Integrated Boiler Management Through Advanced Condition Monitoring and Component Assessment

DE-FE0031683
**Project Objectives and Status**

**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
Structural Integrity Associates
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
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
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.
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)
Condition Monitoring Software Architecture
Key components of the Analytics

Connectors: Standard data connectors that can be 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

```json
{
    "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://155.105.19.244:8881/",
        "userName": "struct1",
        "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

"Component_Type": "Header",
"Component_Name": "Superheat Outlet Header",
"Damage_Mechanism": "AbaqusFatigue",
"Material": "Gr 22",
"Operating_Data": {
  "Fields": [
    {
      "Field_Name": "Temperature",
      "Field_Tag": "3BAA409",
      "Field_Unit": "°C",
      "Field_Correction": 0,
      "Field_Correction_Unit": "°C"
    },
    {
      "Field_Name": "Pressure",
      "Field_Tag": "3BAA416",
      "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"}
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

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

- **Constrained to Remain Planar in tube axial direction**
- **Fixed Circumferential Displacements**
- **Constrained to Remain Planar in header axial direction**
- **Fixed Axial Displacements**

**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
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.
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
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
Crack Modeling
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 or crack tip parameter measurement, Ct.
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)

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

Used to perform subsequent engineering analyses/calculations to help:

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

The following slides provide screenshots from configuration of this project
Main Screen

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.
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.)
Geometry Creation

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
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.
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 months.

Also, an option to switch from the chart to tabular results.
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.

### Creep Damage

<table>
<thead>
<tr>
<th>Date/Time</th>
<th>Temperature (F)</th>
<th>Pressure (Mpa)</th>
<th>Stress (Mpa)</th>
<th>Creep Damage (%)</th>
<th>Oxide Thickness (mil)</th>
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<td>160.7</td>
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</tr>
</tbody>
</table>
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.
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
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
• Documents specific challenges 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 calculation 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
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 penetration 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 Region
(‘You Are Here’)

U.S. DEPARTMENT OF
ENERGY
Installation Near Tube Row #25

- Blue links are conductors in stainless flex conduit.
- Orange: sensing link 1
- Yellow: sensing link 2 (backup)
- Sensor 1 & 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'

Not Shown:
- Existing plant thermocouples
- SI strain gauges to be installed as needed in vicinity of Suprock gauges

Note: Installation of Sentek gauges postponed

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

*Access to SSOH is dependent on entry date to penthouse and sufficient cooling of SSOH*
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
Fiber Bragg grating (FBG)
- Periodic structure inside the fiber
- Reflects a specific wavelength
- Wavelength shifts with temperature

Distributed temperature sensor (DTS)
- Pulsed light separates sensor in time
- Interrogates the reflected wavelength
- High capacity, high spatial resolution and high sensitivity
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
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

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Validation</th>
<th>Fabrication</th>
<th>Packaging</th>
<th>Software</th>
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<td>Strain Sensor</td>
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</table>
DTS Summary

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

![Diagram showing strain vs. temperature and acoustic with labels for sensor, housing, strain, attachment, heat, and acoustic.](image)
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 >1000°C
Welded metal components
1st 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

Fiber Sensor  vs.  Dial Gauge

Mechanical Strain

EPRI

Sentek 2

Sentek 1

Percent Creep [%]

Strain * 100%

Runtime from 600C (Hours)
2nd Test Conclusions

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
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

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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
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
C losing 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