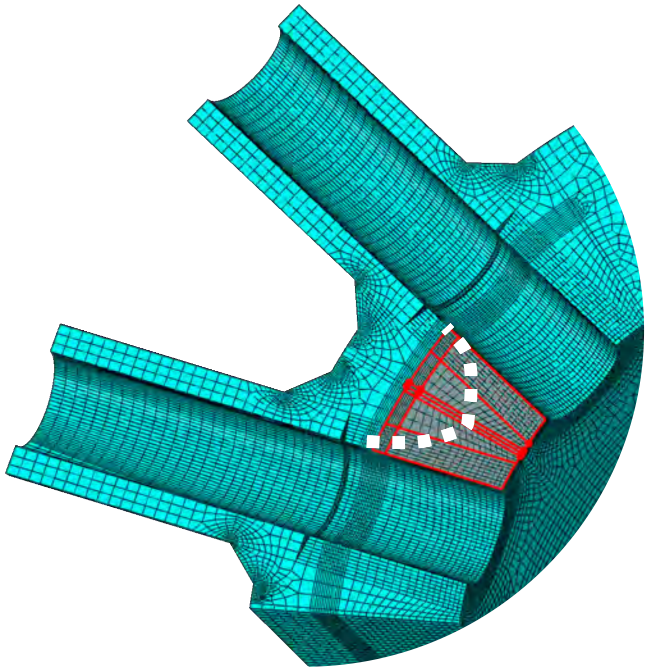
Meshed Model with Crack showing that the Crack doesn't have to conform to mesh boundaries (i.e. Mesh Independent)

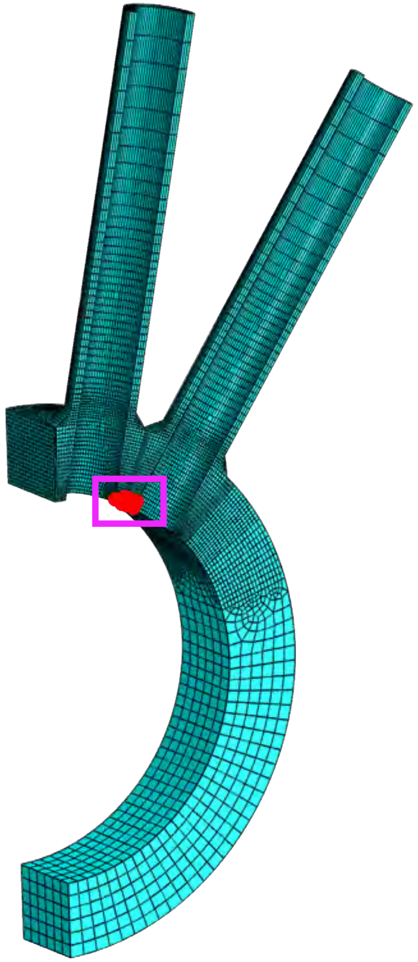
Crack Modeling

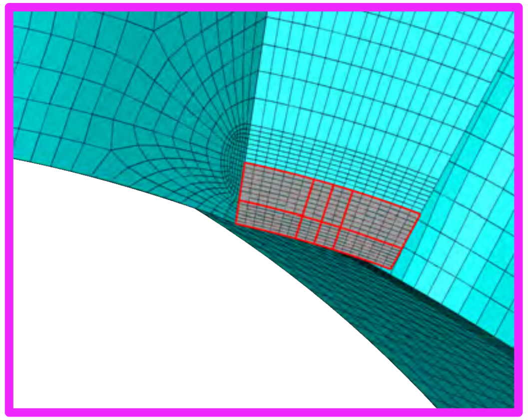
As a result of limitations with XFEM, explicit crack modeling was chosen

- Still provides improved crack tip solutions relative to simplified hand formulations.
- Allows measurement of creep crack tip parameters
- Requires simplification of crack shape (which cannot be measured precisely in the field anyway)
- Requires explicit crack tip mesh (circular partition around crack tip swept across ligament)w

The model shows typical natural ligament crack shape as a dotted white line along with the simplified crack shape in red.





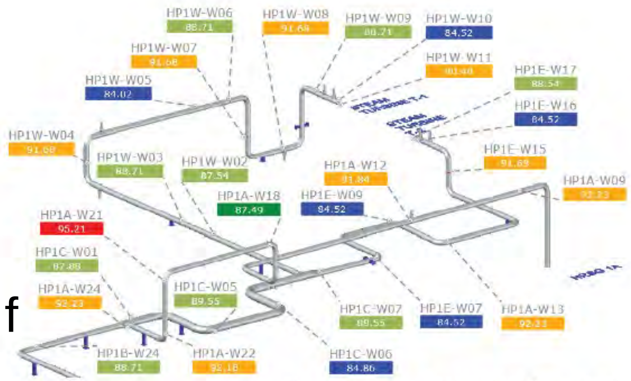


PlantTrack Screenshots

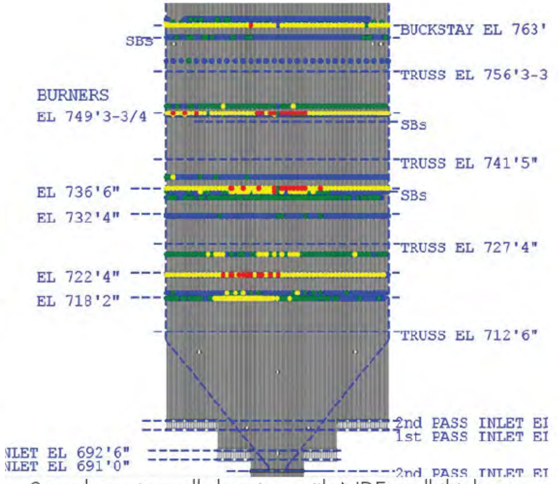
PlantTrack

Existing web-based data management system which provides a graphical user interface for:

- location specific design data
- historical inspection results
- maintenance and repairs actions
- engineering data on either uploaded copies of design drawings or on 3D models



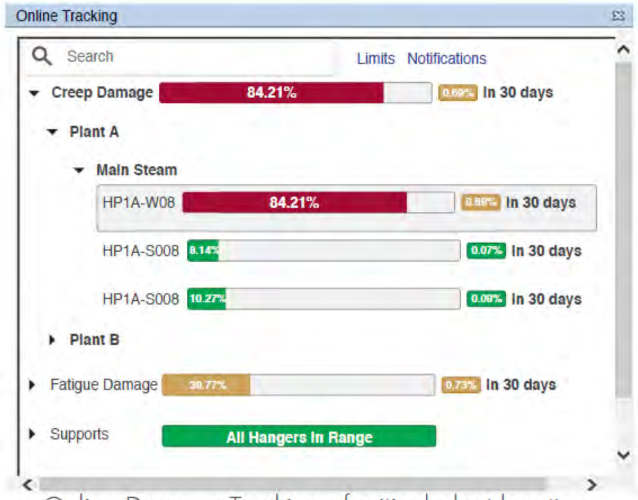
Sample piping system with risk scores (0-100) from SI's Vindex prioritization approach



Sample waterwall drawing with NDE wall thickness readings

Used to perform subsequent engineering analyses/calculations to help:

- prioritize locations for future inspections
- aid in assessments of relevant damage mechanisms
- overall life management



Online Damage Tracking of critical plant locations

The following slides provide screenshots from configuration of this project

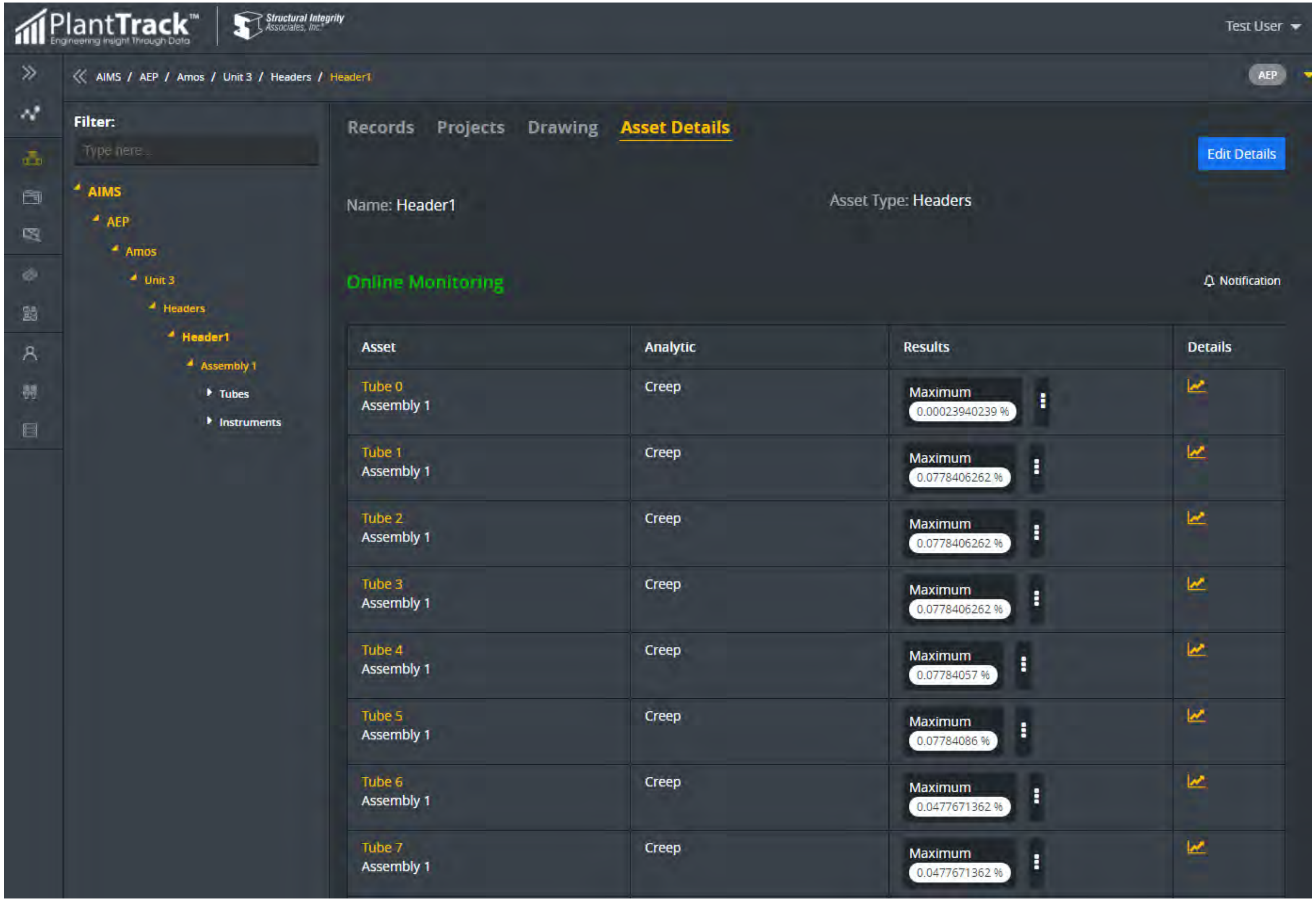
PlantTrack™
Engineering Insight Through Data

Main Screen

NATIONAL ENERGY TECHNOLOGY LABORATORY

The screenshot to the right shows the main PlantTrack screen

- On the left side of the screen as well along the top, there is a file path or tree which shows which components have been configured or can be viewed.
- File structure was built to allow monitoring multiple locations across a plant or utility
- Clicking higher up in the tree would allow the most critical locations from the further down the tree to be summarized and compared so that multiple headers could be prioritized

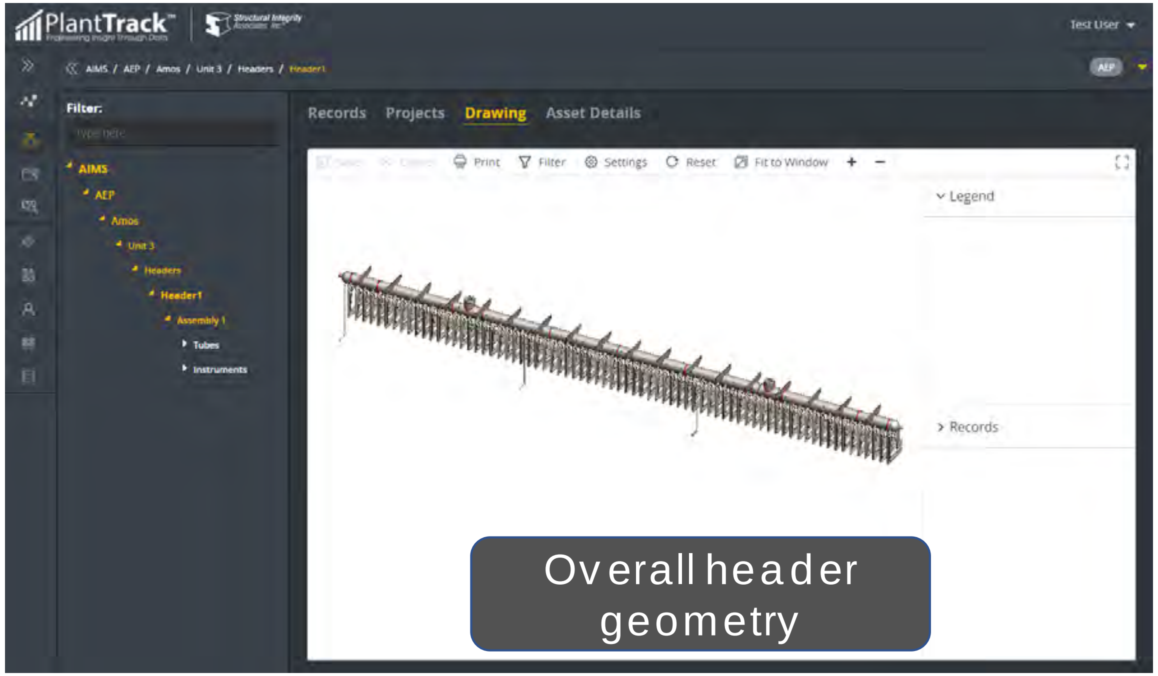


Drawings

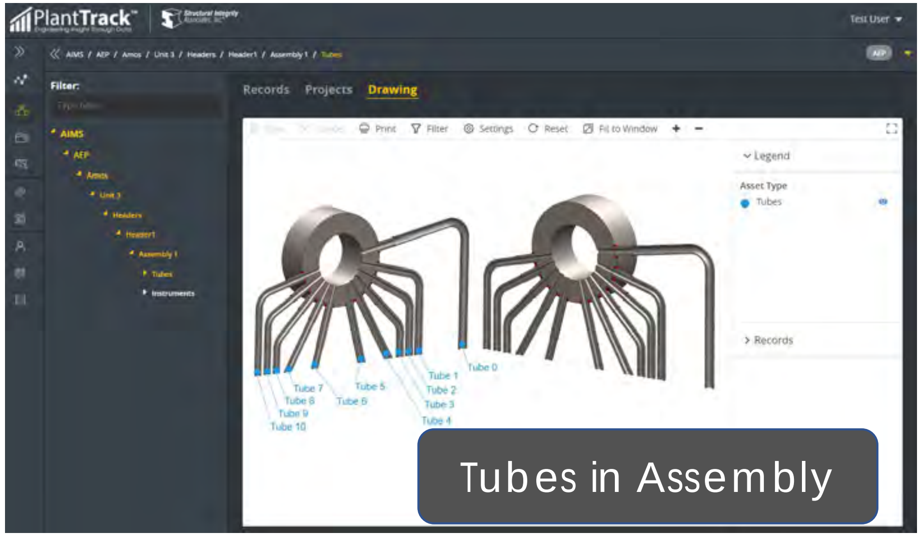
Option to upload drawings of each component in order to show the locations being monitored or to use for tracking historic inspection data

The figures on this slide show the overall header geometry, tubes in an assembly, installed instrumentation

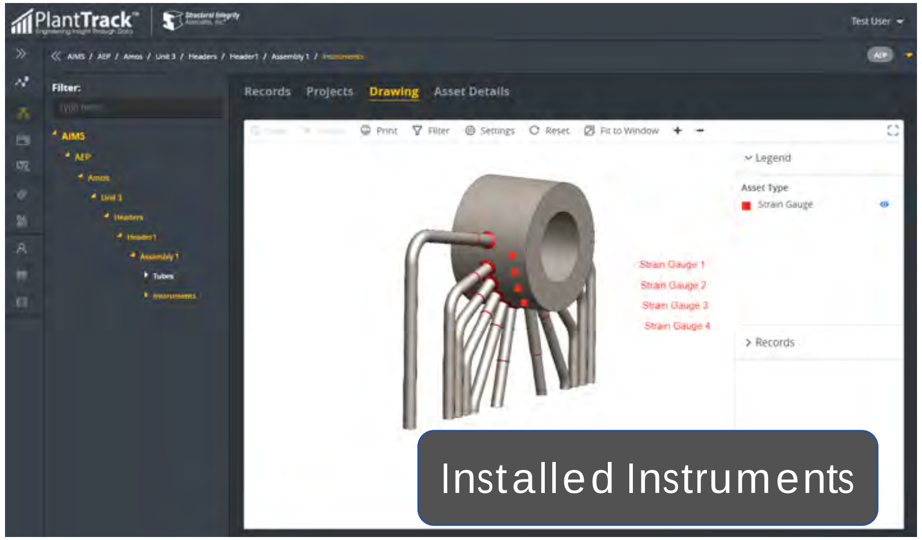
- Option to configure more locations as needed (e.g. hangers, socket welds, seam welds, etc.)



Overall header geometry



Tubes in Assembly



Installed Instruments

Geometry Creation

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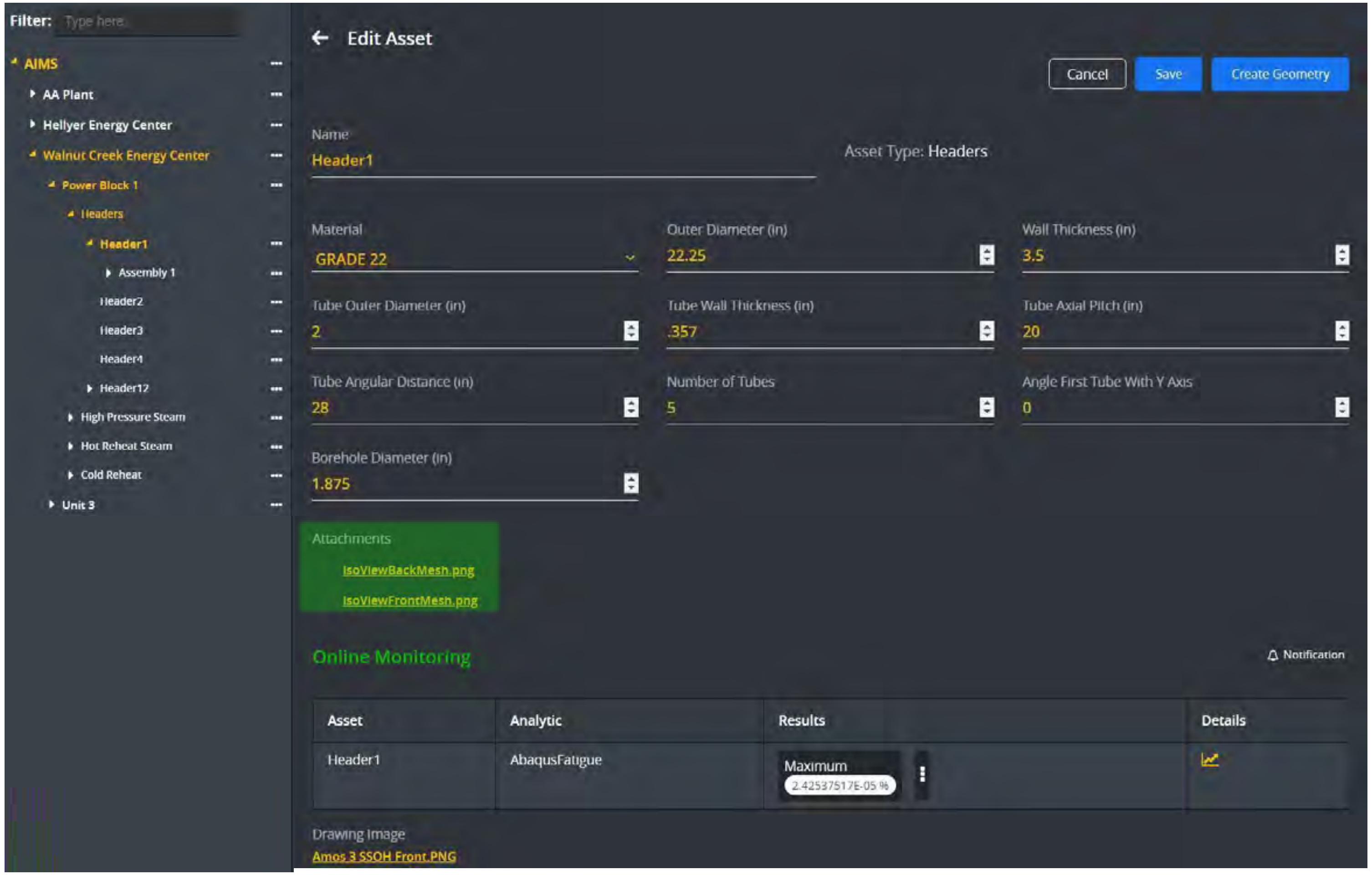
As discussed in earlier sections, as part of this project an initial header geometry creation page was also configured

Once a user fills in the fields and clicks the “Create Geometry” option:

- Scripts launch Abaqus CAE
- Generate the model
- Attached PNG picture files here for verification



Asset Details

Clicking asset details for a unit, plant, header, or assembly shows a list of monitored locations

The screenshot to the right shows that the Amos SSOH header was configured for:

- creep damage on each tube
- fatigue damage (which is currently summarizing the results of all the tubes though each tube's results can be seen by drilling down into this option)
- as well as strain gauge calculations and field measurements

In the future, screen will also show "predicted" crack size once explicit crack modeling has been finalized

- For each location, with and without cracks, there is also the option to upload ultrasonic inspection records showing the as-found crack sizes

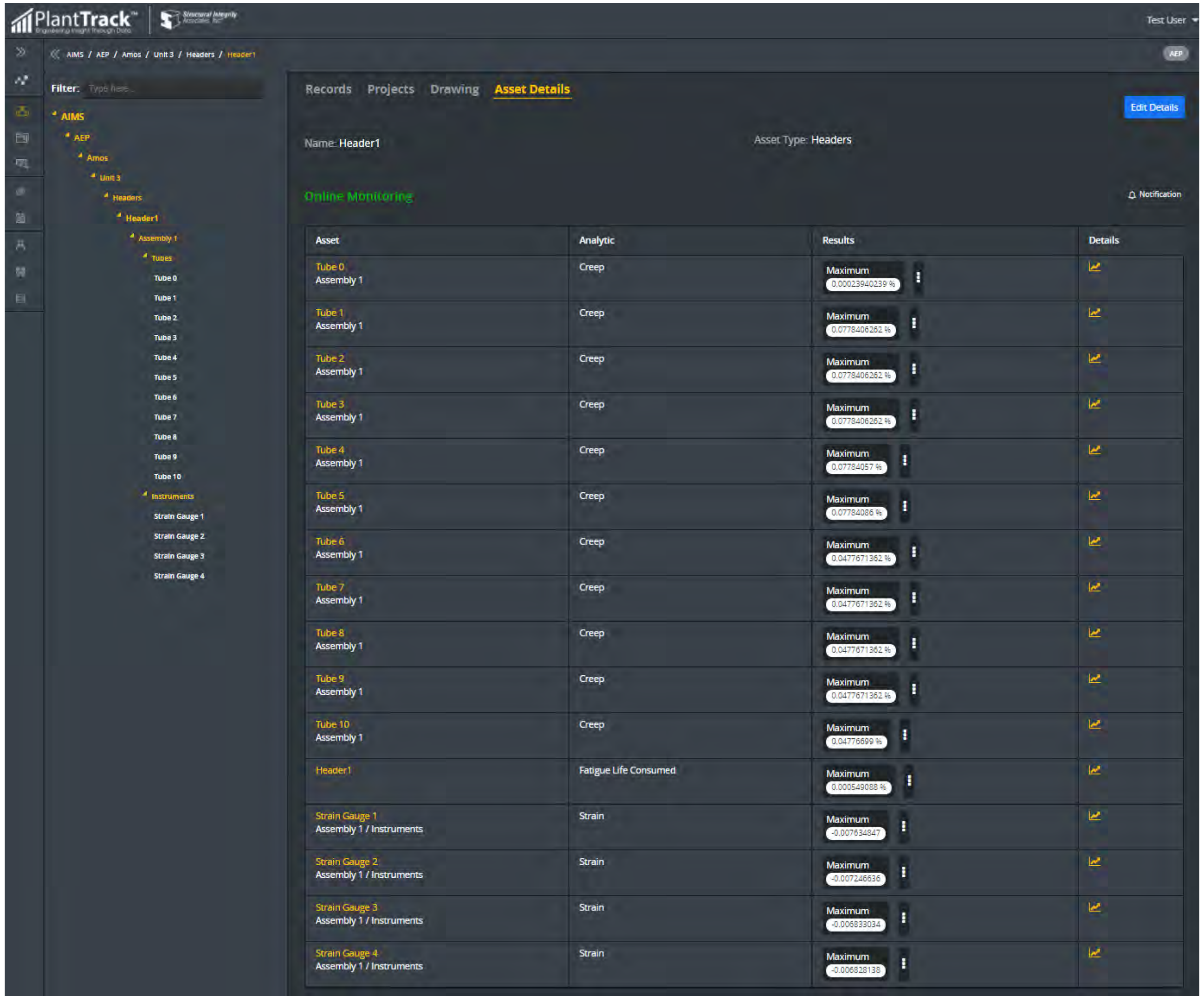


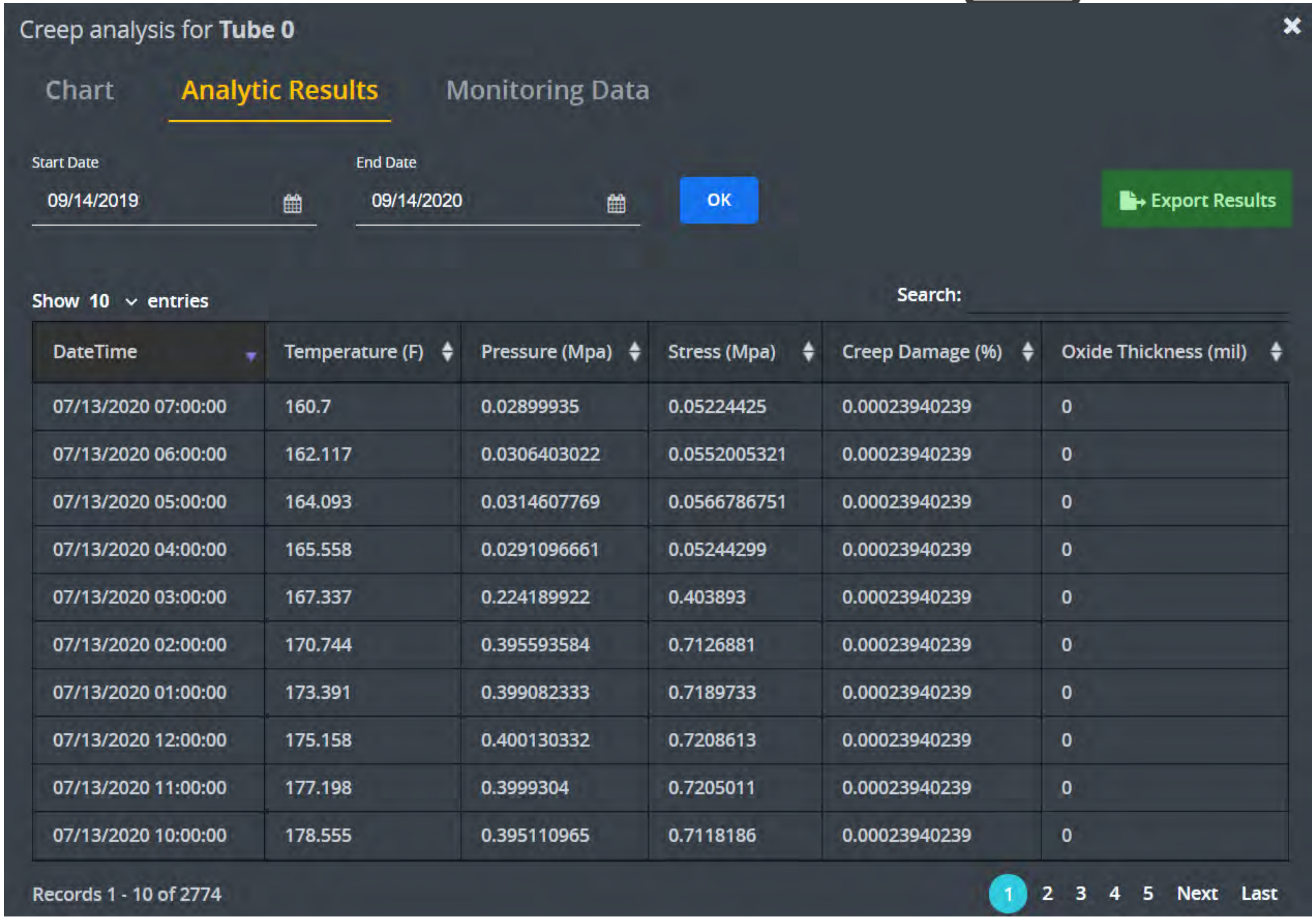
Chart Output

- For each monitored location, there is an option to drill further down into the details of the calculations by clicking the details option
- Plot both the operating data used for monitoring as well as calculated creep or fatigue life at a particular location
- In the top left, there is an option to change the plot time range to drill down to specific startups/shutdowns/and or months
- Also option to switch from the chart to tabular results

Creep Damage

The screenshot to the right shows the tabular results mentioned on the last slide for creep damage

- Export results option which provides the user with an excel file of all the analytic results to interrogate further



DateTime	Temperature (F)	Pressure (Mpa)	Stress (Mpa)	Creep Damage (%)	Oxide Thickness (mil)
07/13/2020 07:00:00	160.7	0.02899935	0.05224425	0.00023940239	0
07/13/2020 06:00:00	162.117	0.0306403022	0.0552005321	0.00023940239	0
07/13/2020 05:00:00	164.093	0.0314607769	0.0566786751	0.00023940239	0
07/13/2020 04:00:00	165.558	0.0291096661	0.05244299	0.00023940239	0
07/13/2020 03:00:00	167.337	0.224189922	0.403893	0.00023940239	0
07/13/2020 02:00:00	170.744	0.395593584	0.7126881	0.00023940239	0
07/13/2020 01:00:00	173.391	0.399082333	0.7189733	0.00023940239	0
07/13/2020 12:00:00	175.158	0.400130332	0.7208613	0.00023940239	0
07/13/2020 11:00:00	177.198	0.3999304	0.7205011	0.00023940239	0
07/13/2020 10:00:00	178.555	0.395110965	0.7118186	0.00023940239	0

Records 1 - 10 of 2774 1 2 3 4 5 Next Last

Fatigue Damage

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As with the last slide which depicted the creep damage for one of the tubes, the plots below show the tabular summaries of fatigue damage calculated from the finite element output

Fatigue Life Consumed analysis for **Header1**

Chart | **Analytic Results** | Monitoring Data

Start Date 09/14/2019 End Date 09/14/2020 OK Export Results

Show 10 entries Search:

DateTime	Location	Position	Fatigue Damage (%)	Stress (Mpa)	Tube Temperature (C)
03/08/2020 04:58:00	Tube0	LEFT	0.000520595	-168.610123	502.820953
03/08/2020 04:58:00	Tube0	MIDDLE	0.000428149	-165.75705	501.508118
03/08/2020 04:58:00	Tube0	RIGHT	0.000530603	-169.499634	501.8528
03/08/2020 04:58:00	Tube10	LEFT	0.000541003	-165.36644	544.091
03/08/2020 04:58:00	Tube10	MIDDLE	0.00046088	-154.843353	544.5023
03/08/2020 04:58:00	Tube10	RIGHT	0.000549088	-164.191467	545.151
03/08/2020 04:58:00	Tube1	LEFT	0.000541003	-166.40773	547.2491
03/08/2020 04:58:00	Tube1	MIDDLE	0.000485223	-154.515533	545.443542
03/08/2020 04:58:00	Tube1	RIGHT	0.000549088	-165.020264	543.3098
03/08/2020 04:58:00	Tube2	LEFT	0.000532919	-167.058044	548.006836

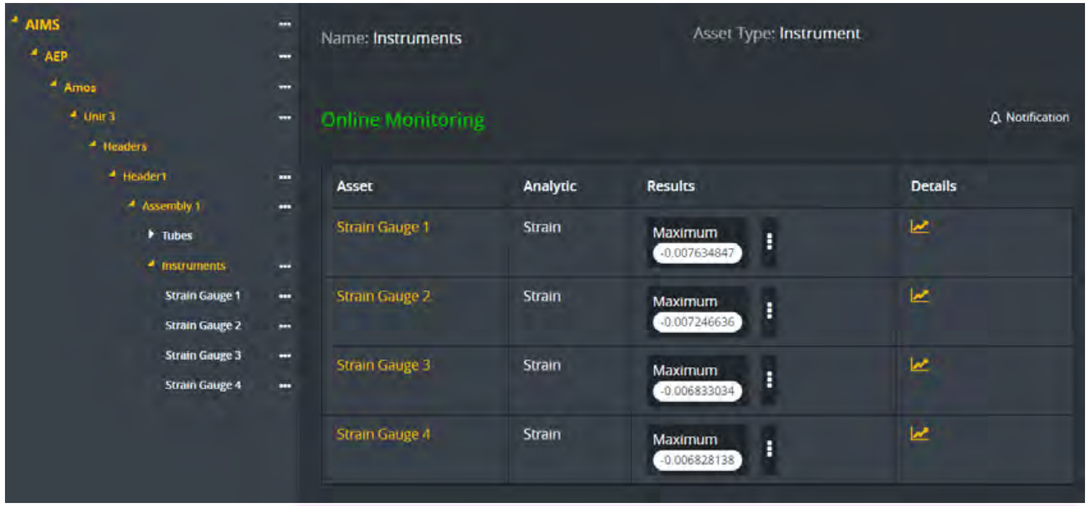
Records 1 - 10 of 8217 1 2 3 4 5 Next Last

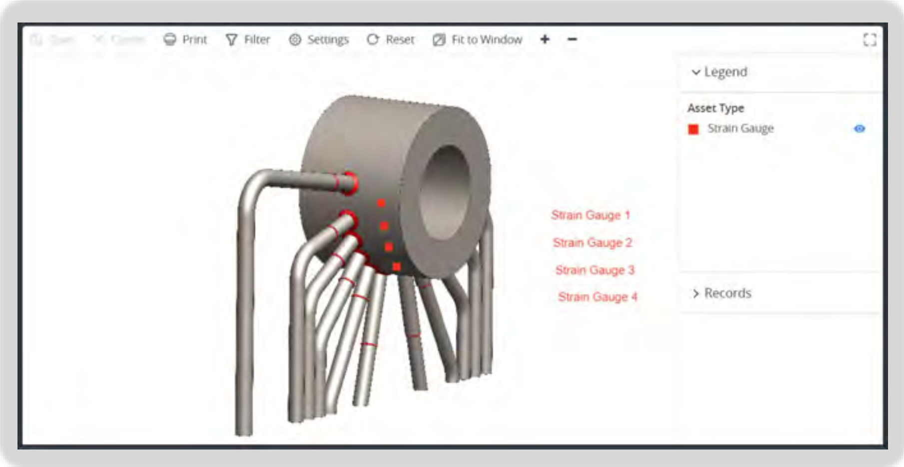
Strain Gauge Measurement

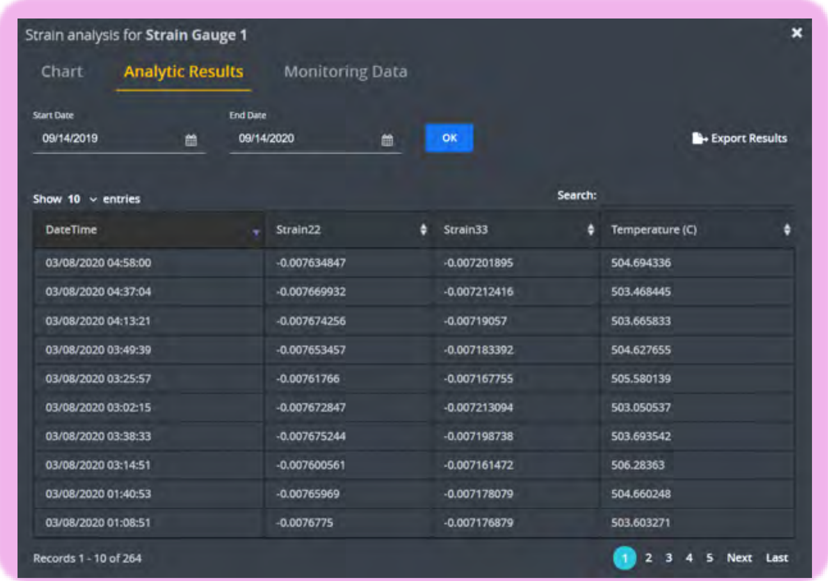
Lastly, the screenshots to the right show a breakdown of the instrumentation on the header

The intentions for the strain gauge measurements are to:

- Show the locations of gauges on the overall header on a drawing
- Show the calculated strain output from the Finite Element model
- Show the measured strain output from the installed gauges (available after the gauges are installed)
- Plot the comparison







DateTime	Strain22	Strain33	Temperature (C)
03/08/2020 04:58:00	-0.007634847	-0.007201895	504.694336
03/08/2020 04:37:04	-0.007669932	-0.007212416	503.468445
03/08/2020 04:13:21	-0.007674256	-0.00719057	503.665833
03/08/2020 03:49:39	-0.007653457	-0.007183392	504.627655
03/08/2020 03:25:57	-0.00761766	-0.007167755	505.580139
03/08/2020 03:02:15	-0.007672847	-0.007213094	503.050537
03/08/2020 03:38:33	-0.007675244	-0.007198738	503.693542
03/08/2020 03:14:51	-0.007600561	-0.007161472	506.28363
03/08/2020 01:40:53	-0.00765969	-0.007178079	504.660248
03/08/2020 01:08:51	-0.0076775	-0.007176879	503.603271

Phase III - 2021

Phase III Tasks – Based on current status

Process real-time operating data from AEP and include strain data in PlantTrack as it becomes available

- Once the strain gauges are installed during the November outage at Amos, real data can be included in PlantTrack to compare against the calculated

Trend damage development and compare the results against the actual strain measurements from Amos and, where necessary make adjustments/refinements to the FE model and scripts

Continue to develop crack growth algorithms

- Primary task is finalizing automated crack tip meshing in the ligaments to support crack size monitoring for Amos

Planned Final Deliverables

Description of online damage/life monitoring system outlining the software components, architecture, and system integration

- This document will not provide the source or compiled code, but rather will outline in further detail that others can understand how the system functions and could conceivably implement a version of it
- Document specific challengers and limitations that were incurred and how these problems were solved or worked around

Description of configuration for Amos host plant, including:

- definition of geometry
- monitoring locations
- specific set-up / assumptions made
- IT architecture

Description of results of operation of the online monitoring software for a period of approximately one-year

- Documentation of boiler transients experienced and estimated damage, with appropriate off-line calculations to provide verification / validation
- Document the practicality of the approach and any lessons learned during the project
- Document any steps that would be required for future commercialization

Installation Plan/Plant Status
EPRI/AEP

Revised Installation Plan

Strain sensors will be installed on the Secondary Superheater Outlet Header (SSOH) Front or near tube row 25 from the left-hand side wall

- Multiple existing header thermocouples will be used
- Repair/replace if necessary

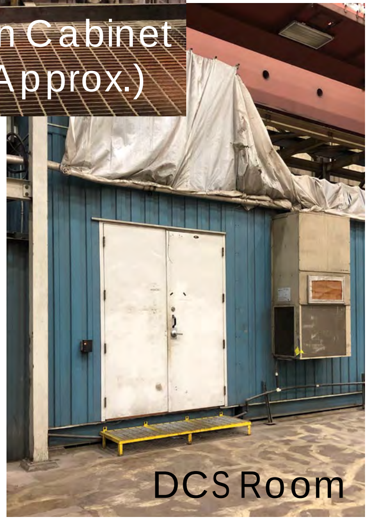
Penetrations to be made through boiler casing

A termination cabinet will be installed on or near the West Side of 307’ 6” elevation

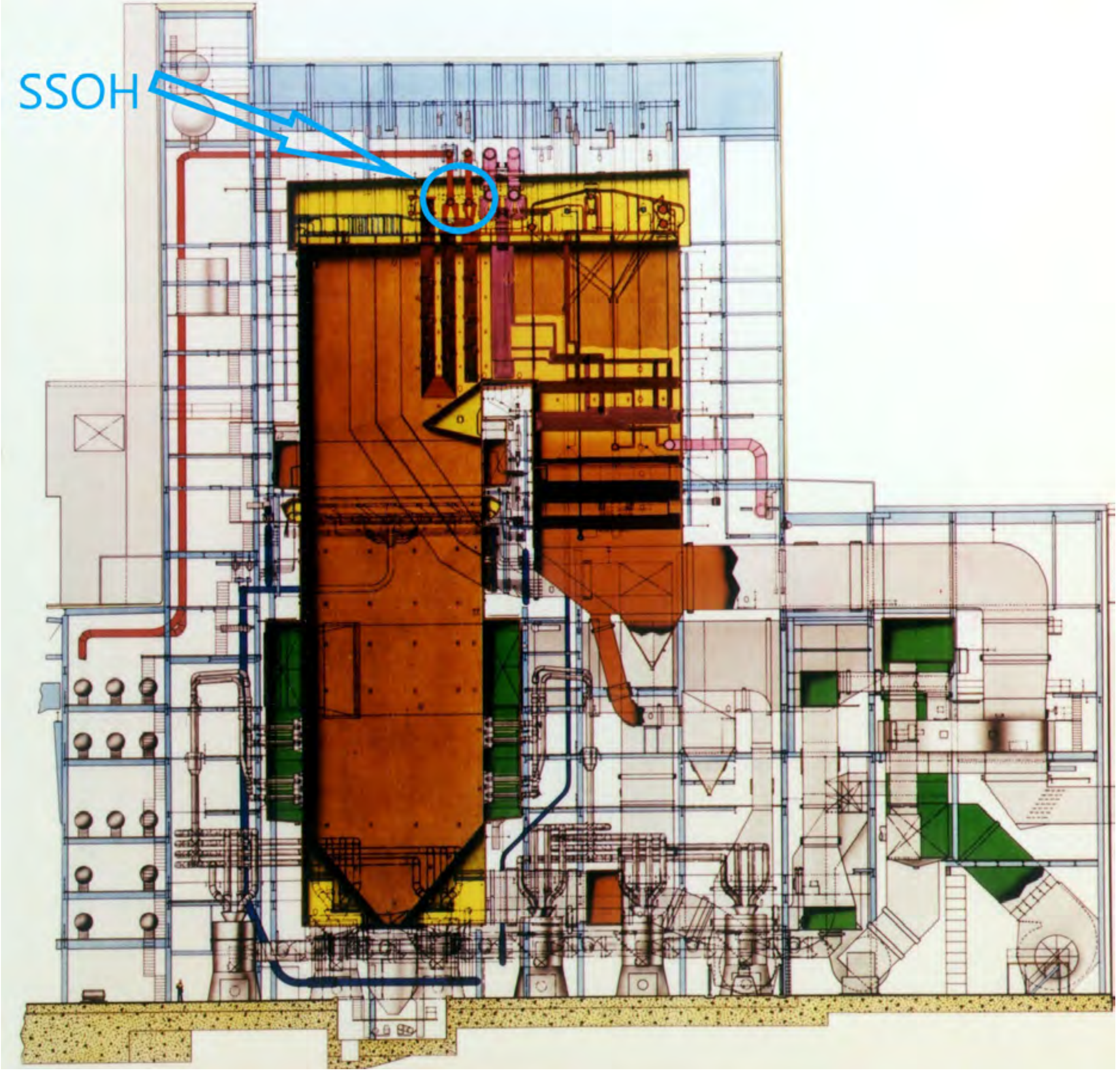
- Conduits from boiler casing penetrations to cabinet
- Data conversion/communication devices to be installed during outage

Data acquisition/data processing equipment will be located inside the DCS room located on the Turbine Floor of Unit 3

- Optical fiber communication cable from cabinet to DCS room

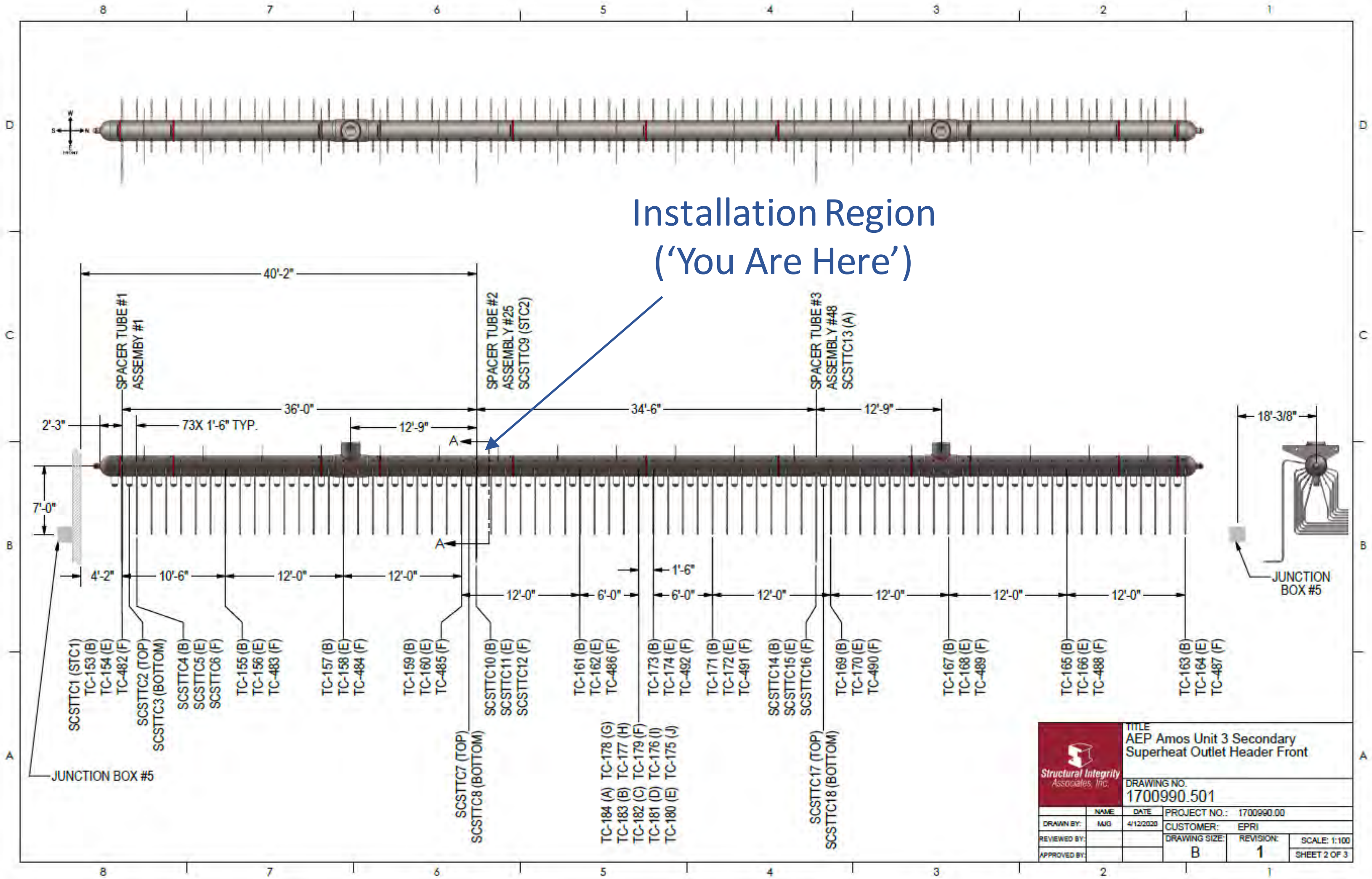


Amos Unit 3

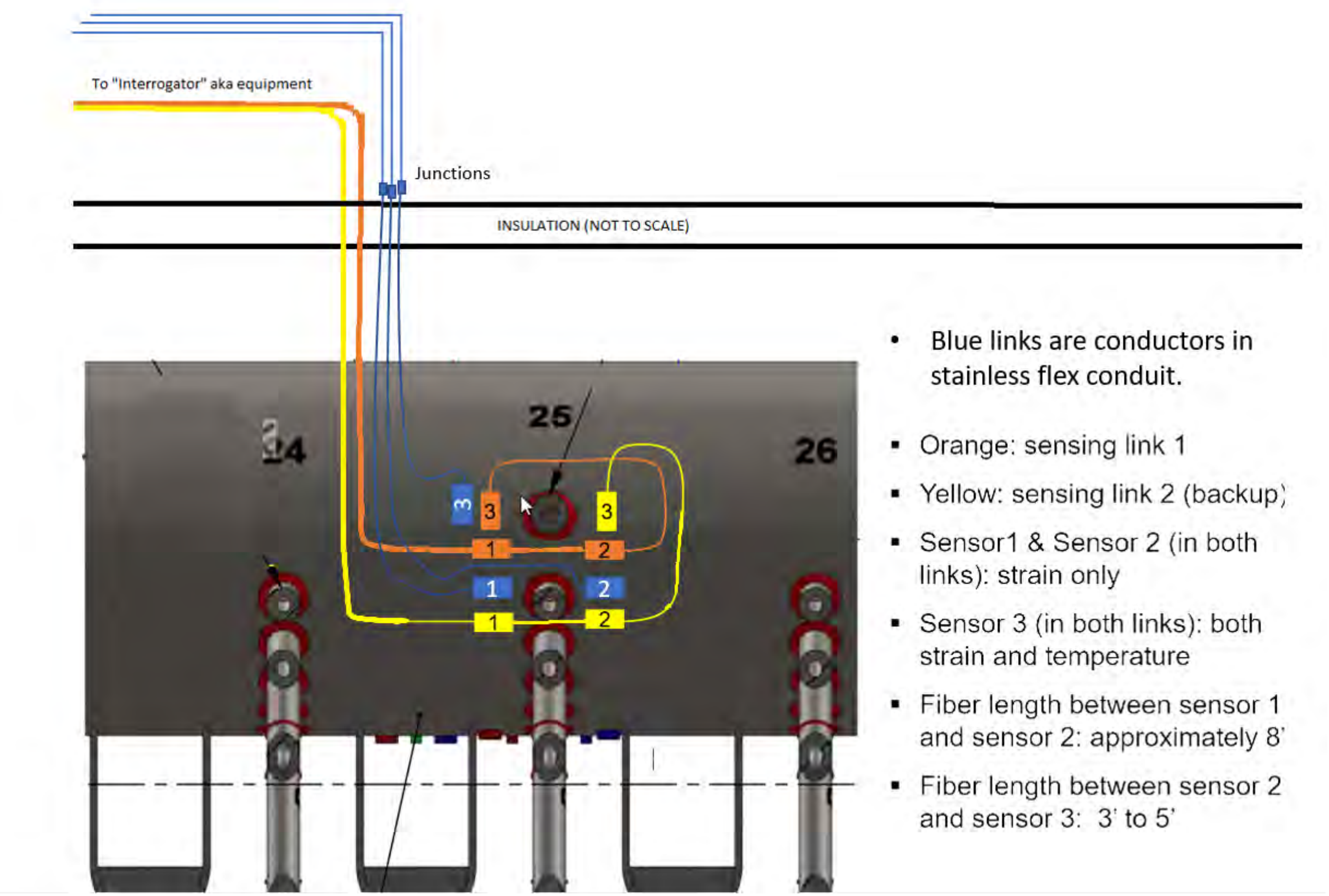


Amos Unit 3

Secondary Superheat Outlet Header Front



Installation Near Tube Row #25



Orange - Sentek Sensing Link 1
Yellow - Sentek Sensing Link 2
Blue - Suprock Strain Gauges

Not Shown:

- Existing plant thermocouples
- SI strain gauges to be installed as needed in vicinity of Suprock gauges

Note: Installation of Sentek gauges postponed

Outage Installation Schedule

Day 1	Unit removed from service
Day 2	Plant begins cooling penthouse, as soon as practical (placeholder - plant is responsible for schedule)
Day 9	Project parties arrive on site for safety training listed in Section 6.0 of Installation Plan
Day 10*	Access to penthouse granted (tentative) Insulation removed for access to SSOH in vicinity of tube row 25 Additional cooling installed at SSOH in vicinity of tube row 25 Project parties (or contractor) identify location on penthouse casing for cable penetrations
Day 11	Cable penetrations performed SI begins prep of header for sensor installation
Day 12	SI and Suprock begin sensor installation
Day 13	Cables routed through penthouse casing penetration and penetration sealed
Day 14	Punchlist items and installation of sensors completed External wiring commences
Day 15	Complete installation of data acquisition systems in DCS room on Turbine Floor Equipment final check-out
* Access to SSOH is dependent on entry date to penthouse and sufficient cooling of SSOH	

Current Status

Amos Unit 3 is Currently in an outage

Contractors are scheduled for installation activities

Plant has requested project parties to be on site on or around 11/16/20 to perform installation start. (equivalent to Day 9 of Outage Installation Schedule)

Advanced Fiber-Optic Design, Packaging and Attachment Methods

Sentek Instrument LLC

Sensor Systems Overview

Distributed temperature sensor (DTS / Sentek LGI-100)

- Fiber Bragg grating (FBG)
- Optical time-domain reflectometry (OTDR)

Distributed acoustic sensor (DAS / Sentek DASnova)

- Fiber-optic interferometry (FOI)
- Optical time-domain reflectometry (OTDR)

Quasi-distributed strain sensor

- FBG + FOI
- Spectral-domain, continuous detection

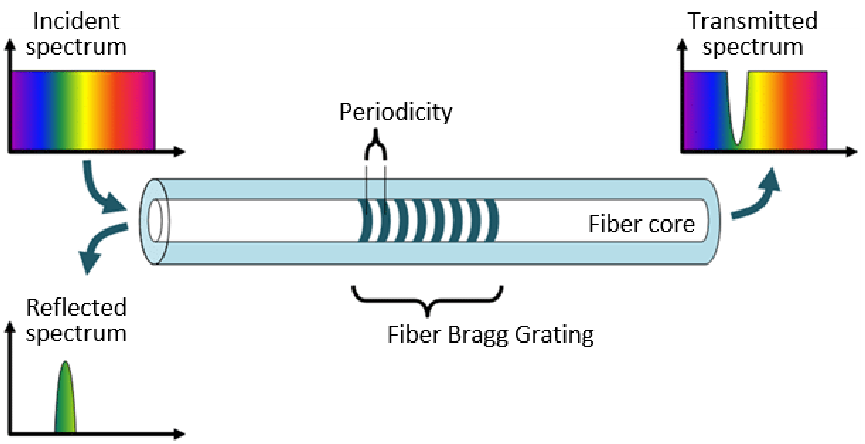
FBG & Sentek DTS Principles

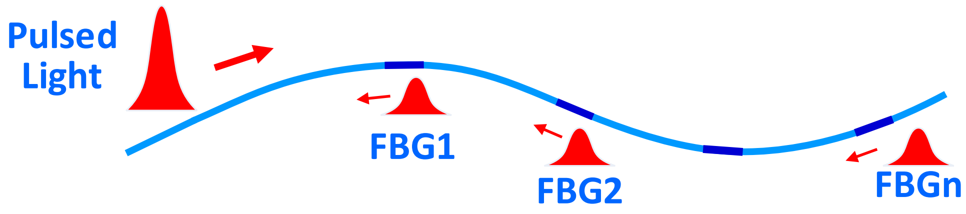
Fiber Bragg grating (FBG)

- Periodic structure inside the fiber
- Reflects a specific wavelength
- Wavelength shifts w/ temperature

Distributed temperature sensor (DTS)

- Pulsed light separates sensor in time
- Interrogates the reflected wavelength
- High capacity, high spatial resolution and high sensitivity





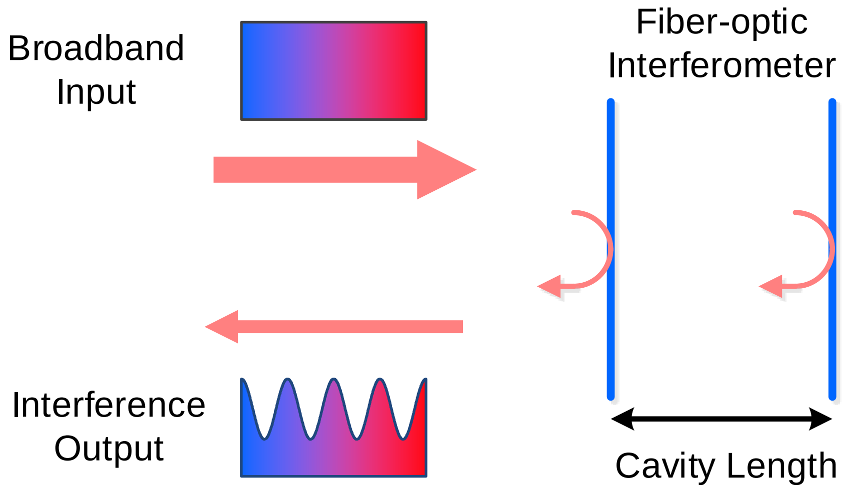
FOI and Sentek DAS Principles

Fiber-optic interferometer (FOI)

- A pair of reflections
- Reflected intensity oscillates w/ wavelength
- Period varies with vibration-induced strain

Sentek distributed acoustic sensor (DAS)

- Pulsed light for sensor separation
- Fringe monitoring for acoustic vibration
- Ultra-high strain sensitivity



Sentek Strain Sensor Principles

FBG + FOI

- Fiber-optic interferometer
- Fiber Bragg grating (FBG)

Sensor Response

- FOI: sensitive to temperature & strain
- *Thermal strain* vs. *Mechanical strain*
- FBG: temperature only (for temperature compensation)

Status of Sensor System Development

Sensor	Validation	Fabrication	Packaging	Software
DTS			In-progress	
DAS			In-progress	
Strain Sensor	In-progress	In-progress		

DTS Summary

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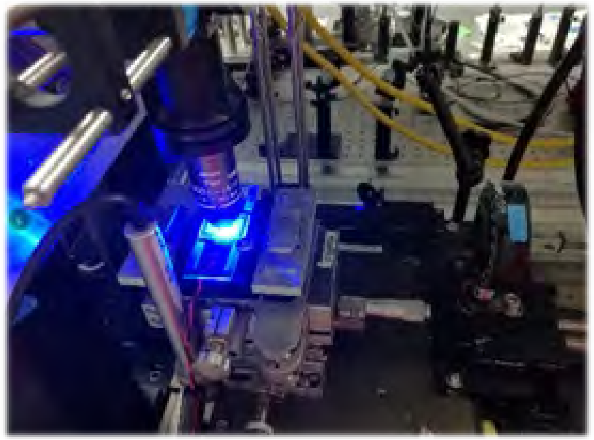
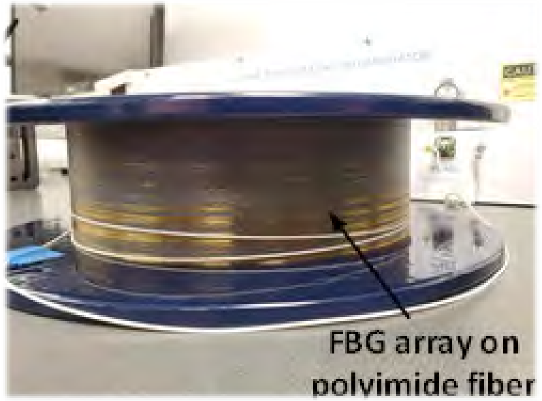
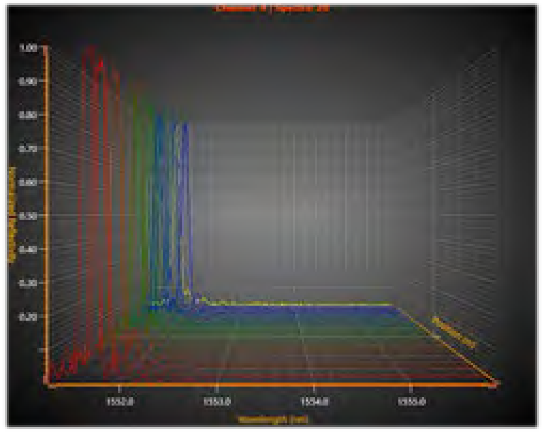
Fabrication



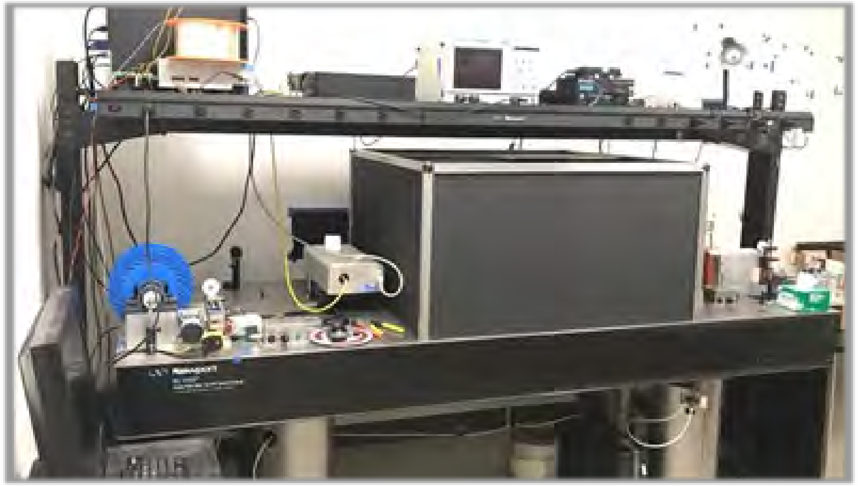
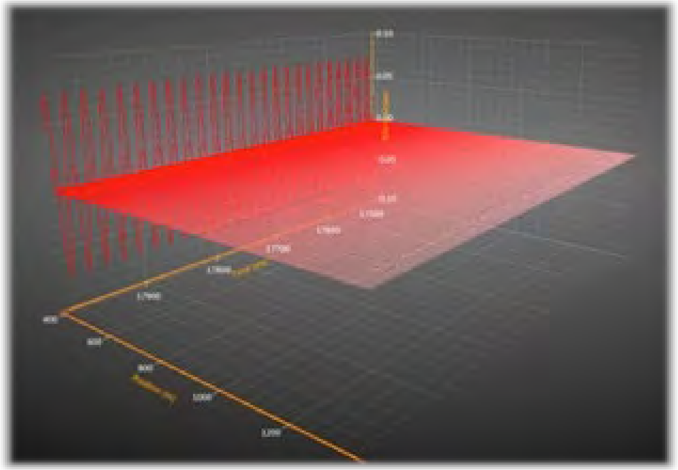
Sensing Fibers



LGI-100 (patented)



DAS Summary

Fabrication	DASnova Interrogator (patent pending)	Sensor Signal Map
		

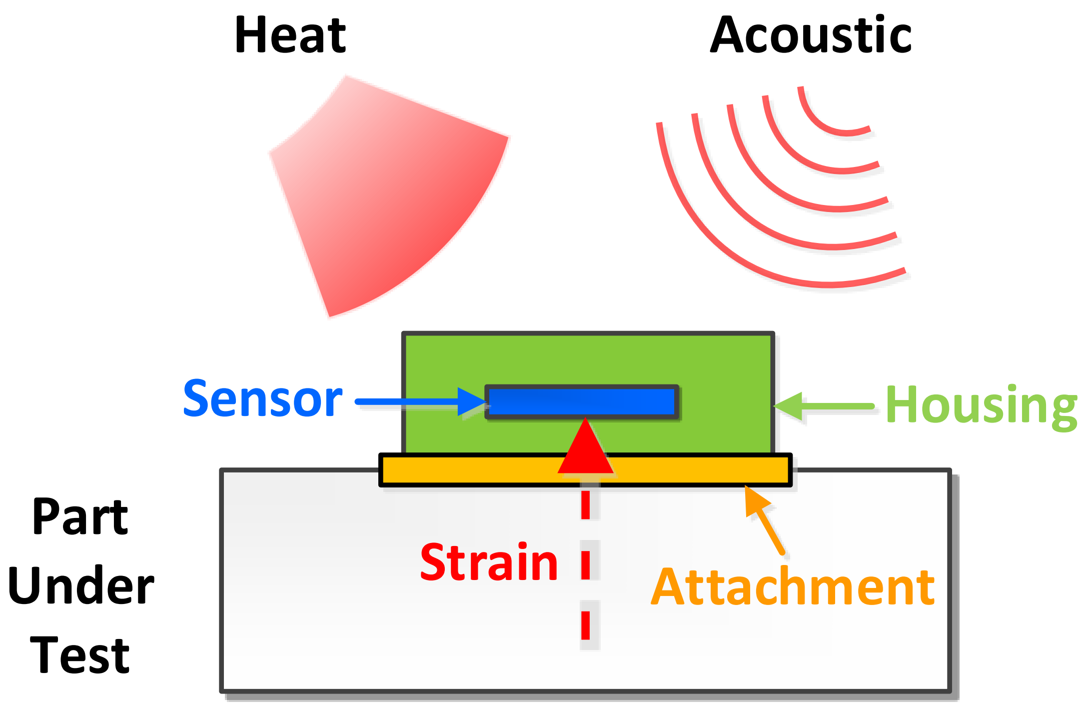
Strain vs. Temperature / Acoustic

Temperature/acoustic

- Easy penetration into sensor

Mechanical strain affected by

- Attachment method
- Housing design
- Materials
- Learn in practice



Strain Sensor Development Review

1st test @ EPRI
Dec 2019

- Valid optical design
- Weak attachment/welding

2nd test @ EPRI
Jul 2020

- Robust attachment
- Robust sensor
- Limited strain response

New design @ Sentek
Aug/Sept 2020

- In-house materials
- Strain transfer enhanced
- Repeatability issue

Next-gen @ Sentek
Sept/Oct 2020

- Custom design
- Enhanced rigidity
- Enhanced strain transfer
- Parts soon to arrive

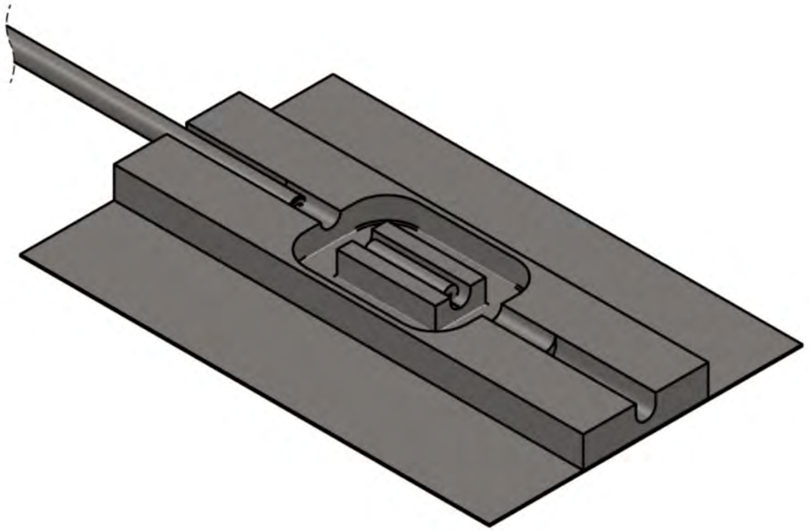
1st Test at EPRI – Sensor Design

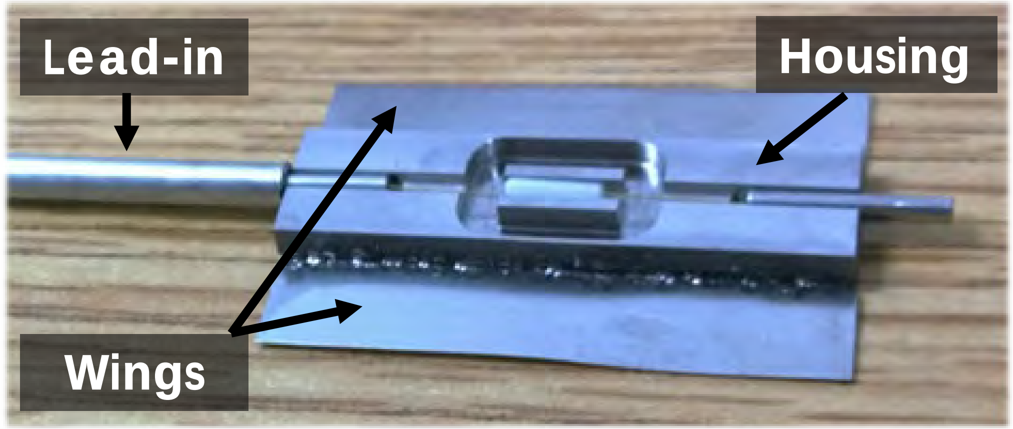
Inconel base and wings

Stainless steel tubing

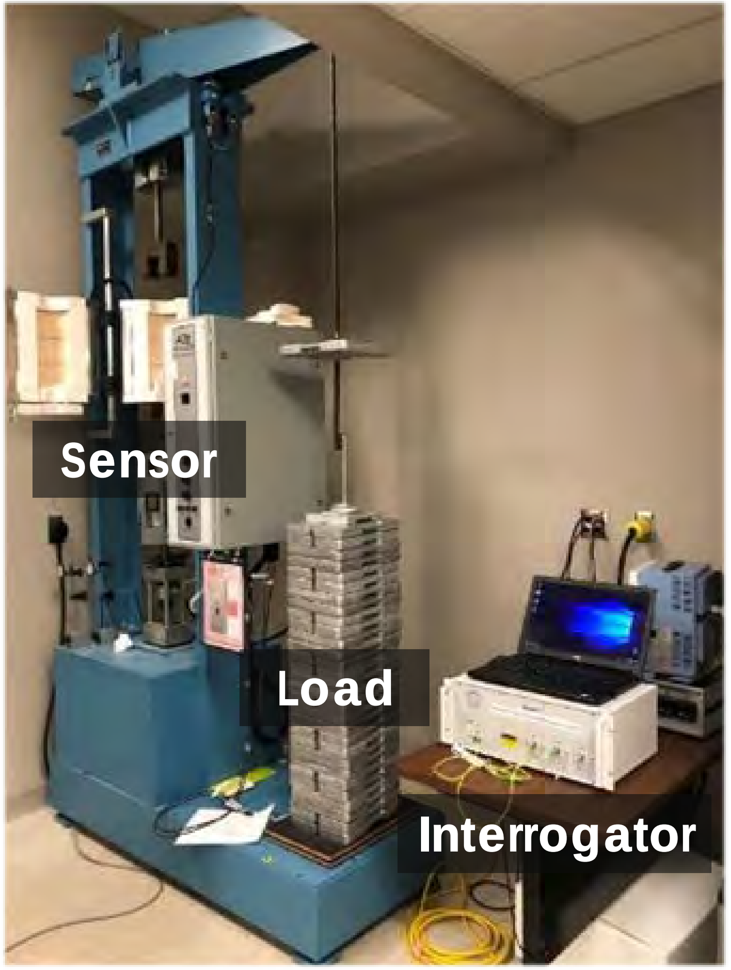
Metallic adhesive for >1000ºC

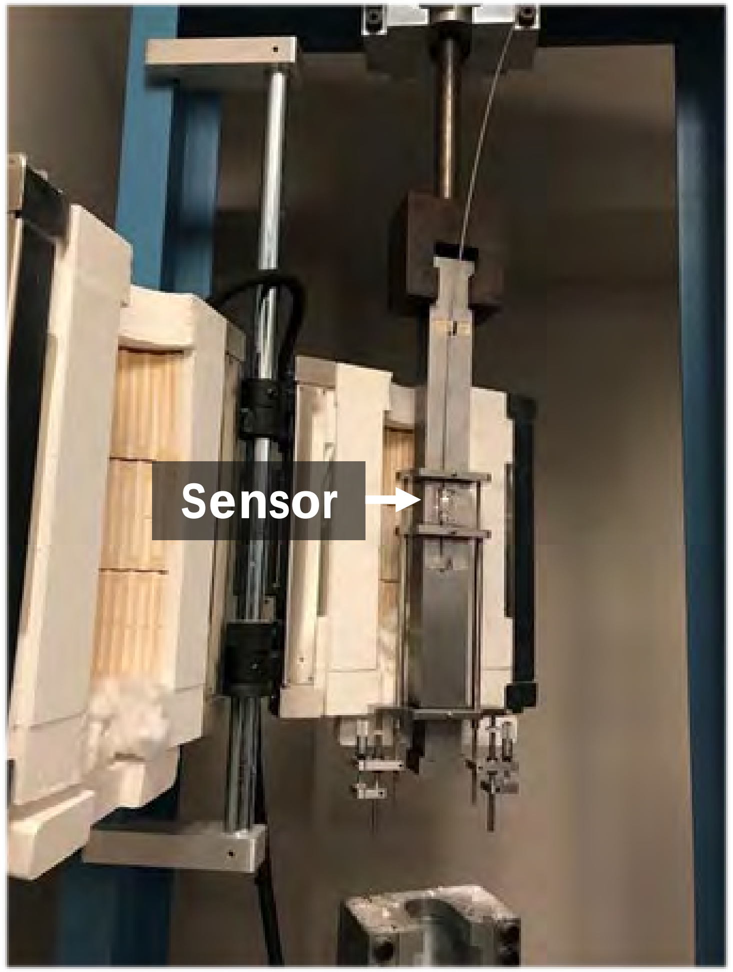
Welded metal components



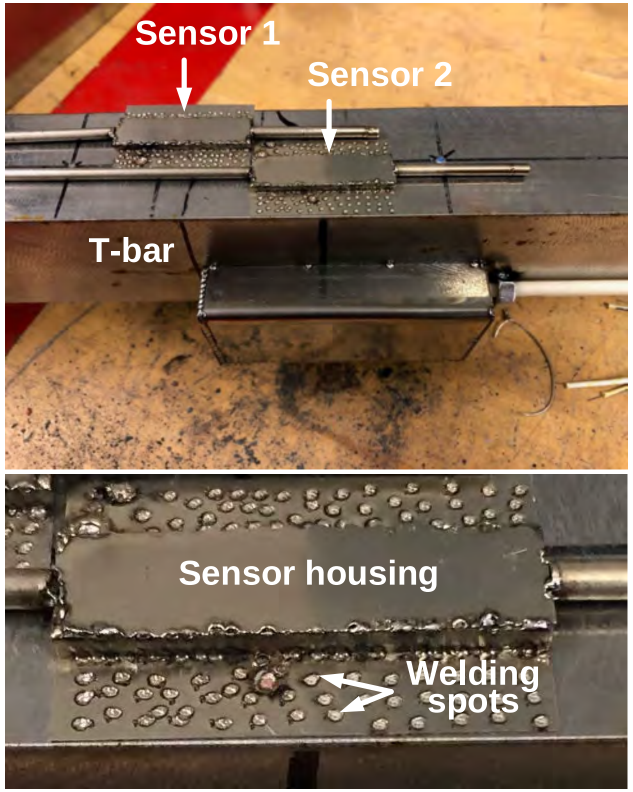


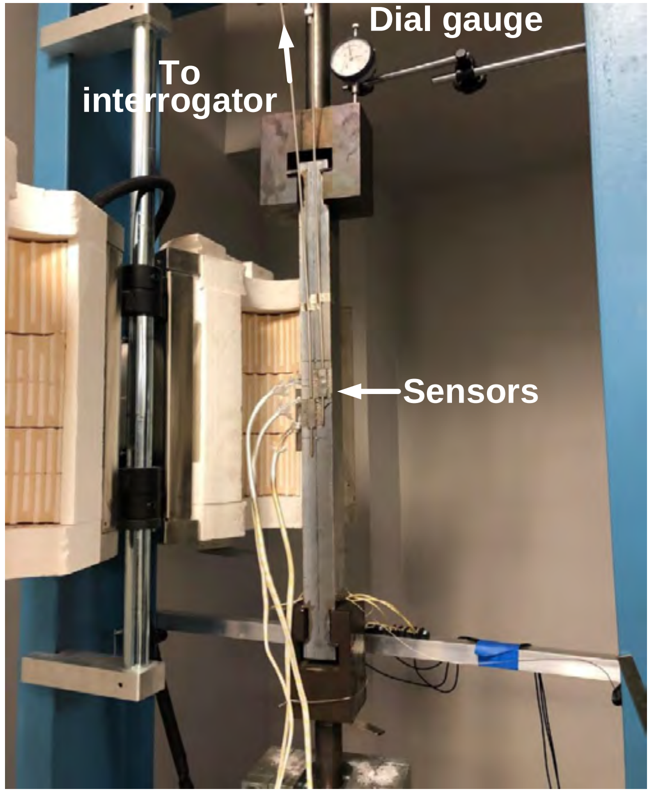
1st Test at EPRI – Sensor Installation





2nd Test at EPRI – Sensor Installation





Strain on T-bar vs. on sensor

- Not the same in practice
- Calibration needed (scaling or transfer factor)
- Ideal scaling factor = 1

Scaling factor affected by

- Size & geometry (thickness)
- Material (Inconel)
- Method of attachment (welding)

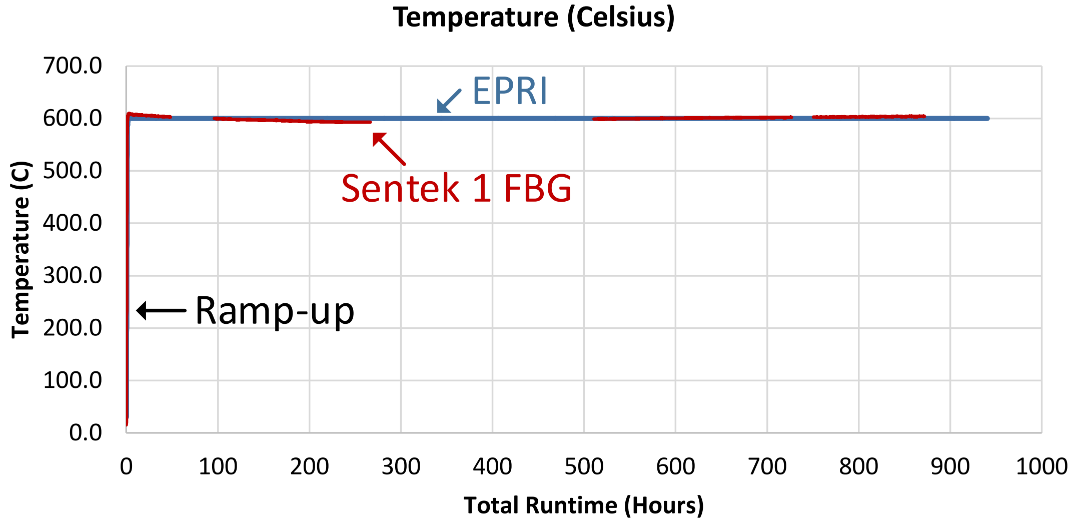
Sensor Performance

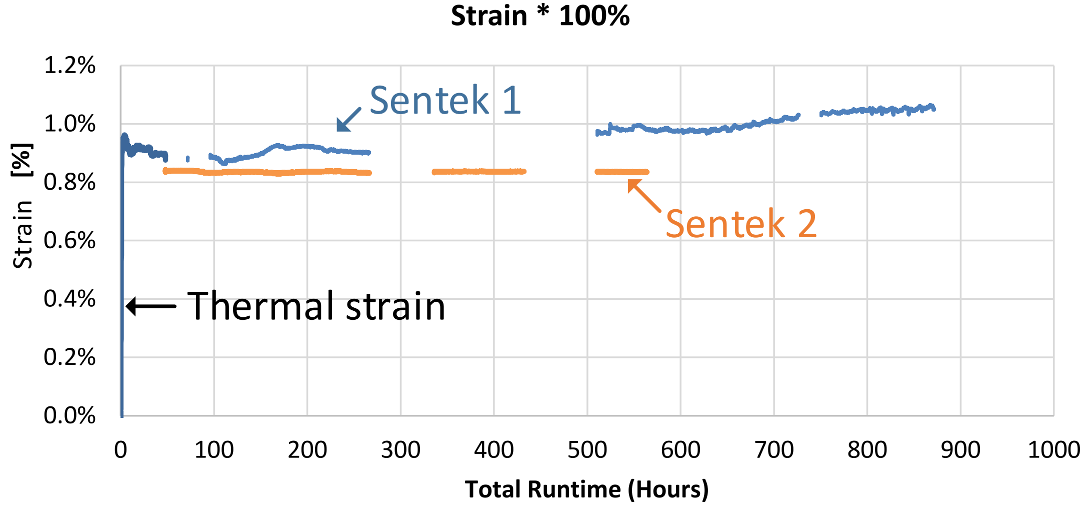
Temperature (Channel 1 FBG)

- Functional
- Slight discrepancy may indicate need for annealing

Strain (Channels 1&2 FOI)

- Ramp-up indicates sensors functional (thermal strain)
- Thermal + mechanical strain





Mechanical Strain

Fiber Sensor vs. Dial Gauge

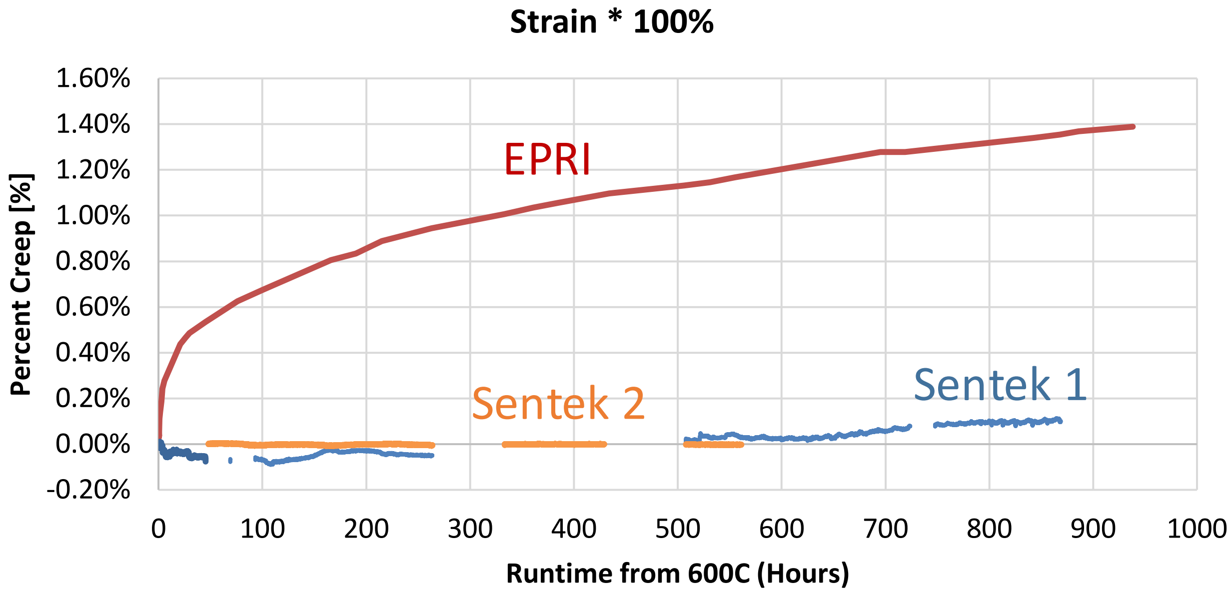
Remove ramp-up (thermal strain)

Channel 1: reduced response

- Small scaling factor
- Large packaging thickness

Channel 2: minimal response

- Minimal scaling factor



2nd Test Conclusions

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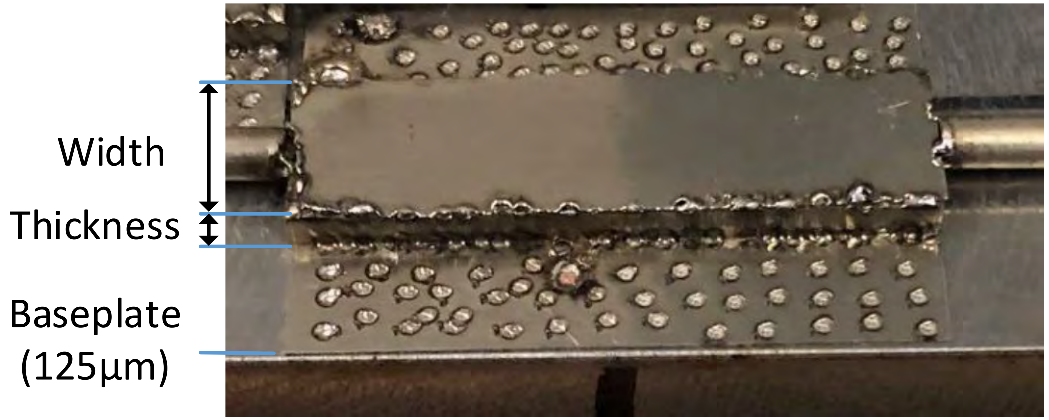
Sensors alive and functional

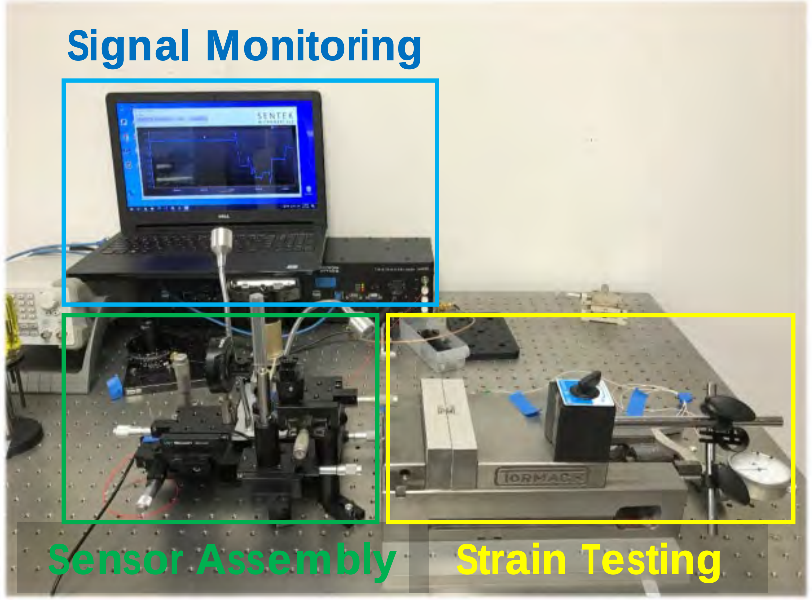
- Temperature sensing validated
- Robustness confirmed

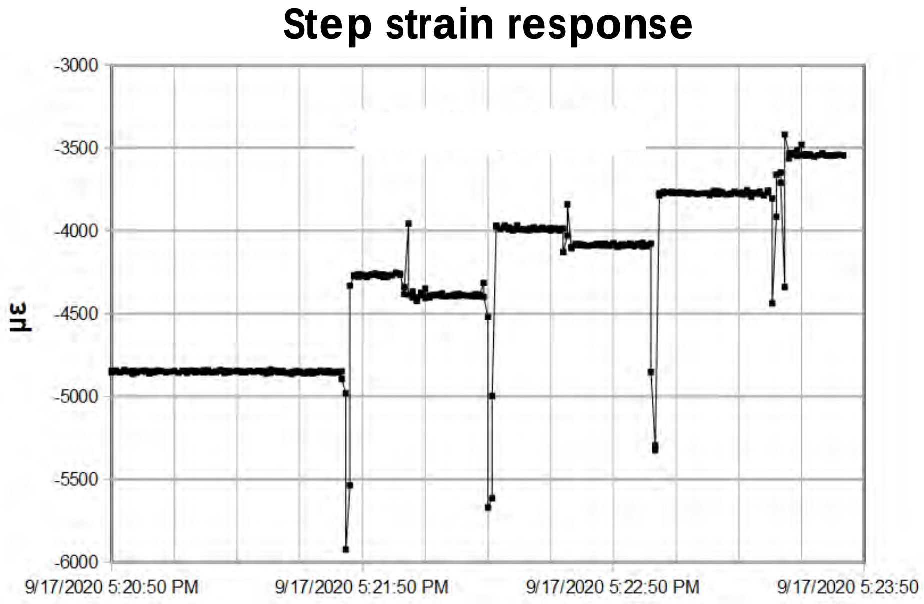
Need to maximize strain transfer

- New design
- Minimize cross-section thickness
- Minimize housing width
- Maximize force transfer
- Use in-house materials for quick results



New Design – Testing





Large strain response

Repeatability issue (reduced rigidity in handling and installation)

Next-generation design

- Custom parts
- Increase rigidity and maintain large strain transfer

Next-generation Design

Custom parts to maximize design flexibility

Enhanced sensor rigidity and repeatability

Enhanced strain transfer factor

Status of Sensor System Development

Sensor	Validation	Fabrication	Packaging	Software
DTS			In-progress	
DAS			In-progress	
Strain Sensor	In-progress	In-progress		

Instrumentation Data Access Plan

EPRI/AEP

Robust data to be generated during monitoring phase

- Multiple instruments, frequent data recording
- Daily output for monitoring
- Plant PI data historian
  - Existing plant instrumentation
  - Plant operating data

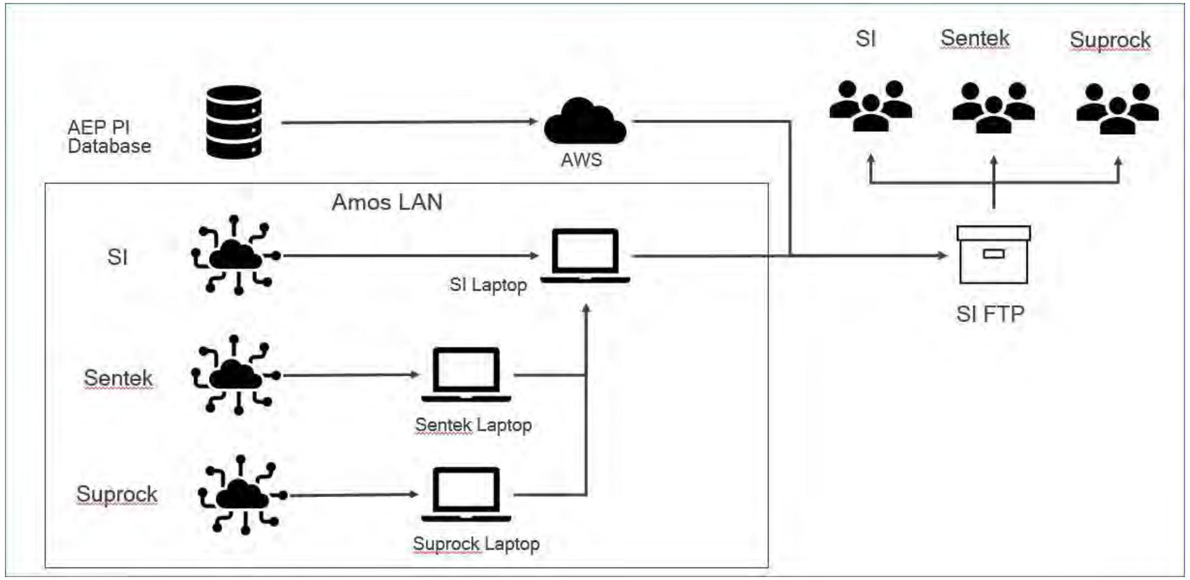
Extensive cyber security discussions held with AEP

- Team access to AEP network not practical
- Structural Integrity Associates has approved limited AEP network access through other work
- Leverage access for DOE project

Proposed Instrumentation Network Configuration

Approach

- Single laptop to have limited network access
  - SI computer already has approved access to AEP network from prior activities
  - Shared folder to be created on SI laptop
  - Other participants will write instrumentation data to shared folder on SI laptop
    - Laptops connected via plant LAN
    - No external network and/or internet access
- AEP will configure laptops when on site at start of demonstration



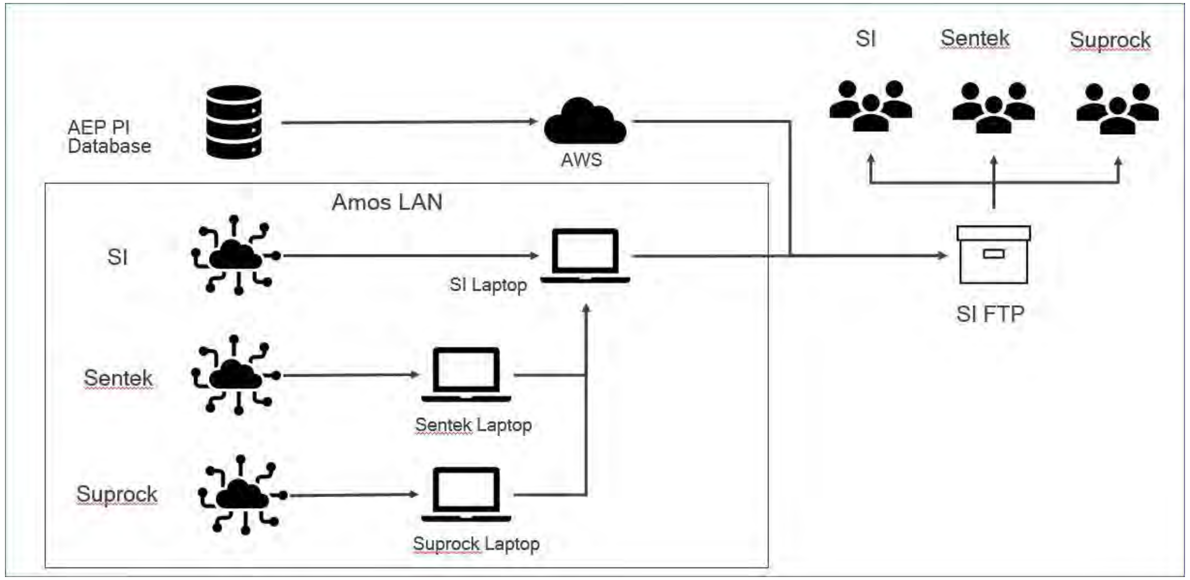
Data Management During Demonstration

AEP will remotely access SI laptop at determined frequency (e.g., daily)

- Retrieve instrumentation data files from shared folder
- Place on external ftp site

AEP will also place plant operating data on ftp site

All project participants will have access to ftp site



Data Monitoring

Project plan is to monitor operation for one year

What if issues arise?

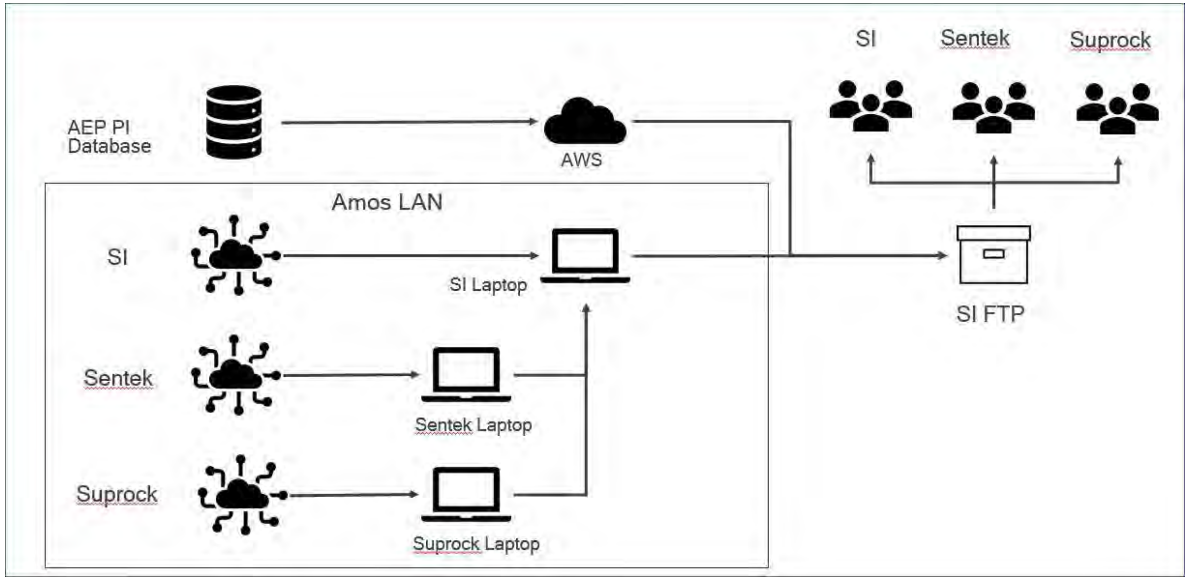
- Laptop operation
- Plant LAN
- Unanticipated outage

AEP will have administrative access to all laptops to address IT issues, as warranted

Plant visits, if necessary

Success of integrated boiler management system can be demonstrated with nominal period of operation (varying operating profiles)

Tracking accumulation of creep/fatigue damage can continue beyond project timeline



Closing Remarks

Closing Remarks

- Integrated boiler management system and additional instrumentation ready for deployment at AEP Amos U3 during 4Q 2020 outage
- Mobilization in progress at Amos U3 to host project activities
- Proposed IT configuration approach developed and agreed by all parties. Implementation ready to commence during outage.
- Installation of Sentek gauges delayed until future outage