EPRI Initiatives related to Flexible Operation of High Temperature Power Plant

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Abstract

Variable demand and an increasing range of electricity supply methods are such that steam plant must perform under cyclic operation. Indeed, the multiplicity of generating options means that even defining a ‘typical’ cycle is difficult. Quantification of the range of potential damage mechanisms is even more complex. In response to the need for greater understanding of cyclic performance issues in high energy components, in 2006 EPRI initiated a series of Annual Expert Workshops on Creep Fatigue. These discussions identified key issues and areas for development related to the design and performance under transient operation. Summary documents, produced from each of the annual meetings, have helped guide this international effort in the field of creep-fatigue. It is apparent that a coordinated effort is critical to ensuring that outcomes are meaningful and effective. Excellence in science and engineering is necessary in aiding the electricity supply industry to meet current challenges associated with safe and reliable operation of plant. The present paper documents the current state of knowledge on creep fatigue behaviour and outlines achievements from the EPRI collaborative work. The overall goal of this effort is to provide the basis of a comprehensive approach to design and life management of components that are subject to creep-fatigue conditions.

Keywords Creep, Fatigue, Flexible Operation

1. Introduction

Utilities increasingly need to adopt generating practices that involve cycles. The number, magnitude, and complexity of the cycles associated with transient type operation have all increased. Thus, starts and stops as well as changes in generating output can lead to problems associated with thermal and /or mechanical loading as well as potential issues with water chemistry and corrosion. For components which operate at high-temperature, damage associated with transient operation is frequently called *creep-fatigue*. However, even in this group of components, specifics of damage mechanisms will vary widely. A schematic illustration of the primary options is shown in Fig 1.

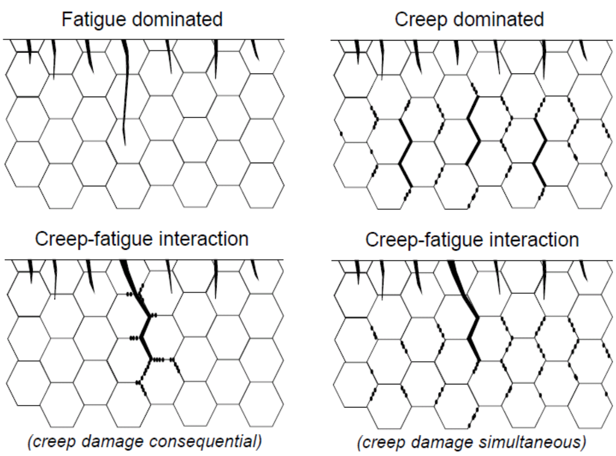


Figure 1. Schematic illustration of different forms of creep-fatigue type damage seen in high energy components.

While many examples of fatigue dominated and creep dominated in-service damage can be presented, the most problematic situation from a predictive point of view is when the effects are interactive. Under these conditions the primary concern is whether damage accumulates more quickly than would be expected for either mechanism alone. As power generating systems seek maximum flexibility from available plants, increasing numbers of components must operate in creep-fatigue conditions. Moreover, recent installation of combustion turbines and heat recovery steam generators have increased the number of materials and components that operate in high-temperature, cyclic conditions. In addition, high-efficiency coal plants operate with even higher steam and metal temperatures than those of traditional plants. Thus, creep-fatigue damage will occur more frequently and in more materials, including low-alloy ferritic steels, austenitic steels, nickel-based alloys, and creep-strength-enhanced steels.

The present paper documents the current state of knowledge on creep fatigue behaviour and outlines achievements from the EPRI collaborative work.

2. Achievements

EPRI’s long-range research program (Technology Innovation) initiated a set of activities in 2006. The initial goals of the work were to:

- Examine how problems of Creep-Fatigue assessment are addressed internationally
- Identify deficiencies that exist with current knowledge and approaches, and
- Recommend improvements in application of the available technology and identify future Research and Development needs.

EPRI’s overall approach to establishing solutions to assessing creep fatigue performance has involved facilitating discussion at annual expert workshops, preparation of critical reports and publications, facilitating the preparation and review of new ASTM standards for laboratory creep fatigue testing and establishing a platform and associated knowledge base of materials behavior. EPRI’s Fossil Materials & Repair Program has funded many specific activities, but the overall success of this effort is due to broad international collaboration with participants bringing their own resources and expertise together including focusing their scopes of work for the benefit of the group. Key elements of these achievements are presented here.

2.1. Expert Workshops

A series of EPRI facilitated Formulative Expert Workshops has succeeded in presenting up-to-the-minute information concerning the current state-of-knowledge of creep-fatigue damage interaction. The meetings have been hosted at different global locations and the presentations made at these workshops have been published by EPRI, Table 1. In addition, the discussions held resulted in the development of an agreed listing of key issues for future consideration. These issues have been reviewed and updated as necessary and continue to be used to guide current and future work.

Table 1. Annual Expert Creep Fatigue Workshops

Year	Location	EPRI Reference
2006	Amsterdam, Holland	1014482
2007	Marco Island, USA	1018511
2008	Kyoto, Japan	1018512
2009	Paris, France	1020673
2010	San Antonio, USA	1024440

2011	Bussan, Korea	1024944
2012	Hilton Head, USA	EPRI Life Management Conference Proceedings (in publication)

Analytical evaluation of creep crack initiation has been considered using different methods. The most widely used overall approaches are ASME, Rules for the Construction of Nuclear Facility Components, Class 1 Components in Elevated Temperature Service, Boiler and Pressure Code, Section III, Division 1— Subsection NH [1], TRD 301, Annex I—Design: Calculation for Cyclic Loading due to Pulsating Internal Pressure or Combined Changes of Internal Pressure and Temperature [2], RCC-MR, Design and Construction Rules for Mechanical Components of FBR Nuclear Islands, Section I [3] and R5, An Assessment Procedure for the High Temperature Response of Structures,[4] .

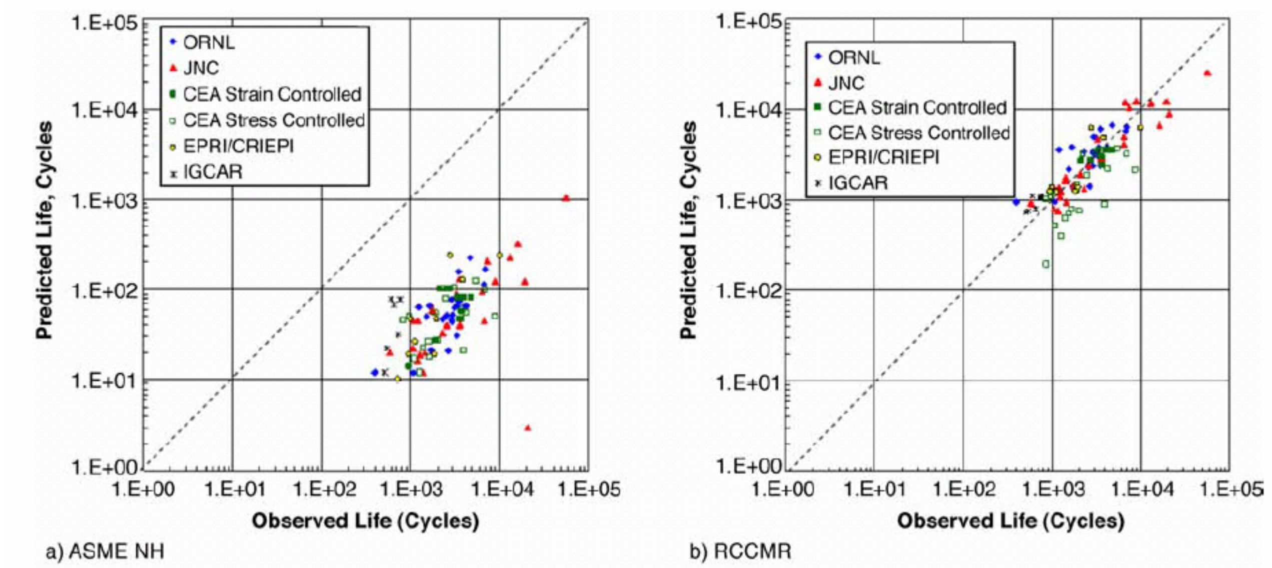


Figure 2. Comparison of the results of different methods of analysis of the same data set of creep fatigue data from Grade 91 steel, performed (a) using ASME NH [1] and (b) using RCCMR [3].

The difference in the approaches leads to very different predictions for creep fatigue behaviour. For example, the recommended interaction line for Grade 91 steel originally proposed in ASME – NH was very conservative. At least some of this excessive conservatism arises because this alloy exhibits complex behavior during cyclic tests at high temperature, and use of time fraction without considering stress-relaxation and strain-softening effects yields a very conservative outcome. The level of conservatism using the standard ASME NH approach is demonstrated by consideration of the results shown in Fig 2(a). Clearly, the calculated lives are at least 10 times less than the observed behavior. Application of an improved methodology, such as that developed in the French Code RCCMR, indicates that by accounting for the metallurgical complexities, the prediction comes into reasonable agreement with the observed behavior, see Fig 2(b).

2.2. Detailed Reports

The EPRI initiative has focused effort in specific agreed areas. One significant activity has been to facilitate preparation of State of Knowledge and other documents on Creep-Fatigue Damage

Interaction. A summary of these Milestone reports is provided in Table 2. It is apparent that the two main methods used to asses creep damage are:

- Time fraction
- Strain fraction (ductility exhaustion)

While these general terms describe the overall methodologies, there are also many variations in the detailed application. These variations and the assumptions that are often required to support the analysis frequently make definitive engineering judgments on accuracy difficult.

Table 2. Milestone Reports

Year	Title	Reference
2007	Creep-Fatigue Damage Accumulation and Interaction Diagram Based on Metallographic Interpretation of Mechanisms	1014837
2008	The State-of-Knowledge Report on Creep-Fatigue Interaction	1016489
2008	Review of Creep Deformation and Failure Models for Creep - Fatigue Assessment,	1018233
2008	Creep Fatigue Damage Interaction: Fatigue Deformation and Failure	1018439
2009	Plant Component Assessment for Creep-Fatigue Damage: Component Assessment Methodologies	1017608
2009	Plant Component Assessment for Creep-Fatigue Damage: Case Studies	1020511
2010	Creep-Fatigue Testing and Assessment Guideline: Material Property Data Requirements for Component Assessment	1019778
2012	Review and analyses of Creep-Fatigue data. Metallographic Atlas and examples of damage	In press

Whether time summation or strain summation is chosen, investigators have usually been at pains to demonstrate an agreement with experimental failure data to within a factor of two. This has generally been managed by increasing use of 'partitioning' rules or other degrees of sophistication so that the original models begin to lose their attractiveness – the most robust have proved to be those which are the easiest to use. By tracing some of the history of the damage laws, it appears that the time fraction rule originally took peak stress as the reference and was therefore conservative. Attempts to integrate down a relaxation curve and refine the appropriate time led to non-conservative predictions of life. Thus the interaction diagram was made bi-linear which restored conservatism.

There have been similar difficulties with analyzing ductility data for strain fraction. One basic question must be asked - which is the most physically correct ductility to take? The assumption of an average strain rate by taking ductility divided by time to failure is not necessarily an accurate reflection of secondary creep rate if both primary and tertiary stages of creep are large. Nevertheless, all models acknowledge the decreasing ductility (of whichever form) with decrease in strain rate, and there seems now to be a general acceptance that the ductility exhaustion approach is consistent and less prone to difficulties with scatter. In many cases, however, one may be forced to apply the time fraction rule because of data restrictions – it is highly unlikely that in long-term stress rupture tests that specimens were fitted with extensometry to determine relevant strain rates, and further there is no guarantee that associated end-of-test ductility values are available.

2.3. Standardization

Many countries have established guidelines and procedures for creep fatigue testing. However, there were differences in detail between many of the recommendations. A key activity facilitated by the EPRI work was thus development of specific ASTM Creep - Fatigue Standards. Currently efforts have resulted in two standards:

- ASTM Standard: Test Method for Creep Fatigue Testing, ASTM E2714-09. This method covers the determination of mechanical properties pertaining to creep-fatigue crack formation in nominally homogeneous materials. It is primarily aimed at providing the material properties required for assessment of defect-free engineering structures containing features that are subject to cyclic loading at temperatures that are sufficiently high to cause creep deformation.
- ASTM Standard: Test Method for Creep-Fatigue Crack Growth Testing, ASTM E2760-10. This test method is concerned with developing creep-crack growth data under cyclic conditions which is used in some more sophisticated assessments of in-service materials when large flaws may be present.

As part of the review and acceptance process by ASTM, the provisional Standards listed above must be evaluated for a precision and bias statement through a round robin test program. A round robin testing program is now complete for ASTM E2714-09[5] (details below) and the precision and bias statement will be added in the next revision of the standard. Planning, preliminary testing, and specimen blank fabrication are now complete for ASTM E2760-10 with round robin testing expected in 2013.

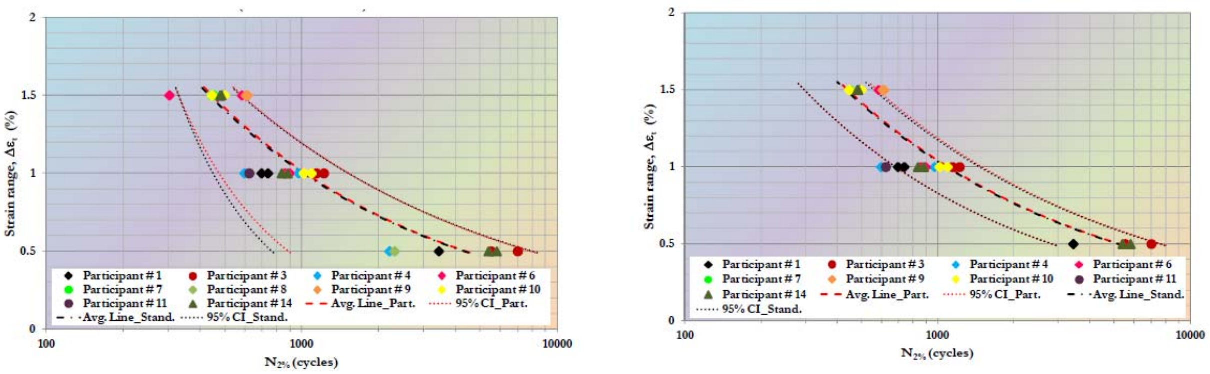
The round robin test program for ASTM E2714-09 utilized Grade 91 steel test blanks (modified 9%Cr-1Mo-V) provided by EPRI. Sixteen laboratories around the world agreed to participate in the study with 13 eventually reporting their test results to EPRI and the ASTM Task Group on Creep-fatigue Crack Formation (E08.05.08). Strain controlled creep-fatigue tests were conducted at 625C at three stain amplitude. Each laboratory followed the provisional standard, but variations in specimen geometry, heating methods, and numbers of tests were acceptable. Statistical analysis of the inter- and intra-laboratory variability was conducted. EPRI highly recommends metallographic assessment as part of the post-test evaluation to see if creep or fatigue damage dominated the failure or if a true creep-fatigue interaction was found. Most laboratories did not do this, so additional post-test metallography was conducted.

Assessment of the data required development of an improved analytical method, not currently prescribed in the standard, to determine the cycles to crack formation. The analysis of the data found the variability factor for the 95% confidence interval bands increased at longer hold times and lower strains. One significant finding was that post-test inspection of specimens was necessary to determine if a test was valid (or not). Uneven heating due to the use of induction heating methods or failures due to bending were not identified by the testing laboratory, but post-test inspection and metallography resulted in some tests being rejected. Fig 3 shows an example of data before (a) and after post-test assessment for validity (b). The round robin (RR) research produced the following recommendations:

- From the results of the RR, the current precision and bias statements in the standard should be modified (this activity is underway)

- The current standard should be modified to include post-test metallographic analysis to ensure that the dominant crack(s) form within the gage length of the specimen and if bending and/or extensive bulging was present in the test specimen warranting rejection of the data.
- A cautionary note should be added in the standard to warn users of the possible effects of heating methods on the C-F lives of test specimens.
- A more in-depth test program should be considered using the available material to characterize the C-F properties of P91 steel and to also investigate the effects of heating methods on the C-F lives.

In addition to these standards, the experts group has produced a code of practice for short-crack growth under creep fatigue conditions [6].



(a) (b)

Figure 3. Comparison of data produced as part of the creep-fatigue RR test program, (a) showing all the data while (b) shows the only data for tests which met the criteria for validity. The 95% confidence interval bands decrease significantly when post-test metallographic evaluation is used to eliminate invalid tests.

3. Discussion

It is clear that updated methodologies for estimating damage in service components should distinguish between sequential damage, for example, steady operation leading to creep followed by cyclic performance resulting in fatigue, and interactive damage, i.e. under conditions where the damage processes lead to rapid damage development. This is particularly important for alloys where time and/or cyclic microstructural changes occur. Damage accumulation in creep-fatigue should be described by a formulation that includes a term giving the influence of creep on fatigue and vice versa. In other words, where damage is truly interactive, the capacity for creep must be reduced due to the fatigue, and the capacity for fatigue must be reduced by creep.

Moreover, the challenges associated with using curve fitting approaches for parametric fitting of experimental data must be considered because although reasonable fits can be obtained to an existing data set, the accuracy of parametric data extrapolations may not be guaranteed. In all cases, there is a major requirement for the results of experimental and analytical programs to be supported by meaningful post test metallographic examination. Thus, post test examination should be performed to document the type, density and character of damage present recording at the very least whether the primary damage is intergranular or transgranular.

The practicality of using complex constitutive equations with many variables also needs to be considered. While design approaches, particularly for turbine components, may be carried out based on detailed knowledge, it is apparent that in-service assessment methods that are slightly conservative and can be applied without the need for extensive materials testing and/or complex stress analysis are required. This is particularly true for boilers and piping. This issue is illustrated by consideration of Fig 4. Here different analytical approaches have been applied to creep fatigue results from Grade 92 steel [7]. The relatively simple strain fraction method results in a consistently conservative prediction of behaviour. In contrast a more detailed modified strain fraction approach shows a much less conservative outcome. Indeed, with this analysis, experimental results and predictions are scattered on both sides of the line showing matching agreement, and all data are well within ±2. The continued validation of simple, sensibly conservative methods for at-risk plant components is necessary because of the implementation of new alloys and operating regimes.

Finally, it is important to note that the effect of Oxidation on Creep - Fatigue Damage interaction and Component Performance must be considered in specific circumstances of the component and details of the in-service environment. It is established that surface scales can lead to damage initiation in some component applications. Thus, when developing laboratory test programs it is important to ensure that the experimental damage mechanisms are relevant to in-service behavior.

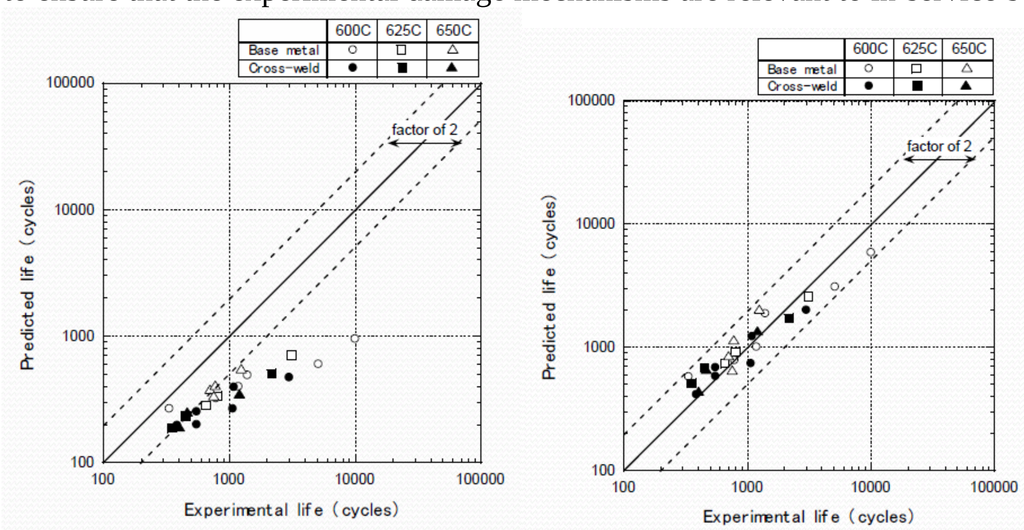


Figure 4. Comparison of Experimental and predicted Creep Fatigue lives for Grade 92 steel tested in the range 600 to 650^{o}C. Analysis was performed using a strain fraction rule in (a) and a more complex Modified Strain Fraction rule in (b). **[7]**

4. On-going Commitment

There are relatively few examples where comprehensive data sets have been established without the need for significant assumptions and/or extrapolations. As an example, challenges with application of the strain fraction/ductility exhaustion methodology often occur because measurements of strain: time behavior are not available. In addition, there are many different suggestions for the appropriate value to use for Strain to Fracture. These variations include:

- Data averaged from available information for the alloy
- Simplified methods for total strain, for example, made using the product of the minimum creep rate and time to failure

- Estimates based on relationships describing creep strain with time for applicable stress/ temperature combinations
- Strain to Failure, Elongation/Reduction of Area, or other measured value for different conditions extrapolated to the conditions of interest

Moreover, although significant information exists for the most widely used boiler and turbine steels; in most cases testing has concentrated on generating parent properties. Thus, less laboratory data exist for weld metals, heat-affected zone (HAZ), or overall weldment performance, even though in many boiler applications, in-service damage in components operating at high temperature frequently occurs associated with welds.

EPRI is working with members of the expert group to establish comprehensive data compilations on the most widely used alloys. It is planned that analysis of the data sets compiled will result in published material data sheets suitable for base line type analysis. Alloys for which Data Compilation Books or ‘Creep-fatigue data sheets’ are planned include:

– Steels used in Boiler Headers and Piping, for example P22, P91 (X10CrMoV9-1), P92, E911,

– Alloys used in turbine rotors and discs (IN718, IN706, X12CrMoWVNbN10-1-1, IN617, etc.

An example of high temperature creep rupture, deformation and ductility data for Grade 91 steel is shown in Fig 5. The output analysis of this type of data would be included in the envisaged Creep-fatigue datasheets. The plan to produce master creep, fatigue, and creep-fatigue equations most relevant to plant operational conditions is critically important as the data input often becomes the most important source of uncertainty in life assessment calculations. Before releasing these summary equations and curves, the Creep-Fatigue datasheets will be provided to the EPRI expert working group for evaluation and approval. Adoption of standardized equations will aid current needs for creep-fatigue assessment as well as future developments in more sophisticated analytical approaches and in new materials.

5. Concluding Remarks

In general, creep-fatigue design considerations are intended to prevent crack initiation, where crack initiation is defined arbitrarily as the presence of cracks that can be detected visually, for example, 1 mm in length. The difference between crack initiation and failure life in a normal laboratory specimen is often a small proportion of the total life, and it can be argued that the failure endurance of a small specimen corresponds to the endurance at crack initiation in a large component. A recent discussion identified the following as primary classification of component types of concern:

- Thick sections, especially welds,
- Changes in section and complex geometries,
- Welds in low ductility (creep brittle) materials,
- Non-stress relieved welds,
- Thin section welds with defects.

The general consensus regarding methods of assessing crack initiation is the following:

- Time-fraction-type stress-based creep damage is insufficient for predicting life reduction due to creep holds. This is especially the case at the small strain ranges of practical interest. This effect cannot be properly described using creep-time fraction on an interaction diagram.

- Calculation of ductility-exhaustion-type strain-based creep damage tends to overestimate the creep fraction used per cycle when all inelastic strain during a hold period is counted. However, use of a modified stress ductility approach or equivalent appeared to provide the best method of assessment.
- As an initial approach to component assessment it seems that application of an easy to use conservative method offers a practical way of undertaking bounding type calculations. Use of these approaches must consider lower bound materials data and simplified stress analysis for both parent and welds.
- For second level assessments there are advantages to use of probabilistic assessment using validated inelastic analysis. Since this approach requires considerable effort on materials relationships and validation of models it will only be used for a very select number of components
- As Power plant operation now involves an increasing range of cyclic operation, issues of creep and cyclic damage increasingly a concern. The following questions summarize topics of focus for EPRI:
  - How to *predict field damage* using available models/ methodologies? Required accuracy? Important attributes?
  - *Monitoring*. Need for instrumentation in performing a component assessment?
  - Availability of relevant materials data to *assessment of an ageing plant (coal or HRSG pressure parts, rotors)*?
  - *Design*. Can we improve on the design for cyclic high temperature service? Should there be design life based on hours, cycles, and oxidation?
  - What is required for practical component assessment?

It is clear the groundwork laid by EPRI on creep-fatigue damage with the collaboration, assistance, and dedication of a large international experts group was a timely activity due to increased cyclic plant operation. While many tasks are now complete, more work is needed. The international group will continue to meet with key activities on completing standardization, developing creep-fatigue datasheets, and focusing on application case studies to improve component assessments.

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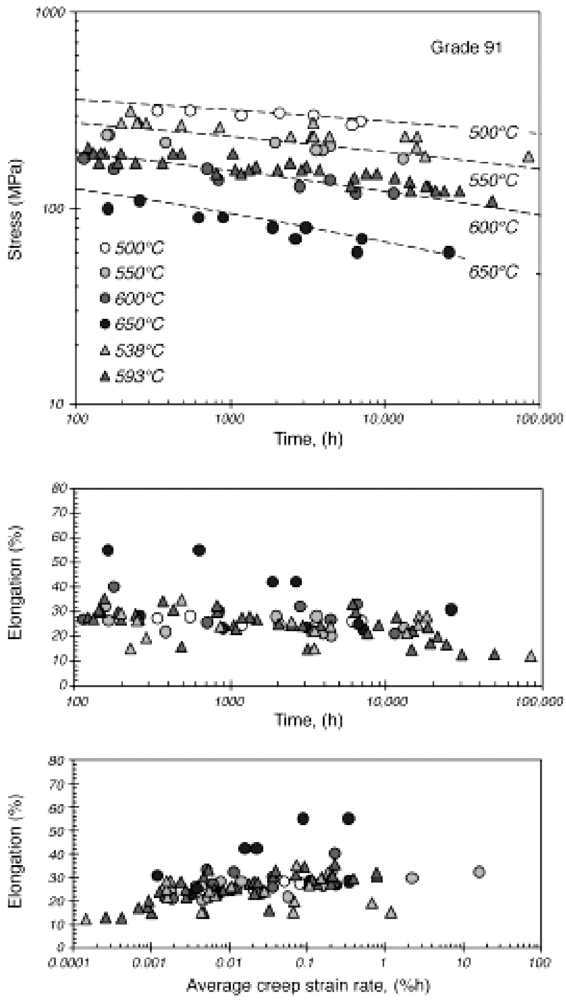

Figure 5. Summary of Properties for Grade 91 steel contained in the data workbook, EPRI report 1019778

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