Application of Creep-FatiguePro at a Supercritical Coal-Fired Boiler

Technology Transfer and Software Configuration for Brindisi Power Station

3002011618

Application of Creep-FatiguePro at a Supercritical Coal-Fired Boiler

Technology Transfer and Software Configuration for Brindisi Power Station

3002011618

Technical Update, February 2018

EPRI Project Manager

S. Rosinski

3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

Structural Integrity Associates, Inc.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

ACKNOWLEDGMENTS

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Structural Integrity Associates, Inc.
5215 Hellyer Ave #210
San Jose, CA 95138

Principal Investigators
M. Berasi
C. Carney
U. Woerz

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Application of Creep-FatiguePro at a Supercritical Coal-Fired Boiler: Technology Transfer and Software Configuration for Brindisi Power Station. EPRI, Palo Alto, CA: 2018. 3002011618.

ABSTRACT

The Creep-FatiguePro™ (CFPro) software was developed by EPRI in the early 1990s as a way to track the accumulation of creep and fatigue damage, based on actual operating conditions—temperature, pressure, and flow rate. Over the years, the software has been upgraded and new features added. The latest update was in 2016 that now gives CFPro the ability to interact directly with a plant's PI data historian. This removed the manual step of loading operating data onto the Windows computer where CFPro is installed, allowing CFPro to operate in an "automated mode." The new feature was successfully tested at ENEL's coal-fired As Pontes plant in Spain.

This project was initiated to support broader application of CFPro across the ENEL generation fleet. ENEL engineers were trained on-site in Italy on how to configure the CFPro software. With EPRI support, ENEL engineers configured CFPro for application at the supercritical coal-fired Brindisi power station in southeastern Italy and implemented at an ENEL server center near Milan for future application to other plants. Support was also provided after three months of operation to validate analysis results and make corrections to the configurations, as needed. This provided ENEL with the engineering background and tools to properly configure and maintain the software.

A separate on-site software installation and user training was also held in Italy. In addition to knowledge transfer to ENEL engineers, the project evaluated whether the CFPro installation process could easily be replicated from the previous As Pontes application in Spain and whether CFPro is suitable for fleetwide implementation.

Although ENEL engineers were successfully trained in the technical aspects of the configuration process, some challenges were evident with software implementation. This report summarizes the project activities and provides insight into future steps for CFPro implementation on a fleetwide basis.

Keywords
Creep/fatigue damage monitoring
Fleetwide monitoring
Life assessment

ELECTRIC POWER RESEARCH INSTITUTE

Deliverable Number: 3002011618

Product Type: Technical Update

Product Title: Application of Creep-FatiguePro at a Supercritical Coal-Fired Boiler: Technology Transfer and Software Configuration for Brindisi Power Station

---

PRIMARY AUDIENCE: Plant engineers responsible for degradation management of coal-fired boiler components; plant personnel responsible for monitoring/managing material creep and fatigue

KEY RESEARCH QUESTION

Tracking the accumulation of creep and fatigue damage in coal-fired boiler components can aid in life management strategies, especially as the plant transitions to more flexible operation. The use of Creep FatiguePro™ (CFPro) is a valuable tool in tracking the accumulation of damage for specific components. In 2016, the software was updated to directly interact with a plant's data historian to access operating parameters that eliminate the need for manual data transfer and to simplify operation and data analysis. Demonstration of the updated CFPro system was completed at the ENEL As Pontes power station in Spain. In this application, CFPro was installed at a central server location that offers the potential for a broader application of CFPro to those plants connected to the central server. The need was identified to train ENEL engineers in configuration of the CFPro platform and to support installation at an additional server center in Italy to further evaluate the potential for fleetwide implementation and identify potential limitations.

RESEARCH OVERVIEW

ENEL engineers were trained on-site in Italy on how to configure the CFPro software. With EPRI support, ENEL engineers configured CFPro for application at the supercritical coal-fired Brindisi power station in southeastern Italy and implemented at an ENEL server center near Milan for future application to other plants. Support was also provided after three months of operation to validate analysis results and make corrections to the configurations, as needed. This provided ENEL with the engineering background and tools to properly configure and maintain the software. A separate on-site software installation and user training was also held in Italy. In addition to knowledge transfer to ENEL engineers, the project evaluated whether the CFPro installation process could easily be replicated from the previous As Pontes application in Spain and whether CFPro is suitable for fleetwide implementation.

KEY FINDINGS

- ENEL engineers were successfully trained in the configuration of CFPro for application at the supercritical Brindisi power station in Italy. The technology transfer activities under this project provided ENEL engineers with the tools to use the software themselves, for potentially expanding it to fleetwide online creep and fatigue damage monitoring in their globally distributed fossil fleet.
- CFPro installation and user training identified potential limitations to fleetwide implementation. A significant contributing factor to these potential limitations is the age of CFPro—written as a stand-alone software designed to run on a dedicated Microsoft Windows computer. This requires local installations in each generating location or region (if PI data are in a centralized server for that region), with each installation potentially requiring specific adjustments because of local network setup. In addition, run time issues and limited ability to execute calculations concurrently would have to be addressed if more monitored locations were to be added.
- To make CFPro a truly suitable solution for fleetwide monitoring, major upgrades are recommended. Conversion from a file system–based to a modern database structure (for example, SQL) is recommended. In addition, and perhaps most importantly, the software should be fully web-based so

that it can be hosted in the cloud, with neutral (API) interfaces to available data sources. This would provide global accessibility of monitoring data through one user interface for corporate engineers. It would also limit IT setup and maintenance effort. Alternatively, rather than "rewriting" CFPro, a more cost-efficient solution could be the integration of its analytical creep and fatigue damage tracking algorithms into an existing, cloud-based monitoring platform. Several scenarios are possible and worth consideration that could be particularly beneficial for utilities with globally distributed generating fleets.

WHY THIS MATTERS

The training of utility engineers to configure CFPro is an important step in the overall objective of facilitating fleetwide application of the Creep-FatiguePro system to track creep and fatigue damage accumulation. Installation at two ENEL server centers through this and prior EPRI efforts provided valuable insight into potential limitations of the current CFPro platform in meeting this objective. Results from this work will be used to inform future EPRI R&D in this area to evolve the Creep-FatiguePro platform to support fleetwide deployment.

HOW TO APPLY RESULTS

This project was successful in training ENEL staff to set up and configure CFPro for application at the supercritical Brindisi power station in Italy. The technology transfer activities under this project provided staff with the tools to use the software for potentially expanding it to fleetwide online creep and fatigue damage monitoring in their globally distributed fossil fleet. With CFPro now applied in two distinct central server locations and configured for two separate plants, valuable insight will continue to be gained into the suitability of CFPro for fleetwide implementation.

LEARNING AND ENGAGEMENT OPPORTUNITIES

EPRI has supported the development of Creep-FatiguePro™ since the early 1990s to aid in life management strategies through the tracking of accumulated creep and fatigue damage in fossil-fueled power plant components. Background on the development of CFPro, including conversion of plant operating data into stress versus time, and the recent application of an updated version of Creep-FatiguePro at the ENEL As Pontes power station can be found in the following reports:

- *Creep-FatiguePro: Online Creep-Fatigue Damage and Crack Growth Monitoring System.* EPRI. Palo Alto, CA: 1992. TR-100907.
- *Application of Creep-FatiguePro at a Cycling Coal-Fired Boiler: Demonstration of Software Enhancements at the As Pontes Power Station.* EPRI. Palo Alto, CA: 2016. 3002009206.

EPRI CONTACT: Stan Rosinski, Technical Executive, srosinski@epri.com

PROGRAM: Boiler Life and Availability Improvement, Program 63

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

CONTENTS

LIST OF FIGURES

1 INTRODUCTION

Fossil power generation stations (coal or natural gas fired) in Europe and North America have seen a shift in their operation. Due to changes in regulations—related to the addition of renewables or deregulation—many of these stations, which were originally designed for baseload operation, are now required to operate in cycling or load-following mode. This trend is expected to continue, and it poses unique challenges for utilities who own and operate these plants. While the economics were more straightforward for baseload plants operated in a regulated market, the unknowns of volatile operation make the creation of business cases much harder. One of these unknowns is the actual cost due to life consumption (damage) to high value equipment in a plant. Two examples of such equipment are boilers (in the case of coal fired plants) or Heat Recovery Steam Generators (HRSGs, in the case of gas-fired, combined cycle plants). Frequent cyclic operation takes a toll on the high pressure and temperature components, especially final stage headers and piping systems. The main damage mechanisms in these components are creep and thermal fatigue.

Knowing actual creep and fatigue life consumption in high pressure boiler components can be valuable information to utilities, helping them adjust their maintenance strategy to these new operating requirements. It can also help in assessing the 'actual cost' of cyclic operation, and subsequently guide dispatch scenarios and decisions.

Without this knowledge, damage accumulation can go undetected until failure or rupture occurs. Figure 1-1 shows a boiler header that cracked due to combined fatigue and creep damage. In such a case, the steam leakage leads to a forced shutdown of the plant, resulting in economic damage. In a more dramatic scenario, a rupture can have catastrophic or even fatal consequences. Such an example is shown in Figure 1-2, where a high energy steam line ruptured.

In order to track creep and fatigue damage accumulation, EPRI initiated and sponsored the development of Creep-FatiguePro™ (CFPro) in the early 1990s [1]. In short, CFPro is a software program that takes the component geometry and the ongoing changes in operating conditions (temperatures, pressures and flow rates) into account. From these it calculates trends for the consumption of component life due to creep and/or fatigue. In addition to anticipating the time until damage will occur, it can also anticipate how long it will take for damage to become critical to a component's life. For example, a crack might occur on a component's surface, but there might be sufficient material thickness left underneath to allow for safe operation for many more hours. With its crack growth analysis feature, CFPro can calculate how many hours it will take the crack to propagate to a point where the remaining material thickness is not sufficient for safe operation.

Figure 1-1
Cracked boiler header due to creep/fatigue damage

Figure 1-2
Rupture of seam welded high energy pipe

CFPro results can be accessed through different types of reports. Figure 1-3 shows an example of a report for a defined period of time showing creep damage, fatigue damage, creep crack growth and fatigue crack growth. Alternatively to the report-style output, results can be visualized in graphs. Figure 1-4 shows an example of such a graph showing creep and fatigue damage over time for a specific monitored location.

Creep-FatiguePro Monitoring System
Creep-FatiguePro CFP3CALC.DLL version3.01b-02217

Installation for: Utility XYZ
Plant A (mean)

Location Damage and Crack Growth Report for:
---- Unit #: 2, ---- System: High-Energy Piping System

Start of Monitoring : 05/13/93 00:00:00
Results up to Date : 08/30/93 23:59:30 (110.00 days)

****

** DAMAGE ACCUMULATION RESULTS (life fraction)

Location	Initial Damage	Monitored Fatigue Damage	Monitored Creep Damage	Total Current Damage	Allow. Damage	% of Allow
1: MS-16-ID	0.000000	0.000011	0.001119	0.001130	0.1000	1.13
2: MS-16-OD	0.000000	0.000000	0.003060	0.003060	0.1000	3.06
3: MS-11-ID	0.000000	0.000138	0.001807	0.001944	0.1000	1.94
4: MS-11-OD	0.000000	0.000002	0.004545	0.004547	0.1000	4.55

** CRACK GROWTH RESULTS

(inches)

Location	Initial Crk Size	Monitored Fatigue Crk Grwth	Monitored Creep Crk Grwth	Total Current Crk Size	Allow. Crk Size	% of Allow
1: MS-16-ID	0.100000	0.000039	0.000935	0.100974	0.7917	12.75
2: MS-16-OD	0.100000	0.000001	0.002526	0.102528	0.7917	12.95
3: MS-11-ID	0.100000	0.000276	0.001525	0.101801	0.5833	17.45
4: MS-11-OD	0.100000	0.000010	0.004155	0.104166	0.5833	17.86

****

Figure 1-3
Example report in CFPro

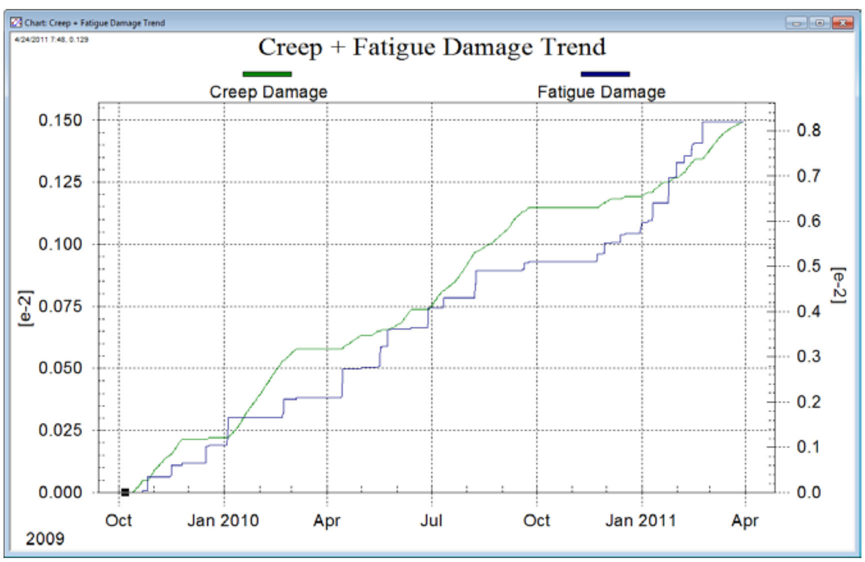

Figure 1-4
Creep and fatigue damage trend chart for monitored location

While CFPro was originally developed as a response to unexpected creep/fatigue damage failures in coal fired stations in the 1980s, it is equally applicable to assess the impacts of cyclic and infrequent operation that both coal-fired and gas-fired plants face. It can be used for creep and fatigue damage trending of any thick-walled, high temperature power plant component, such as piping, headers, turbine casings, rotors and valve bodies.

Before use, the CFPro software requires a configuration process for defining stress transfer functions for creep and fatigue damage and crack growth analysis, based on the actual component geometry. This typically involves finite element analysis for components with complex geometry, or simple closed form analytical solutions for components where stresses can be reasonably well approximated using these basic formulas.

To evaluate the benefits of component life consumption monitoring with CFPro, the software was configured, installed and implemented at ENEL's coal-fired As Pontes plant in northeastern Spain [2] for monitoring the superheat outlet header. Archived plant instrument data for the last 6.5 years of operation were processed in CFPro and the results reviewed to assess the impact of unit operations on component life consumption. The CFPro monitoring results were concluded to be beneficial relative to traditional off-line assessment techniques typically used for component life consumption evaluation (see [2] for more details). To gain more experience with the CFPro monitoring approach, it was recommended to extend the monitoring to more components and plants with different operating regimes.

Before the installation of CFPro at the As Pontes plant, the software was upgraded with functionality that allows the direct interaction with the PI Data Historian, where all the operating data is stored. With this interface, an automated operating mode is possible where CFPro automatically retrieves operating data from the PI server and performs the calculations in pre-defined intervals (in this case every night). Before that upgrade, the import of operating data was a manual step. A plant engineer needed to download the operating data from the data historian, upload it to CFPro, and start the calculation. With the new interface, this manual step is not necessary anymore. In addition, a user interface using the PI system (with PI ProcessBook™) was developed. Figure 1-5 shows an example of a ProcessBook™ chart with calculated damage accumulations at different locations. This allows both local plant users and central engineering users to access the results, as long as they have access to the same PI server. In the case of the installation for As Pontes, these were all the ENEL/ENDESA plants in Spain. The historian data for these plants is replicated in the centralized server center in Madrid, which is where CFPro was installed. Figure 1-6 shows a schematic of this setup. Since CFPro is installed on the centralized server, other plants can be added without the need of new software installations. Only the calculations themselves would have to be configured.

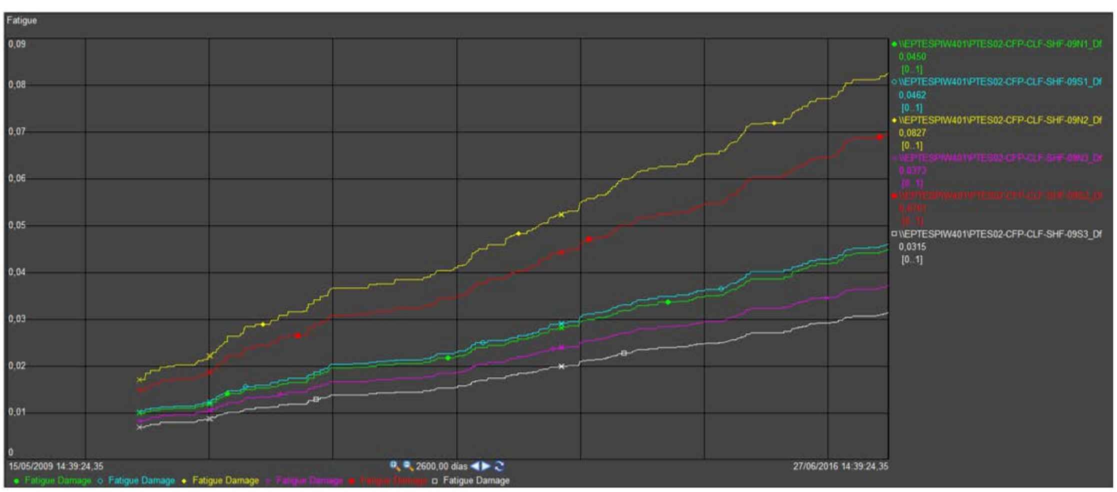

Figure 1-5
Example of PI ProcessBook™ UI showing damage accumulation at different locations

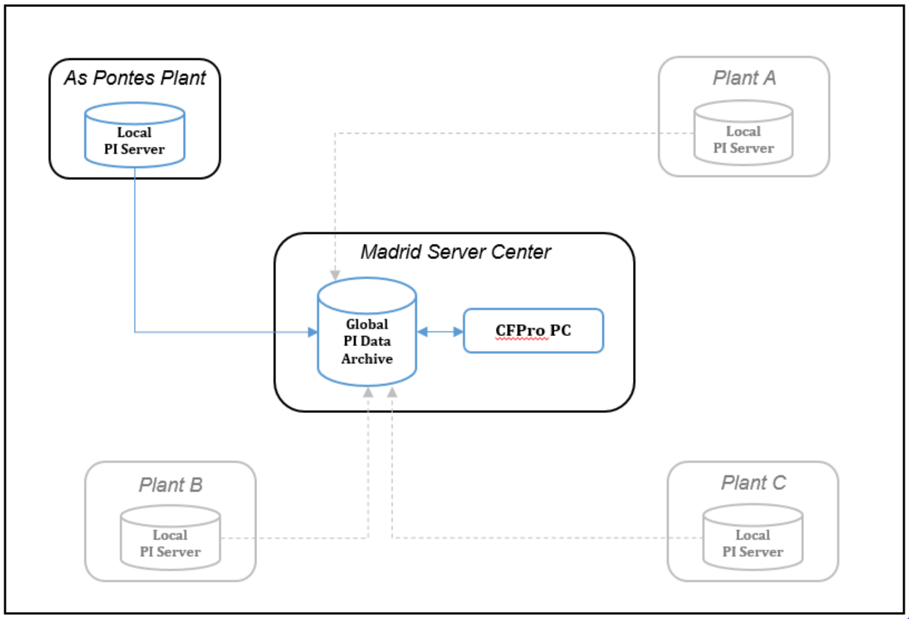

Figure 1-6
CFPro installation in utility network

After the installation of CFPro at the ENDESA plant region in Spain, ENEL was interested in installing a fleet monitoring system for its fossil plants in Italy. To support their planned fleet-wide application of CFPro, ENEL was interested in learning how to configure the CFPro software for a given monitoring application. This would then allow them to complete these plant and component-specific configuration tasks directly as they proceeded with their fleet-wide application of the life consumption monitoring system. This interest lead to the scope of this project. The coal-fired Brindisi plant was chosen as the initial implementation for the Italian region. Support was provided for this implementation in two ways. First, remote guidance and review was provided to ENEL during their initial Finite Element Analysis performed to generate the necessary configuration data for the header components they selected for life consumption monitoring. Second, a one week configuration training was held on site in Italy, at which ENEL engineers learned how to configure CFPro for their planned monitoring applications. Support was also provided for the software installation at the centralized server center near Milan.

This report summarizes the work that has been performed as part of this technology transfer effort. This includes the configuration process for the monitored locations at the Brindisi plant, specifically these were ligament locations at the superheater and reheater outlet headers. In addition, preliminary analysis results were reviewed and interpreted (after an initial three months of operation).

The configuration process and training is discussed in Section 2. Section 3 describes the software installation procedure and testing. The local differences in server/network settings compared to the previous installation in Madrid are discussed. This lead to some installation difficulties at first. It is explained how these were overcome and what needs to be considered in future installations. This reveals some of the challenges and limitations of CFPro for fleet-wide implementation. Analysis results for three months of data are discussed in Section 4. Section 5 summarizes the work and provides an outlook on potential improvements for fleet-wide creep/fatigue monitoring system.

2
CREEP-FATIGUEPRO™ CONFIGURATION

The general approach used by CFPro to monitor creep and fatigue damage accumulation and crack growth in fossil plant components is summarized as follows:

1. Temperature, pressure, and flow rate data for the monitored equipment, typically available from existing plant instrumentation, is extracted from the plant computer/data acquisition system at a specified interval (typically 1 to 5 minutes) and stored in the appropriate format for data processing by the CFPro analysis software. Traditionally, this was a manual effort, which has now been eliminated with the development of the direct interface to the PI system.
2. Component-specific analytical stress transfer functions programmed into CFPro compute creep and fatigue stresses as a function of time from the collected plant instrument readings.
3. Based on the monitored temperatures, calculated stresses, and built-in material creep and fatigue strength properties, CFPro determines the creep and fatigue damage expended with time. Accumulated creep and fatigue damage is tracked over time using the life fraction (or usage factor) approach—a computed parameter where a value of 1.0 indicates that the component has reached its expected end of life.
4. To account for creep-fatigue interaction, a "Total Damage" parameter is also calculated, using a default creep-fatigue interaction (CFI) curve. This is a bi-linear relationship that defines end-of-life as a function of the creep and fatigue usage factors—see the blue line in Figure 2-1. For example, assume we have monitored damage of 0.342 fatigue and 0.057 creep. Using Figure 2-1, create a line segment that begins at (0, 0), extends through the given point (0.342, 0.057), and ends at the CFI limiting line at a creep damage fraction value of 0.1. Since the given point is at 0.057 creep compared to the limiting line value of 0.1 creep, the given point is 57% along the length of that line segment, and the Total Damage value is 0.570.
5. Also based on the monitored temperatures and calculated stresses, as well as built-in material creep and fatigue crack growth properties and fracture mechanics flaw models appropriate for the geometries being monitored, CFPro calculates the expected creep and fatigue crack growth versus time. Crack growth calculations are made for either known initial flaws (determined through prior inspection) or for postulated defects (with initial size typically based on the assumed minimum detection limit of any prior or applicable NDE). For this project, crack growth analysis was not in the scope as no existing cracks were known at the point in time.

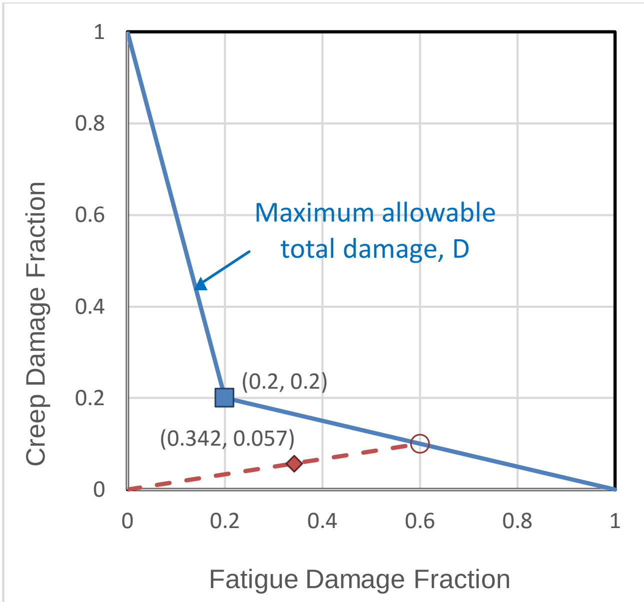

Figure 2-1
CFPro default creep-fatigue damage interaction curve

6. Pre-determined allowable levels of damage accumulation and crack growth are programmed into CFPro for comparison to the actual monitored damage/crack growth levels. The monitored damage accumulation and crack growth rates are projected into the future to determine the expected additional operating time required to reach the allowable values. The specified allowable damage level may correspond to the level at which crack initiation is expected, or some incremental damage level considered detectable through NDE based on known condition of the component at the start of monitoring. Similarly, the specified allowable crack size may correspond to the fracture-mechanics calculated critical flaw size for onset of rapid through-wall flaw propagation, or an incremental crack growth amount considered detectable through NDE. Projection of the remaining time to reach the allowable damage/crack size levels subsequently represent predicted times to end-of-life or to a point at which component inspection is advisable to determine actual material condition.

Application of CFPro to a given plant monitoring application requires derivation of unit and component specific data to support the above monitoring approach and calculations. The derived configuration data is stored in configuration databases accessed by the CFPro calculation software. The CFPro calculation routines for stress, damage accumulation and crack growth are general in nature. All application-specific data required is contained in the configuration databases.

Monitoring application-specific configuration data that must be derived or specified in the CFPro databases consist of the following:

- Specification of the plant instruments providing the necessary temperature, pressure and flow rate input at a given component monitoring location.
- Derivation of the analytical stress transfer functions used to compute creep and fatigue stress histories from the plant instrument data.

- Specification of the creep and fatigue strength material properties data required to compute damage accumulation from the derived stress histories.
- Specification of the fracture mechanics flaw model, and the creep and fatigue crack growth material properties data required to compute crack growth from the derived stress histories.
- Specification of initial and allowable damage and crack size levels at each component monitoring location.

CFPro contains a built-in library of general purpose fracture mechanics flaw models typically used for modeling of flaws in fossil plant components such as axially or circumferentially oriented surface or embedded flaws in piping seam welds and girth welds, ligament cracks in boiler headers, and cracking in valve bodies, steam chests, turbine casings and rotors. The configuration requirement with respect to flaw model subsequently is minimal and involves selection and specification of the appropriate flaw model in the configuration database.

CFPro similarly contains a built-in library of material properties data for the material types commonly found in fossil plant components monitored with the software. This includes base material, weld and/or weld HAZ properties of carbon steel, Grade 11 (1¼Cr) and Grade 22 (2¼Cr) low alloy steels, Grade 91 (9Cr-1Mo-V) creep strength enhanced ferritic steel and Cr-Mo-V steel. The configuration requirement with respect to material properties is similarly minimal and involves selection and specification of the appropriate materials type in the configuration database. It is noted that material properties data for other material types can be added to the library as may be required for a given monitoring application. Similarly, the existing material properties data for a given material type can be edited as considered necessary to account for known material condition of a given component being monitored.

Regarding initial and allowable damage and crack size data, determination of these values is made based on known condition and service history of the monitored components, and intended application of the monitoring results (prediction of remaining life to crack initiation or through-wall flaw propagation, or accumulation of damage or crack growth increment warranting component inspection) and can be supported by external fracture mechanics-based critical flaw size and other related calculations.

The above leaves derivation of the *analytical stress transfer functions* used to compute creep and fatigue stress versus time histories from the plant instrument data as the primary and most time-consuming configuration task required for application of CFPro to a given plant component life consumption monitoring need.

A general discussion of stress transfer function derivation is provided below. This is followed by sections describing the specific stress transfer function derivations completed for the high temperature header monitoring application at the ENEL Brindisi station in Italy.

2.1 Stress Transfer Function General Requirements

One of the primary benefits of on-line monitoring with CFPro is its use of actual plant operating data for predicting damage accumulation and crack growth. This eliminates a significant amount of uncertainty and potential over-conservatism associated with offline evaluations based on rated temperature and pressure, and assumed operating conditions with respect to startup/shutdown frequency and severity. CFPro accomplishes this by interfacing with the PI or other equivalent plant data acquisition/archival system to collect necessary temperature/pressure/flow rate data, and then using *stress transfer functions* to convert this plant data to stress-versus-time at each component life consumption monitoring location.

Stress transfer functions are geometry-dependent functions which must be determined for all significant stress sources considered to be present in the monitored component. For the plant pressure part components typically monitored with CFPro (high energy piping, boiler headers, drums, valves, turbine casings, steam chests), internal pressure loading and thermal transients are the primary sources of stress for which transfer functions are required. In the case of high energy piping, transfer functions to address piping deadweight and global restrained thermal expansion effects must also be included. For turbine rotors, rotational stresses must be considered.

With the exception of thermal transients, the magnitude of stresses produced by the above-noted loadings are dependent only on the instantaneous reading of the applicable plant instrument (i.e., pressure transducer reading for pressure stress, thermocouple temperature for piping thermal expansion stress, rotor RPM for rotational stress). For this reason, determination of stress transfer functions for these loadings is relatively straightforward. For simple geometries such as straight sections of piping, these transfer functions can be determined using standard closed form solutions (i.e., thick-walled cylinder pressure stress formula for piping pressure stress transfer functions). For more complex geometries such as the tube bore ligament region of a boiler header, or turbine valve chests and casings, detailed Finite Element (FE) analyses are typically performed to derive the necessary stress transfer functions.

Concerning thermal transients, the resulting stresses are more complicated to determine as they are dependent not only on the instantaneous temperature reading at that time, but also on the prior temperature vs. time history of the fluid in the component. A specialized technique referred to as the *Green's Function* approach is employed in CFPro for the calculation of these thermal transient-related stresses. The *Green's Function* is the stress vs. time response of a component to a unit step change in fluid temperature boundary condition. The *Green's Function* stress versus time response is numerically integrated over the actual incremental steam temperature change history experienced at the given monitored component to derive the thermal transient stress versus time at the component monitoring location. Similar to the stress transfer functions for pressure and other loadings, the *Green's Function* stress response can be determined through detailed FE stress analysis in the case of complex component geometries, or through alternative numerical techniques for simplified geometries.

Separate transfer functions applicable to fatigue damage/crack growth calculations, and creep damage/crack growth calculations, are typically specified in CFPro for each monitor location. Fatigue stress transfer functions are derived based on elastically-calculated stresses and are required for loadings which are transient or cyclic in nature. Creep stress transfer functions are required for primary sustained loadings and, to avoid over conservatism, must reflect or account for the effects of creep redistribution and/or relaxation of the initial elastic stress levels over time.

A final note with respect to stress transfer functions relates to the requirements for *damage* versus *crack growth* calculations. Damage calculations require knowledge of only the worst-case stress at a point (typically at the surface of a component), whereas, crack growth calculations require knowledge of the complete through-thickness stress profile. Actual through-thickness stress profiles, determined through either closed-form solution or FE analysis, are fit to a cubic polynomial function of distance, with the resulting curve-fit coefficients configured in CFPro. An equation of the following form is then used in CFPro to calculate stresses at any distance through the thickness:

$$\sigma(\mathrm{x},\mathrm{p}) = p[C_0 + C_1 x + C_2 x^2 + C_3 x^3] \qquad \textbf{Eq. 2-1}$$

Where, $C_0,,,C_3$ = cubic polynomial curve fit coefficients

x = distance through component wall thickness from surface

p = value of applicable plant instrument reading (pressure, temperature, etc.) as a function of time

2.2 Brindisi High Temperature Header Stress Transfer Functions

CFPro was implemented under the current project for life consumption monitoring of the final superheater (SH) and reheater outlet headers in the Unit 1 supercritical boiler at the Brindisi station. The unit has separate front and rear SH outlet headers, and one RH outlet header. Pertinent geometry, material and design conditions of these headers are as follows:

Front SH outlet header:

- Header body 325 mm ID x 152 mm wall thickness (12.795” x 5.984”)
- Header body OD 629 mm (24.764”)
- 20055 mm main header body length (~65’ 9”)
- Grade 22 material (2¼Cr-1Mo)
- Two outlet nozzles at ~1/4 pts across header length
- 34 tube assemblies across header length on 609.6 mm (24”) typical axial spacing
- 13 tubes in each assembly with radial header entry @ 13^{o} typical circumferential spacing
- Tube stubs 51 mm OD x 14.3 mm wall thickness (2” x 0.563”)
- Tube stub and bore penetration ID 22.4 mm (0.882”)
- Design conditions 268 bar @ 540^{o}C (3887 psi @ 1004^{o}F)

Rear SH outlet header:

- Header body 325 mm ID x 160 mm wall thickness (12.795” x 6.299”)
- Header body OD 645 mm (25.394”)
- 19370 mm main header body length (~63’ 6”)
- Grade 22 material (2¼Cr-1Mo)
- Two outlet nozzles at ~1/4 pts across header length

- 32 tube assemblies across header length on 609.6 mm (24”) typical axial spacing
- 13 tubes in each assembly with radial header entry @ 13° typical circumferential spacing
- Typical Tube stubs 51 mm OD x 14.3 mm wall thickness (2” x 0.563”)
- Tube stub and bore penetration ID 22.4 mm (0.882”)
- Design conditions 268 bar @ 540°C (3887 psi @ 1004°F)

RH outlet header:

- Header body 720 mm ID x 82 mm wall thickness (28.346” x 3.228”)
- Header body OD 884 mm (34.803”)
- 24300 mm main header body length (~79’ 9”)
- Grade 22 material (2¼Cr-1Mo)
- Two end outlet nozzles
- 4 tube rows with 87 tube assemblies across header length on 228.6 mm (9”) typical axial spacing
- 4 tube rows with 174 tube assemblies across header length on 114.3 mm (4.5”) typical axial spacing
- Tubes have non-radial header entry @ 101.6mm (4”) side spacing
- Tube stubs 57 mm OD x 5.8 mm wall thickness (2.25” x 0.228”)
- Tube stub and bore penetration ID 45.4 mm (1.787”)
- Design conditions 52 bar @ 540°C (754 psi @ 1004°F)

For high temperature headers such as these, one primary location of service-related damage development is internal cracking occurring in the tube boreholes and ligament regions between adjacent tube boreholes in the header. This cracking is attributed to long term creep-fatigue and occurs at rates dependent on the magnitude of steam temperatures entering the header through the individual tube legs across the header length, and the frequency and severity of steam temperature changes occurring during unit startups, shutdowns, load change and normal load generation operation. CFPro was subsequently implemented for life consumption monitoring of the circumferential ligaments between adjacent tube bore holes in each of the three headers. For each header, life consumption monitoring locations were established for 5 to 7 representative ligaments across the header length in order to evaluate the impact of local tube leg steam temperature variations on creep-fatigue damage accumulation rates.

Global finite element models of the overall configuration of each header were generated by ENEL to support the CFPro configuration, in addition to a local sub-model of one representative tube assembly in each header. Derivation of stress transfer functions for internal pressure and thermal transient loadings, required for the CFPro configuration, were accomplished with the local sub-model of each header. While the global models of each header were used by ENEL primarily for other non-CFPro related assessments, thermo-fluid dynamics analyses were performed with the global models to determine local convective heat transfer film coefficients for comparison to closed-form solutions, and ultimately for application in the sub-model finite element analyses performed to generate the thermal transient stress transfer functions.

Figure 2-2 shows the global and local sub-models generated by ENEL for the SH outlet headers.

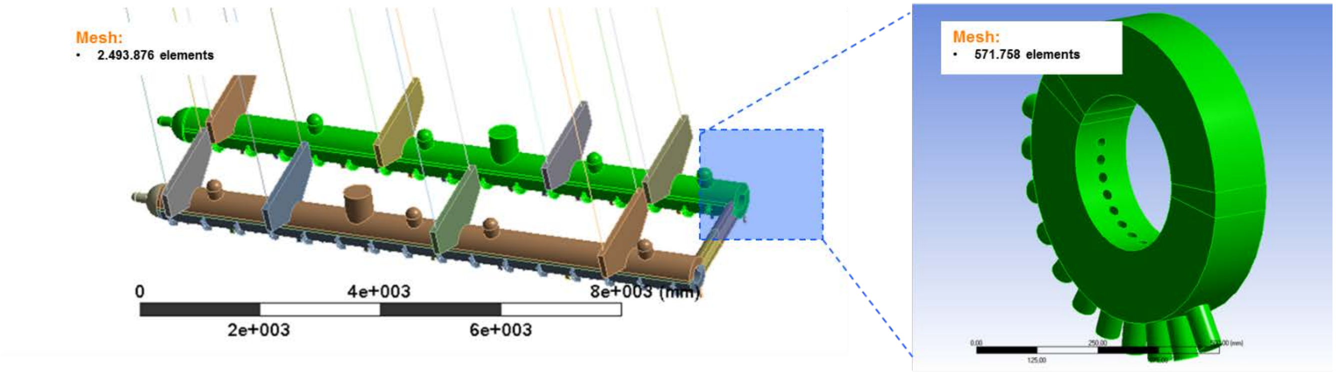

Figure 2-2
Global and local sub-models of the SH outlet headers

As noted previously, ENEL completed all of the finite element analyses required to derive the stress transfer functions required in CFPro for determination of internal pressure and thermal transient stresses from plant instrument (steam temperature, pressure and flow rate) data. Remote assistance was provided to ENEL during this process. Following completion of the finite element analyses by ENEL, one week of site configuration training was subsequently conducted in Italy to review the finite element stress results, configure the CFPro databases with the derived stress transfer functions as well as all other configuration data required for the header monitoring application (material properties, initial/allowable damage levels, crack growth flaw models, initial/allowable crack sizes, plant instrument definitions), and to process and review the results from an initial period of monitored plant operations.

3
SYSTEM INSTALLATION AND TEST

3.1 Overview of CFPro Software

Creep-FatiguePro (CFPro) is a software system, developed by EPRI [1] that calculates damage accumulation and/or crack growth for selected components in a power plant. Since it uses actual operating conditions as input (rather than design assumptions or expected operating conditions), CFPro can calculate more reliable damage results, reducing uncertainty in component analyses and allowing plants to manage component lifetimes with lower levels of conservatism.

The CFPro software runs on a single Windows PC. It was designed as an interactive desktop application with display windows, a menu bar, shortcut keys, etc., but it also supports unattended “batch mode” operation. A screenshot of the CFPro application is shown in Figure 3-1.

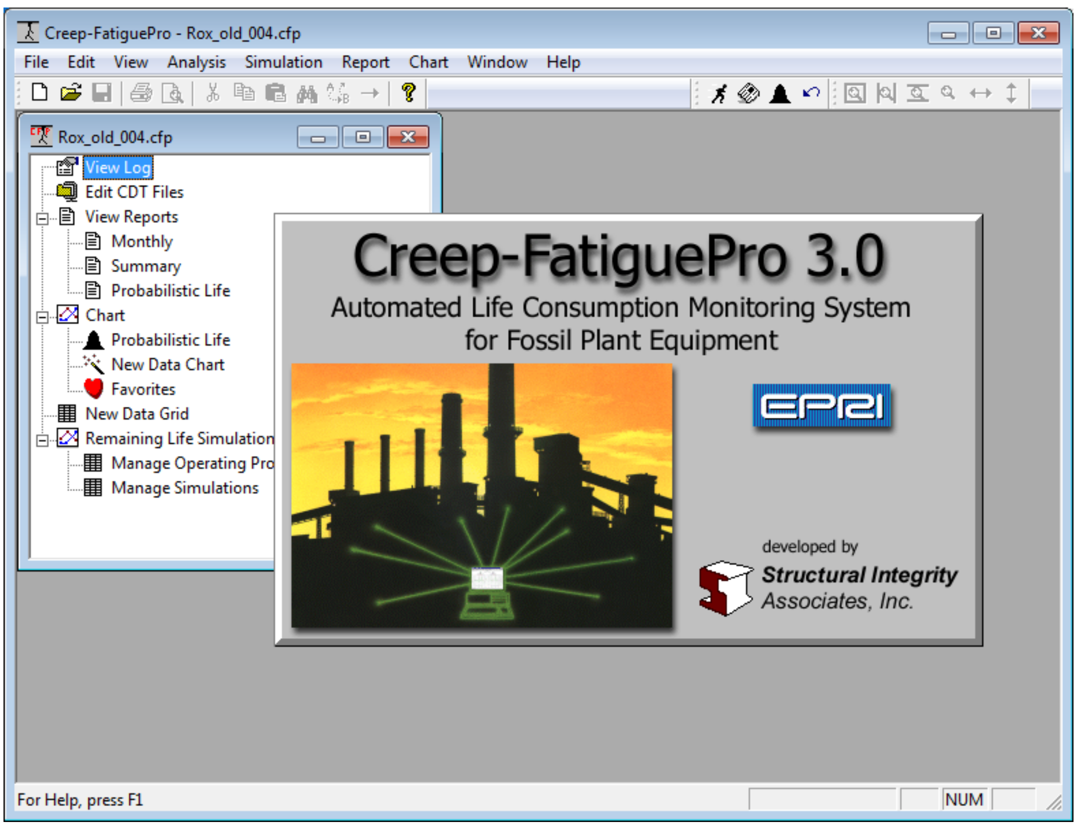

Figure 3-1
CFPro software main application window

A CFPro system consists of 3 parts: the CFPro application, a project Database, and the plant input data. A block diagram showing the interaction of these components is given as Figure 3-2.

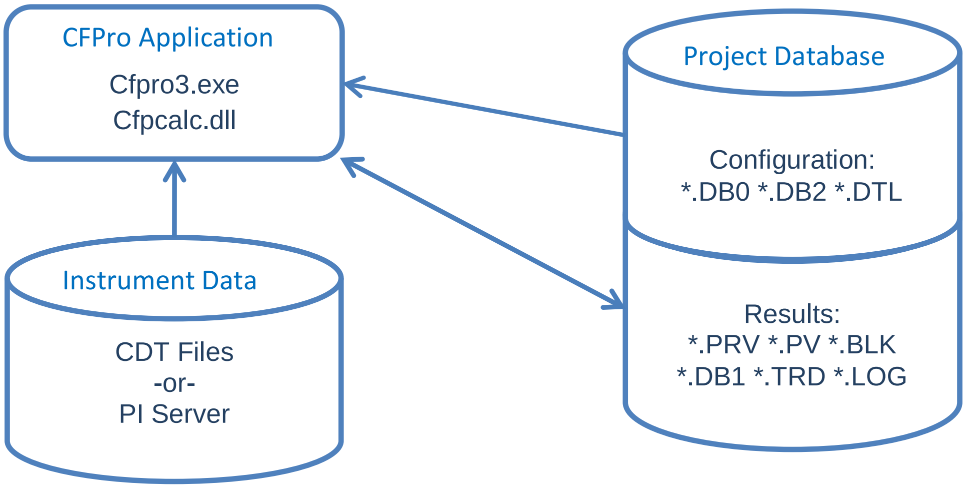

Figure 3-2
CFPro software architecture block diagram

The project Database (DB) is a set of related files that (a) defines the locations to be monitored and the plant instruments to be used to monitor them, (b) contains the configuration data developed for each monitored location (as described in Section 2 above), and (c) accumulates the damage/crack growth results for each location over time. CFPro can maintain several different project DBs to monitor multiple plants/units from a single installation.

Historically, CFPro reads the plant operating data from specially-formatted text input files called “CDT files”. This generally requires custom software to create CDT files from whatever digital data archive is available at each plant, plus procedures to copy those files to the CFPro computer and process them manually. Recently, CFPro has been modified to read plant input data directly from a PI-System server (a popular real-time data management system sold by OSIsoft). This feature makes it much easier for plants with a PI system to implement CFPro.

To perform monitoring calculations, the user starts the CFPro application and loads a project DB. Next, they select the plant instrument data to run, either as CDT files or by choosing a PI Server that contains the plant data. Then they start the analysis, and CFPro calculates the incremental damage/crack growth corresponding to the given plant input data. The new damage/crack growth is automatically appended to any damage/crack growth already present in the DB.

The CFPro application also provides several display windows, reports, and graphing features to review the accumulated results (see examples in Figure 1-3 and Figure 1-4). In addition, plants with a PI system can choose to upload selected monitoring results back to the PI Server, where they can be reviewed using any of the normal PI review tools (such as ProcessBook™ and DataLink™). An example of a PI ProcessBook™ UI is shown in Figure 1-5.

3.2 Installation Process

CFPro installation consists of five stages (presented here as an outline; the whole process is explained in detail in the CFPro User's manual):

1. Planning: Identify and prepare all of the resources that will be required for the CFPro system. This includes procuring a Windows PC on which to install the CFPro software, identifying a PI Server that contains the plant input data, creating a user account from which to run CFPro, and configuring that user with rights to access the PI Server.
2. Install Software: On the CFPro PC, run the CFPro Setup program, create folders for any monitoring projects you want to have, and fill them with project DB files (prepared as described in Section 2, above). After the software is installed, open each project and test the PI connection (this also creates a PI-points file for use in the next step).
3. Configure the PI Server: Using the PI-points file(s) created in the previous step, add Points to the designated PI Server to receive the CFPro results. Make sure that the CFPro user account has the necessary permissions to read and write to those Points.
4. Initial Analysis: Perform a start-up analysis run for each monitoring project. This step establishes a start-of-monitoring date for each project, and also demonstrates that each project is configured correctly and ready to run.
5. (optional) Automatic Operation: Create a scheduled task on the CFPro PC to run the CFPro program at regular intervals (e.g., every night at 1:00 am, or weekly, etc.)

3.2.1 Installation Plan

For the installation at Brindisi, it was decided to install the CFPro program on a rack-mounted Windows server in the La Casella server center near Milan. This PC was already connected to the ENEL wide-area network (WAN), and had the PI-System software pre-installed.

It was decided that the CFPro project files would also be stored locally on the same server PC. Project files would be stored in a directory tree structure that would make it easy to expand CFPro monitoring to other plants and units.

Since this was an evaluation system, an off-line PI Server was created by ENEL to supply the plant data for the CFPro system. This setup provides a layer of protection to the production PI Server(s), since CFPro will not access them directly. But it does require additional work, since the plant data required for monitoring must be replicated onto the off-line PI Server.

The general structure of the installation at La Casella is illustrated in Figure 3-3.

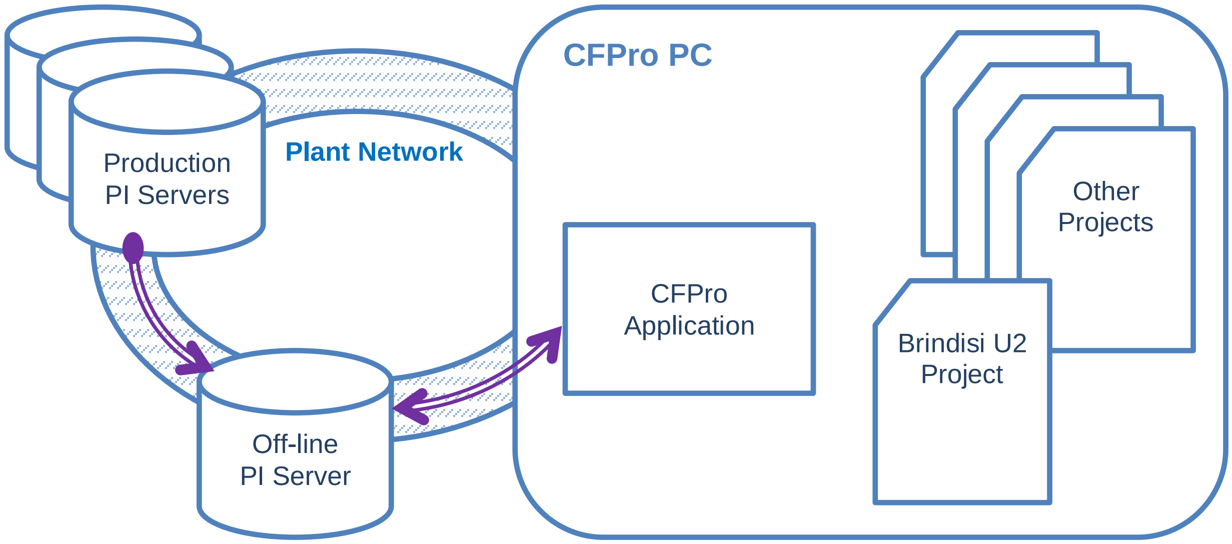

Figure 3-3
CFPro installation plan

3.2.2 Software Installation

The selected CFPro PC was already connected to the WAN, and had the PI system pre-installed, so all the prerequisites were met. The CFPro setup program was copied onto a USB thumb drive, and then onto the CFPro PC. The setup program was executed, and the CFPro software was installed to a folder “D:\APP_PI\CFPRO” on the PC local hard drive. A second new folder “D:\APP_PI\Brindisi\BS1\CFPro\Unit1” was created for the Brindisi demo project, and a preliminary set of DB files were copied to that folder.

After installation, the new CFPro application was started. It opened as expected, and the users were able to create a new project, referencing the preliminary DB files and the off-line PI Server. Using that project, it was then attempted to start an analysis run. As expected, it did not run, but it did successfully connect to the PI Server and produce the “PIPoints.txt” file (as required for the next step of installation).

However, inspection revealed that the PIPoints file did not contain the expected list of result points. Instead it listed an instrument point; this occurs when the PI Server does not contain one or more of the required plant instruments. The offline PI Server was checked, and it was found that one of the required instruments had not been copied to the offline PI Server. A job was started to replicate the missing Point, and when it completed the CFPro software was run again. This time, the PIPoint file it created contained a list of result points, as expected.

3.2.3 PI Server Configuration

The next step of installation was to add Points to the PI Server to which CFPro can write the monitoring results. This allows users anywhere in the ENEL network to view the results, using the PI System. As delivered, CFPro uploads 6 result variables for each monitored location:

[*plant*]-CFP-[*location*]_Df	accumulated fatigue damage fraction
[*plant*]-CFP-[*location*]_Dc	accumulated creep damage fraction
[*plant*]-CFP-[*location*]_Cf	accumulated fatigue crack growth
[*plant*]-CFP-[*location*]_Cc	accumulated creep crack growth
[*plant*]-CFP-[*location*]_crk	calculated total (initial + growth) crack size
[*plant*]-CFP-[*location*]_dmg	calculated total (CFI) damage fraction

The PIPoints.txt file creates a list of all of the PI Points that need to be added to the PI Server in order for CFPro to send its results to PI. That list is formatted so that it can be used with the piconfig tool (part of the PI system) to create the Points.

However, the PI system engineer working on this project preferred not to use piconfig; instead he had a different tool that he used to create PI Points. This was not a problem—he was able to copy the Points list out of the PIPoints.txt file and into his own tool, and successfully added all the result Points to the offline PI Server.

Once the Points were added to the PI Server, it was necessary to modify their access rights to allow CFPro to write to those Points (the default access when Points are created is read-only access). The users were able to modify the rights quite easily using the PI console. Since Windows security was used (and not PI User security) there was no dedicated PI user and password for CFPro to use. Therefore, write access was given to the “PIWorld” group for all of our new Points.

3.2.4 Initial Project Setup

At this point it was time to perform the initial analysis run using the demonstration project. This step serves two purposes. If the analysis runs without errors, then it demonstrates that the preceding steps of the installation were successful. Also, it establishes the start of monitoring for the given project; from this point forward, each subsequent analysis will add to the results from all the prior analyses.

Working with the ENEL PI system engineer, it was determined that the off-line PI Server was loaded with plant instrument data back to mid-September of 2016. Therefore, it was decided to start this initial analysis on 9/21/2016.

CFPro was started, the Brindisi demo project loaded, and an analysis run started for 7 days: 9/21/2016–9/28/2016. The analysis ran, and completed. This successfully completed the installation.

3.2.5 Task Scheduling

The last step in the installation was to set up the system for unattended operation—where CFPro starts automatically each night, runs any new plant data that is available, saves the new results and then quits.

The preferred way to set up unattended operation is to use the Windows Task Scheduler. Task Scheduler is a utility built into the Windows OS that can be used to run other programs whenever certain conditions occur—including on a time schedule.

Following the instructions in the CFPro User Manual, the Task Scheduler was opened and a task to run "Cfpro3.exe" (with the Brindisi demo project) every night at 1:18 AM was created. After that, a new task was selected and "Action, Run" was chosen from the Task Scheduler menu. The CFPro application started, the demo project loaded automatically, and the analysis run started. It began to run 30 days of plant input data (the default amount for an auto run).

The automated run went just as intended, except that the analysis took much longer to run than expected (compared to the initial analysis that was run manually). From prior experience, an analysis using PI data would typically take about 1 minute per day processed. This analysis took about 10 minutes per day. Looking at 5 hours total to complete the run, the run was stopped early to investigate the speed problem.

Significant time was spent testing the CFPro software to determine the cause of the slow-down. In the end, it was discovered that the long execution times were related to how much data CFPro was writing back to the PI Server. In response, the software was modified to write less result data to the PI server. With this strategy, a reasonable execution time of approximately 5 minutes per day was achieved.

3.2.6 Lessons Learned

Installing CFPro on an existing PC server or workstation is easier, especially if the PI software is already installed & working on that PC.

Configuration of PI Points for uploading the CFPro results remains an error-prone process. Although this is a temporary issue (i.e., once all the right points are created, the problem is solved), the prospect of creating more projects over time, or of adding locations to existing projects, means that CFPro could benefit from better tools to perform this set-up task. The ENEL project team had several suggestions for improvements along these lines.

PI System security was easier for this installation than it was for the previous effort at As Pontes. This stems from two factors. First, there was awareness that PI security could be a problem, so explicit plans to deal with it were made up front. Second, the La Casella center was already using a strategy of PI security linked to their network user security. With this setup, there was no need to create PI users and explicit security rules. This resulted in less work to connect to the PI servers.

On the other hand, PI System performance (especially over the WAN) was a problem this time. To date, the CFPro systems with a direct PI link has only been installed at two sites. In the first case (As Pontes in Spain) using the PI data link produced almost no slowdown compared to running CFPro with CDT input files. But in this case (Brindisi in Italy) analysis runs using the PI data link were many times slower than using CDT files. There are too many differences in the details of each installation to be able to narrow it down to the specific influencing factor(s). Hence, before extending this type of CFPro installation widely, it would be desirable to further investigate this effect, and to develop best-practice guidelines for connecting CFPro to a PI System.

Finally, automated (scheduled) operation can be challenging. In order to be successful with a minimum of human interaction, all details of the process must be considered carefully during the installation. Several of these challenges have been learned from previous trial (e.g., running with no window; proper user account and PI system access rights; limiting the number of days per run), but this project has raised two new issues:

- Run (execution) time can be a concern. If a system has 10 different CFPro projects to run, and if each project could take 2½ hours to run, then all of those runs cannot be sequenced to complete overnight, every night. Some other strategy will be required, such as staggering execution for different projects across multiple nights.
- A solution is needed to prevent collisions, i.e., where two or more copies of CFPro try to run at the same time. The CFPro software is not written to operate concurrently, and doing so could corrupt the DBs of the projects being run. This is unlikely to be a problem in systems with just one or two projects, but the odds of a potential conflict increase with the number of monitoring projects.

3.4 Demonstration and Training

ENEL originally scheduled two days of training for the CFPro system: one day for the staff that would be maintaining the system, and one day for the end users at the plant. The first day was planned to cover how to create new monitoring projects and keep the system running. The second day was planned to cover what CFPro did, why they were using it, and how to review the results.

Given the difficulties in completing the installation, the first day of training was dropped. This seems like a lost opportunity, but all of the participants were closely involved in debugging and correcting the installation problems, which effectively served as an on-the-job training session. It became evident during the classroom training on the second day that they had learned all the material intended for the first training session by participating in the installation. In fact, they were able to teach much of the second day's class.

Prior to the classroom training, the installed software was used with the demonstration project to process 26 days (24-June-2017 to 19-Jul-2017) of data from Brindisi, Unit 1. Since running weeks of data takes a long time (relative to a six-hour class), it was necessary to run the analysis before the training session. Also, since CFPro was installed for unattended operation, the normal user experience will be to interact with the results, not to make analysis runs or modify projects.

The user training session consisted of three presentations. The first presentation was an introduction to Creep-FatiguePro; it explained what the software did, and how it worked. The second presentation was a demonstration of how to use the CFPro system. This covered both the CFPro application and the PI-system review features. It was also discussed why ENEL wanted to use the system (i.e., to better manage how the plants were used for load-following generation.)

The third session was essentially a forum, where the ENEL project team led a review of the results from the demonstration project, using the PI data review tools (primarily using PI to plot the CFPro system data). Plots of the calculated damage was called up alongside the local instruments, and demonstrated how different transients during operation contributed more or less damage. This session was the most engaging of the three, and generated much discussion among the attendees. The ability to use the CFPro system to ask questions and make correlations was much more effective at teaching the material than the slides of notes and illustrations had been.

4
ANALYSIS RESULTS

At the time of this report, three months of processed plant instrument data were available to review. Figure 4-1 shows unit MW load, SH pressure and RH pressure over this 3-month period. The plotted data indicates that the unit experienced five shutdowns during the 3-month period, and almost daily load cycling between minimum and maximum load levels of approximately 300 MW and 600 MW during the operating intervals between shutdowns. SH and RH pressure during load generation operations fluctuated minimally about 250 barg and 25 barg, respectively.

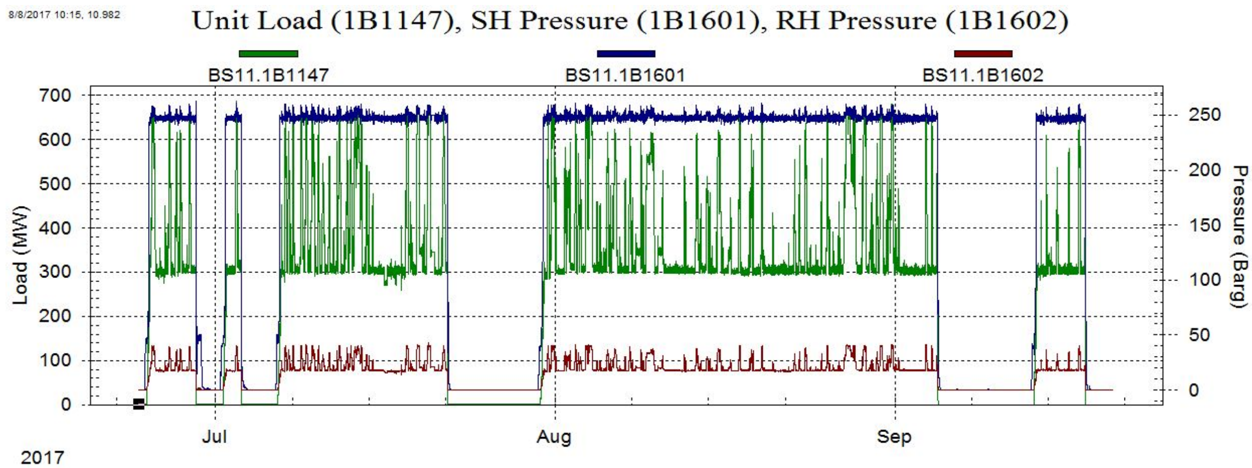

Figure 4-1
Unit Load, SH and RH pressure over the initial 3-month period

A primary interest of ENEL with this monitoring application was to determine the impact of increased unit cycling operation on fatigue damage accumulation and life consumption rates in critical plant components. Further, ENEL was interested in evaluating the extent to which varying temperature ramp rates during unit startups, shutdowns and other transient periods affected fatigue damage accumulation in the components. The initial monitoring results for one representative header, the front SH outlet header, are discussed below.

4.1 Initial Monitor Results for the Front SH Outlet Header

Figure 4-2 shows the steam temperature histories at each of the six circumferential ligament monitoring locations across the length of the front SH outlet header over the full 3-month initial monitoring period, and Figure 4-3 shows a close-up of a representative 2-week period of load generation operation. The plotted temperatures are from thermocouples located on one of the header tube legs at each of the monitored ligaments. Figure 4-3 shows a steady temperature difference of approximately 50ºC between the lowest temperature tube leg (~510ºC at tube 13/assembly 58) and the highest temperature tube leg (~560ºC at both tubes 9 and 13/assembly 33). This 50ºC temperature difference can be expected to have an appreciable impact on creep damage accumulation rates between the two locations.

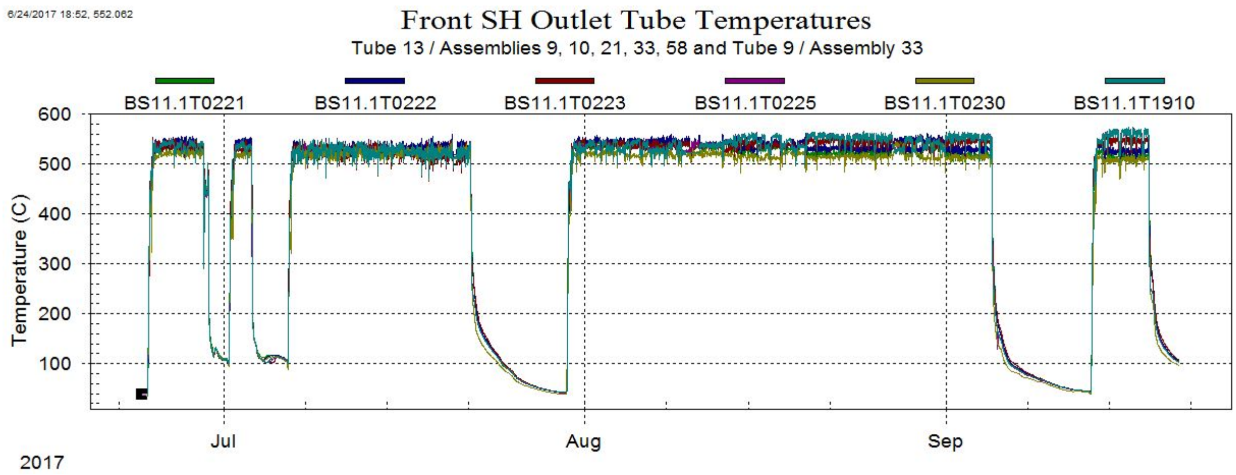

Figure 4-2
Front SH outlet header tube temperatures over the initial 3-month period

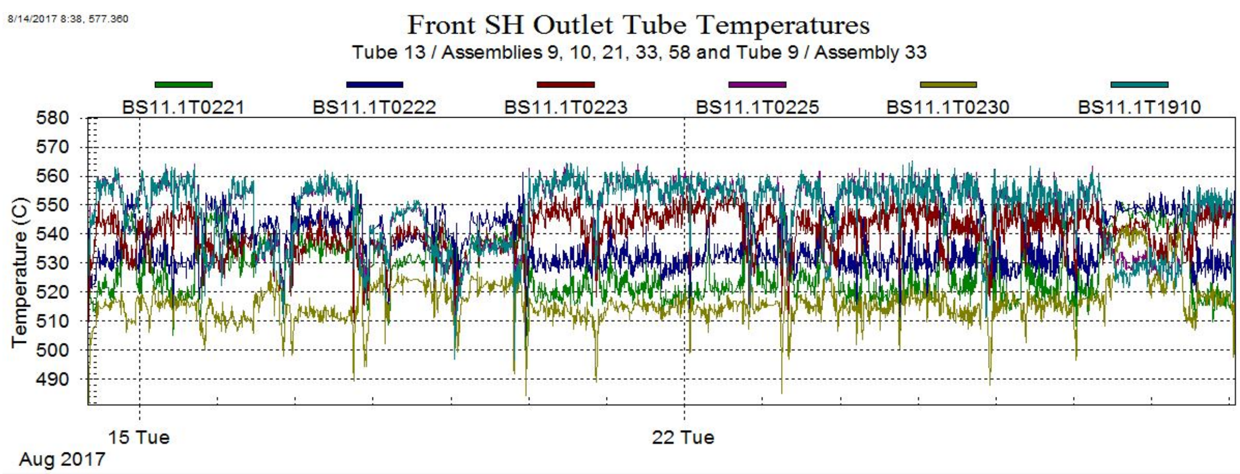

Figure 4-3
Front SH outlet header tube temperatures over representative 2-week period

Figures 4-4 and 4-5 show the accumulated creep damage and fatigue damage calculated for each of the six ligament monitoring locations across the front SH outlet header. Referring to Figure 4-4, note that the greatest creep damage accumulation is predicted at the tube 9/assembly 33 and tube 13/assembly 33 ligaments, and the least creep damage is predicted at the tube 13/assembly 58 ligament. This is consistent with the temperature profiles plotted in Figure 4-3.

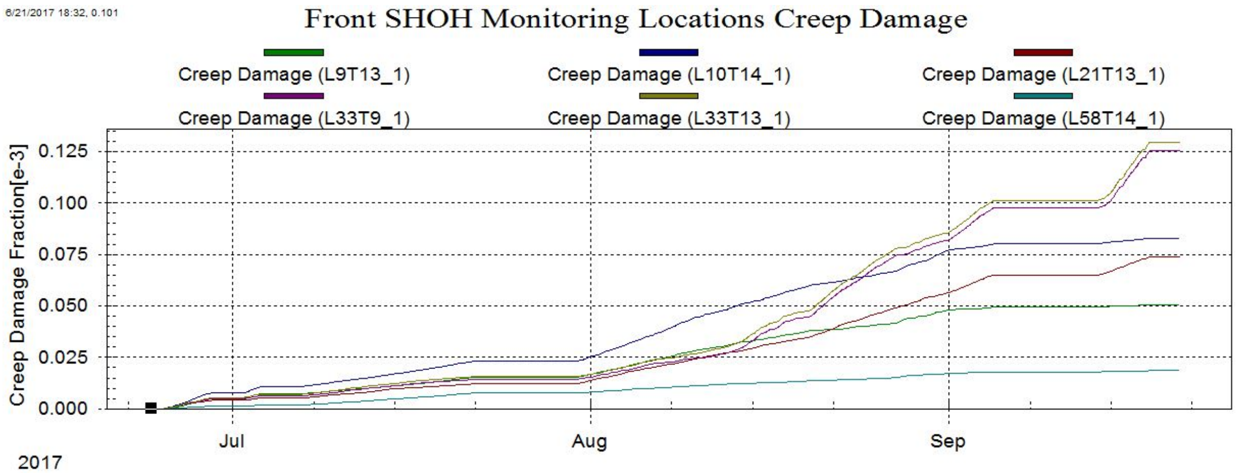

Figure 4-4
Accumulated creep damage at the front SH outlet header monitored ligaments

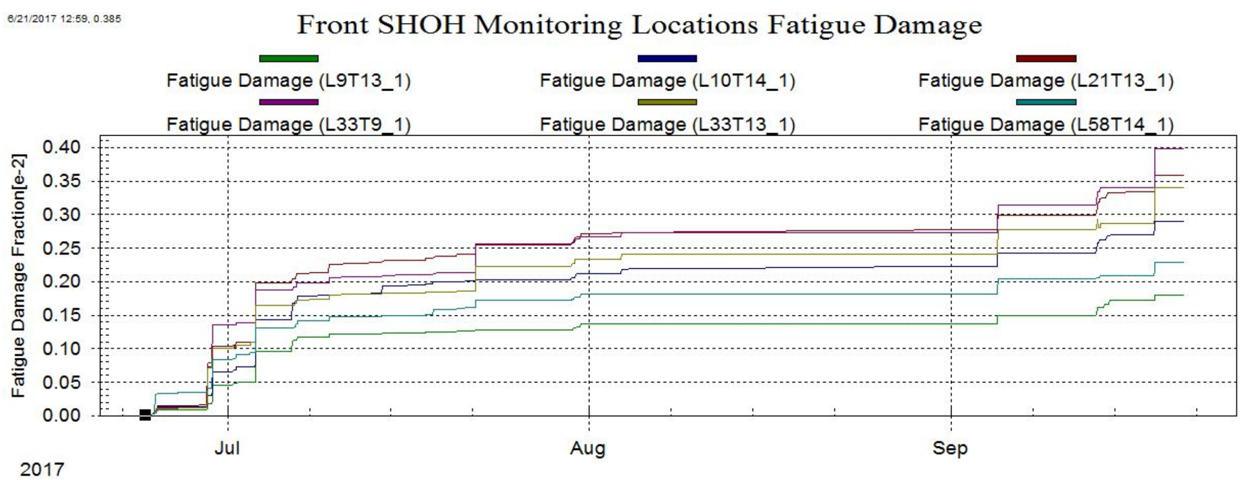

Figure 4-5
Accumulated fatigue damage at the front SH outlet header monitored ligaments

Note further from Figures 4-4 and 4-5 that calculated fatigue damage accumulation at the header ligaments is an order of magnitude larger than the calculated creep damage (0.004 accumulated fatigue damage versus 0.00013 accumulated creep damage). This is not unexpected as tube bore ligament cracking in high-temperature headers is largely attributed to thermal transient stresses under cyclic operating conditions. This is illustrated further in Figures 4-6, 4-7 and 4-8, which plot temperature, creep/fatigue stresses and creep/fatigue damage accumulation for the ligament location exhibiting the maximum damage accumulation (tube 9/assembly 33).

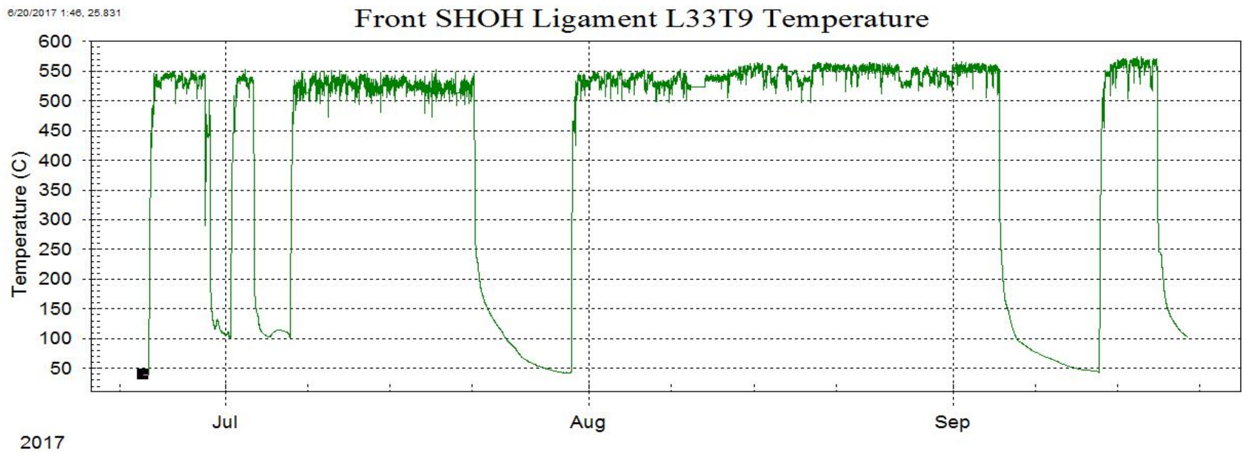

Figure 4-6
Temperature history at the tube 9/assembly 33 ligament

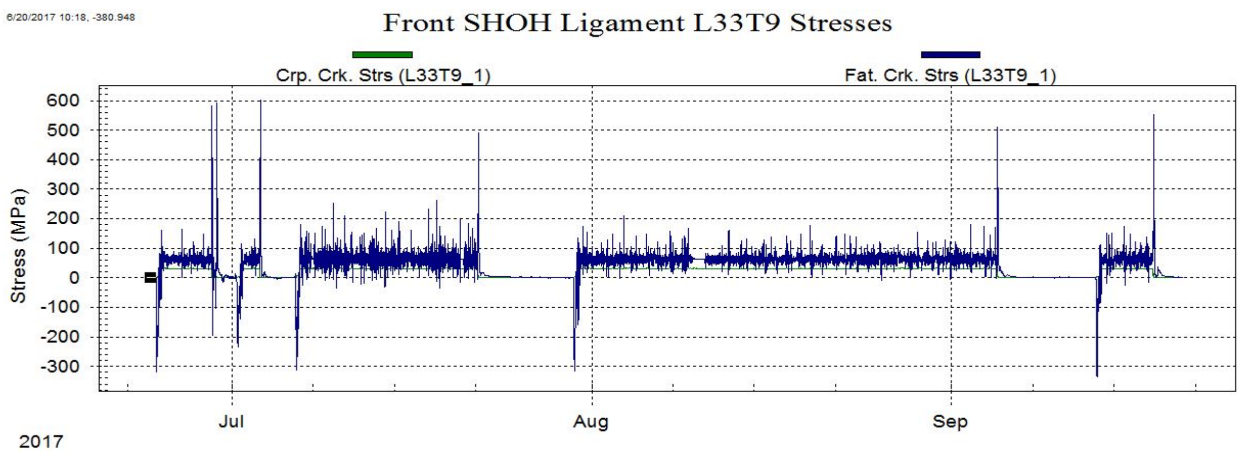

Figure 4-7
Creep and fatigue stresses at the tube 9/assembly 33 ligament

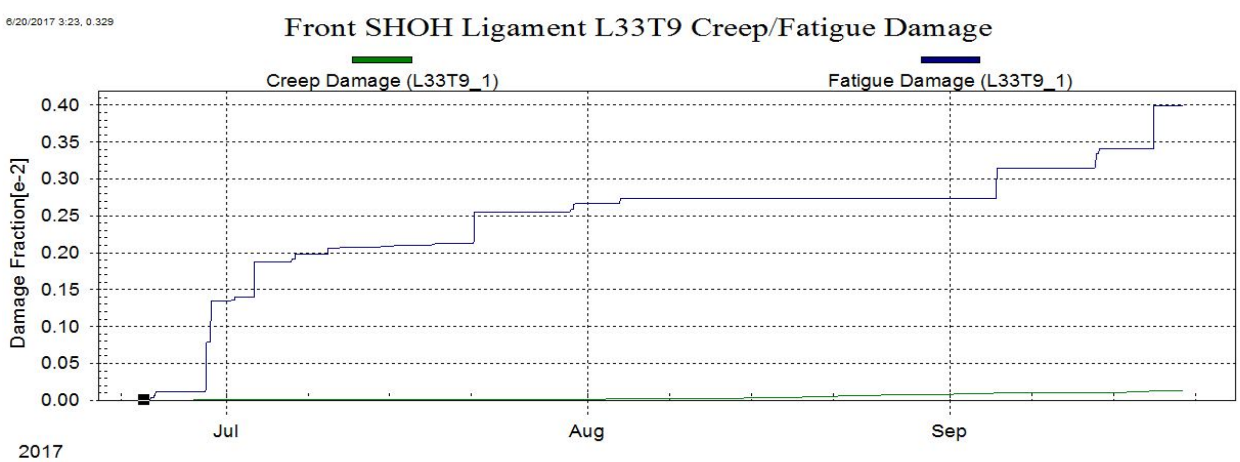

Figure 4-8
Creep and fatigue damage accumulation at the tube 9/assembly 33 ligament

Note from Figures 4-6, 4-7, and 4-8, that the majority of the total accumulated fatigue damage is calculated during the shutdown/startup events, with only minimal fatigue damage experienced during the daily load-cycling operation. This is also not unexpected as tube bore ligament cracking is largely attributed to on/off cyclic operation as opposed to load cycle operation.

Also from Figures 4-6, 4-7, and 4-8, note that fatigue stresses and fatigue damage increments are similar between the two 7-8 day shutdown/startup events occurring in late July and early September. Conversely, relatively higher fatigue stresses and fatigue damage increments are experienced during at least one of the shorter 2-day shutdown/startup events occurring in late June/early July. Figures 4-9 and 4-10 show close-ups of temperature and stresses during these two short shutdown/startup events. These figures indicate that the greater fatigue stress and fatigue damage increment experienced during the first shutdown is due to a rapid down/up temperature upset occurring prior to or at the start of the unit shutdown.

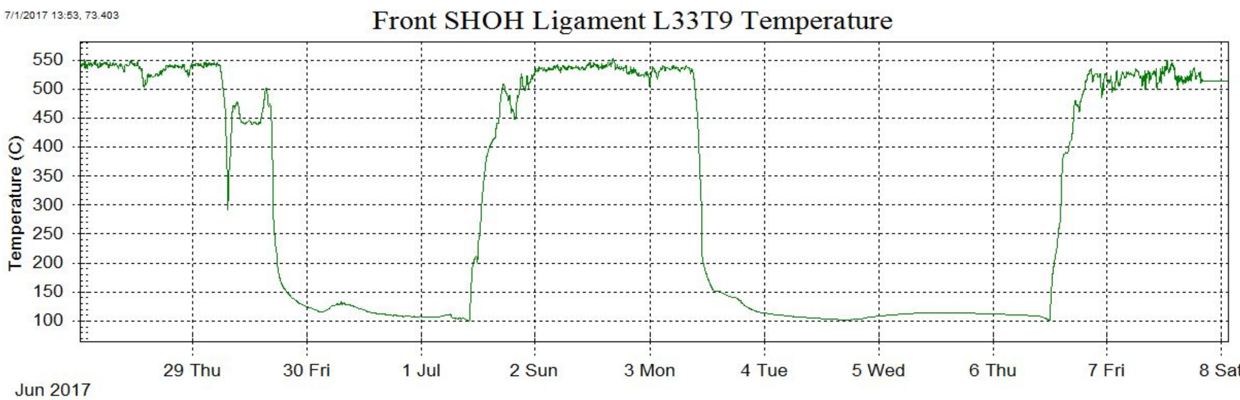

Figure 4-9
Temperature at the tube 9/assembly 33 ligament during the first two short shutdown/startup events

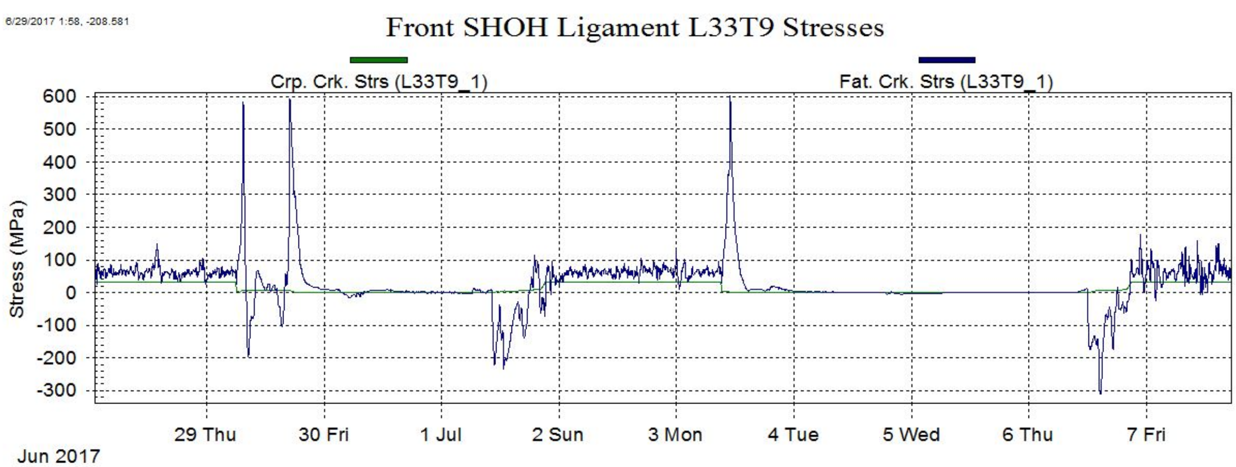

Figure 4-10
Stresses at the tube 9/assembly 33 ligament during the first two short shutdown/startup events

Aside from this one temperature excursion occurring during the first shutdown/startup event, this initial 3-month period of monitoring does not indicate substantial differences between temperature ramp rates, stresses and corresponding fatigue damage accumulation during the observed shutdown/startup events. These results are only for one small 3-month period of unit operations. ENEL plans to continue with the implemented CFPro monitoring of the headers to track creep-fatigue life consumption over the course of long-term operation and to assess how variations in unit operations affect damage accumulation and life consumption of the headers.

5 CONCLUSIONS

This project was successful in training ENEL staff to set up and configure CFPro for application at the supercritical Brindisi power station in Italy. The technology transfer activities under this project provides ENEL engineers the tools to utilize the software themselves, for potentially expanding it to fleet-wide online creep and fatigue damage monitoring in their globally distributed fossil fleet. Following a successful first application of CFPro in 2016 at the subcritical As Pontes plant in Spain, this follow-on project represents the second application to ENEL's fleet. With CFPro now applied in two different regions, this project also provided valuable insight into the suitability of CFPro for fleet-wide implementation.

ENEL performed the finite element analyses which were required as input for the CFPro configuration process. Review and guidance was provided, as needed, since this was the first time ENEL engineers performed these specific kinds of analyses related to CFPro. Upon successful completion of these analyses, a one week configuration training was conducted on site at the Pisa training facility, which allowed for an interactive learning environment. At the end of the configuration training, the configuration files were created for the locations of interest in the superheat and reheat headers at Brindisi.

CFPro installation and user training was conducted during a one week, on-site session at the ENEL server center near Milan. Although the Brindisi plant is located in the southeastern part of Italy, installing CFPro in this centralized server center in northern Italy provides the option to expand CFPro monitoring to other generation units in the Italian region. This is possible, as long as the operating data (PI server data) of the individual plants is replicated and available in this central server center. Although it was expected that the installation would be similar to the former installation in ENEL's region in Spain, specific challenges were identified and addressed during the installation process. For example, not all data tags were copied to the dedicated 'offline' PI server, where the operating data is replicated. This was discovered and corrected, after some troubleshooting.

Additionally, it was discovered that the program execution time was significantly longer than at the As Pontes application, and some adjustments to read/write data rates had to be made. This helped to improve the execution speed; however, it is not yet clear what exactly triggered the slow-down. With the desire for more regional installations to support fleet-wide implementation, this would have to be investigated and understood further.

In addition to these process and setup implications, two new areas of concern were identified during the installation phase, which may lead to a limitation for fleet-wide implementation. These include:

- Run (execution) time: If a system has multiple CFPro projects to run, it may not be possible to sequence those runs to complete overnight. Some other strategy will be required, such as staggering execution for different projects across multiple nights.
- A solution is needed to prevent collisions, i.e., where two or more copies of CFPro attempt to run at the same time. The CFPro software currently does not support concurrent operation, and doing so could corrupt the database (.DB) files of the projects being run. This is unlikely to be a problem in systems with just one or two projects (monitored plants), but the odds of a potential conflict increase with the number of monitoring projects.

Finally, results of the configured creep and fatigue damage monitoring locations at Brindisi were reviewed. Result files were provided by ENEL for a three-month operating period. The data revealed that some adjustments to the configuration were necessary, based on experienced damage rates on similar plants with similar operating regimes. Inconsistencies were identified between temperature profiles and related rates of damage accumulation. A review and potential adjustment of the configuration after analyzing a certain period of operating data is a standard part of the CFPro configuration process. The need to correct the configuration for Brindisi served as a good learning experience for ENEL.

This technology transfer project successfully trained ENEL engineers in the configuration and use of the CFPro monitoring software. ENEL engineers should be well-positioned to handle the majority of the configuration process themselves. This provides ENEL with the tools to expand CFPro for online creep and fatigue damage monitoring to other generating units. Potential limitations to a fleet-wide implementation were identified on the software side. A significant contributing factor to these potential limitations is the age of CFPro - written almost 30 years ago as a standalone software designed to run on a dedicated Microsoft Windows computer. This requires local installations in each generating location or region (if PI data is in a centralized server for that region), with each installation potentially requiring specific adjustments due to local network setup. In addition, run time issues and limited ability to execute calculations concurrently would have to be addressed if more monitored locations were to be added.

To make CFPro a truly suitable solution for fleet-wide monitoring, major upgrades are recommended. Conversion from a file system based to a modern database structure (e.g. SQL) is recommended. Additionally, and perhaps most importantly, the software should be fully web-based so that it can be hosted in the cloud, with neutral (API) interfaces to available data sources. This would provide global accessibility of monitoring data through one user interface for corporate engineers. It would also limit IT setup and maintenance effort. Alternatively, rather than ‘re-writing’ CFPro, a more cost-efficient solution could be the integration of its analytical creep and fatigue damage tracking algorithms into an existing, cloud-based monitoring platform. Several scenarios are possible and worth consideration that could be particularly beneficial for utilities with globally distributed generating fleets.

A
REFERENCES

1. *Creep-FatiguePro: On-Line Creep-Fatigue Damage and Crack Growth Monitoring System*. EPRI, Palo Alto, CA: 1992. TR-100907.
2. *Application of Creep-FatiguePro at a Cycling Coal-Fired Boiler*. EPRI, Palo Alto, CA: 2016. 3002009206.
3. American Society of Mechanical Engineers, 2010 ASME Boiler and Pressure Vessel Code, 2011a Addenda, Section I, Rules for Construction of Power Boilers, New York, July 1, 2011.

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

3002011618

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com