Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 160 (2016) 292 – 299

Procedia Engineering

www.elsevier.com/locate/procedia

XVIII International Colloquium on Mechanical Fatigue of Metals (ICMFM XVIII)

INCEFA-PLUS programme overview and update

K.J.Mottershead[a], M. Bruchhausen[b], T. Metais[c], S. Cicero[d] *

[a]*Amec Foster Wheeler, Clean Energy, Birchwood, Warrington, UK*
[b]*European Commission, Joint Research Centre (JRC), Institute for Energy and Transport (IET) 1755 LE Petten, The Netherlands*
[c]*EDF, EDF-SEPTEN, Lyon, France*
[d]*University of Cantabria, Santander, Spain*

Abstract

INCEFA-PLUS is a five year project supported by the European Commission HORIZON2020 programme which commenced in mid 2015. 16 organisations from across Europe have combined forces to deliver new experimental data and a fatigue assessment procedure which will support the development of improved guidelines for assessment of environmental fatigue damage to ensure safe operation of nuclear power plants.
Prior to the start of INCEFA-PLUS, an in-kind study was undertaken by several European organisations with the aim of developing the current state of the art for this technical area. This study identified three experimental variables which required further study in order to support improved assessment methodology for environmental fatigue, namely the effects of mean stress/strain, hold time and surface finish. Within INCEFA-PLUS, the effects of these three variables, plus strain amplitude, on fatigue endurance of austenitic stainless steels in light water reactor environments are therefore being studied experimentally. The data obtained will be collected and standardised in an online environmental fatigue database. In order to facilitate the exchange of fatigue data a standardized data format will be developed in the framework of a CEN workshop, to which international participants are welcome to participate. The outcome of the workshop will be a pre-normative document, a CEN Workshop Agreement (CWA) which will set a standard for enabling the exchange of fatigue data not only within the project but within the fatigue community. Based on the data generated and the resulting improvement in understanding, it is planned that INCEFA-PLUS will develop and disseminate methods for including the new insights into assessment procedures for environmental fatigue degradation. This will take better account of the effects of mean strain, hold time and surface finish.
This paper will provide more details on the background to this project and the way the project is organized to meet its objectives. Details will be provided as to how uncertainties due to variations in testing practice and specimen preparation have been minimized. Additionally, the choices associated with testing for the effects of surface finish, hold time and mean stress will be described along with the status of decisions so far within the project. The paper will also report current status of the project and when findings are likely to be disseminated.

* Corresponding author. Tel.: +44-1925-462680.
E-mail address: kevin.mottershead@amecfw.com

Peer-review under responsibility of the University of Oviedo
doi:10.1016/j.proeng.2017.04.001

Peer-review under responsibility of the University of Oviedo

Keywords: Environmentally Assisted Fatigue (EAF); Nuclear, Horizon2020; stainless steel

1. Introduction

The global objective of the INCEFA-PLUS project is to develop new guidelines for the assessment of environmental fatigue damage susceptibility for NPP components. The project is divided in three main parts. The first is focused on the characterization and testing of a limited selection of typical stainless steel alloys employed in NPPs (mainly low carbon austenitic but also including Ti and Ni stabilized stainless steels). The second part of this project involves the development of a modified procedure for estimating the fatigue degradation of the materials. The final part is concerned with dissemination.

This brief paper will introduce the project, how it is organized, and the expectations for it. The status of the project as of May 2016 will also be presented, along with short term expectations for the following 12 months.

Nomenclature

AMEC	Amec Foster Wheeler
ANL	Argonne National Laboratory
CEA	Commissariat à l'Energie Atomique et aux Energies Alternatives
CEN	European Committee for Standardization
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
DOI	Digital Object Identifier
EAF	Environmentally Assisted Fatigue
EC	European Commission
EDF	Electricité de France
EKK	E.ON Kern Kraft
EPRI	Electric Power Research Institute
HCF	High Cycle Fatigue
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
JRC	European Commission, Joint Research Centre
LCF	Low Cycle Fatigue
LEI	Lithuanian Energy Institute
LWR	Light Water Reactor
NPP	Nuclear Power Plant
NUGENIA	NUclear GENeration II and III Association
PSI	Paul Scherrer Institute
UC	University of Cantabria
USNRC	US Nuclear Regulatory Commission
VTT	Teknologian tutkimuskeskus VTT
WP	Work Package
XML	Extensible Markup Language (computer readable document encoding rules)

2. Project Background

There has been significant research effort in recent years addressing the influence of high temperature LWR coolant environments on fatigue of pressure vessel and circuit materials. The USNRC Regulatory Guide 1.207 addresses the influence of light water reactor environments on fatigue life of reactor materials [[1]], together with a supporting ANL report, NUREG/CR-6909 [[2]][†] in which formulae are presented for the prediction of fatigue endurance of ferritic and austenitic steels, as well as nickel-based alloys, in air and in high temperature water. It is clear that the effect of light water reactor coolant environments can be to significantly reduce fatigue endurance life compared to what would be expected based on data obtained in air. It is also clear that the adoption of the formulae presented in NUREG/CR-6909 requires a significant change in approach for plant safety assessments, especially with regard to taking into account the strain rates of plant transients. Application of the revised procedures can result in predictions of very high cumulative fatigue usage factors for some plant components and transients which appear inconsistent with the relatively good performance of stainless steel components in operating reactors over several decades. However, despite the extensive nature of the data that have been used to derive the relationships provided in the NUREG/CR-6909 document, there are a significant number of knowledge gaps. These gaps have been reviewed in a recent study that was sponsored by EPRI [[3]]. This review was updated within a European context during 2013 through a NUGENIA endorsed in-kind project called INCEFA (Increasing safety in NPPs by Covering gaps in Environmental Fatigue Assessment). The contributors to this project were:

Amec Foster Wheeler (UK)
AREVA (France and Germany)
CEA (France)
CIEMAT (Spain)
EDF (France)
EKK (Germany)
INESCO (Spain)
JRC (The Netherlands)
PSI (Switzerland)
SCK-CEN (Belgium)
UJV-Rez (Czech Republic)
UC (Spain)
VTT (Finland)

The result of this collaborative project was a European view on the state of the art for EAF assessment capability covering three broad areas [[4]]:

1. International variations in EAF assessment procedures and goals.
2. Current understanding of knowledge gaps affecting assessment capability.
3. Ideas for improving understanding to the benefit of assessment capability.

This review [[4]] discussed the current state of understanding on a significant number of issues affecting accuracy of fatigue life prediction, and was able to identify areas where additional work was considered desirable. In addition to stress/strain amplitude, three of these potential future research areas were of common interest to all parties:

- Effects of surface condition
- Effects of hold time

† *A significant March 2014 update to NUREG/CR-6909 [Rev. 1] is available now in draft form.*

- Effects of mean stress/strain

Based on these conclusions, the consortium bid successfully for EC support, under the Horizon2020 framework program, for a 5 year program. The aim of this program is to further the understanding of these three sensitivities, and recommend modifications to current assessment procedures so as to better account for these effects. The resulting project was named INCEFA-PLUS and is participated in by the original INCEFA consortium plus:

LEI (Lithuania)
IRSN (France)
Rolls-Royce (UK)

The program is approximately 33% EC funded (~€2.5M), with the balance of funding coming from national research programs.

3. INCEFA-PLUS Project Organisation

The project comprises four Work Packages as illustrated in Figure 1.

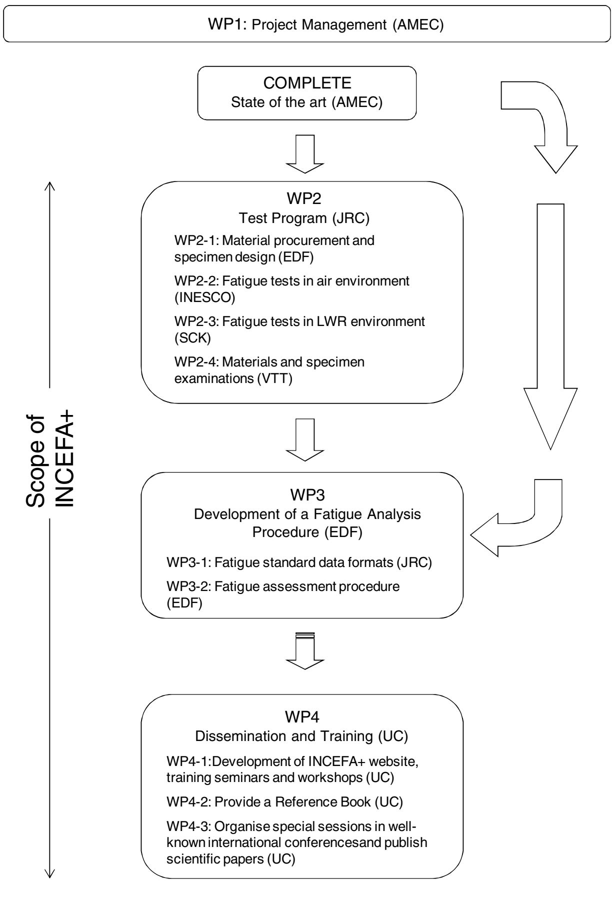

Figure 1: **INCEFA-PLUS organizational flow chart**

To summarize, this project can be divided in three parts:

1) A first part focusing on the testing and experimental campaign;
2) In a second part a data standard for fatigue data will be developed which will simplify analyzing the experimental results generated in WP2 as well as using other existing methodologies to build a new fatigue methodology (including fatigue curves and a method to account for EAF);
3) A third part concerned with the dissemination of the lessons learned through the project.

Key program information includes:

- 5 years total duration starting July 2015.
- Approximately 3 year test programme commencing mid 2016.
- Total of 13 participating laboratories with 11 committed to testing in air and/or water.
- In addition to participants' own 300 series stainless steels, 12 of the 13 laboratories will also include tests on a common plant-relevant 304L stainless steel sourced by EDF. This allows variation between laboratories to be quantified and allowed for.
- All participating laboratories are committed to testing all three highlighted sensitivities.
- All participating laboratories are committed, so far as practicable, to using common test conditions.
- All partners are committed to supplying data in a common agreed format. The project supports a CEN workshop [[5]] aimed at developing a digital model to implement numerically the contents of the ISO norm on fatigue (ISO 12106). International participants are welcome to join this workshop any time before its termination in September 2017.
- Whilst most testing will be on standard solid test specimens, some laboratories will also test hollow specimens, and one will test bi-directionally loaded cruciform specimens.
- Development of test matrices is being tackled using the Design of Experiment methodology. This approach ensures that the program tackles interdependencies between sensitivities, whereby fatigue endurance sensitivity to one parameter can be affected by variation in another [6].
- All partners are committed to material characterization for non-common materials, consistent with the data being created for the common material.
- A specimen characterization program is included with the objectives of a) understanding the surface finishes obtained, and b) understanding of possible reasons for outlier results.

Key deliverables the project is committed to include:

- An agreed protocol for Environmentally Assisted Fatigue testing that the consortium will abide by, and which could form the basis of a future ISO standard.
- The CEN Workshop Agreement on standardized fatigue data formats and development of an XML data interface.
- Publicly citable test data, individually identified by Digital Object Identifiers (DOIs).
- Fully characterized test materials, supplemented with additional material characterization aimed at understanding data outliers.
- New fatigue curves.
- New or modified fatigue analysis procedures.
- Two open access training seminars.
- A reference book, suitable for possible future conversion to an assessment standard.
- Dissemination of project findings through project participation in international conferences.

4. Current project status and short term expectations

As of May 2016 the project has been running for approximately 10 months. Key achievements so far have been:

- Agreement of the majority of test conditions for the first 1 year phase of testing:
    - Temperature: In air some tests may be at room temperature to check against the standard curve. However, most air and water tests will be performed at 300°C. (The temperature range may be extended to capture transients.)
    - Surface finish: This will differ for solid and hollow specimens. For solid specimens two finishes will be used, a "polished laboratory finish" (R_a = 0.2 µm; R_t = 3 µm) and a "worst case typical plant finish" (R_a = 7 µm; R_t = 50 µm). Hollow specimen bores will be machined to a common procedure with likely surface finish being between the values selected for solid specimens.
    - Strain amplitude: Two values will be used, 0.3% and 0.6%.
    - Strain rate: Initially only a single strain rate is foreseen, 0.01%/s.
    - Specification of conditions was particularly demanding for hold time and mean stress/strain; these challenges and their current statuses are described later in this paper.
- Development of the testing protocol.
- Development of specimen machining specifications.
- Agreement of common material characterisation requirements.
    - All partners are committed to supporting destructive characterization of one example of every specimen to be tested, much of which will be done at VTT.
- Preparation of new testing capabilities to complement existing ones.

5. Hold Time Considerations

As already noted, the choice of test conditions for hold time has been challenging, due to both conflicting data in open literature and the need to consider plant relevant holds within manageable test durations. As of May 2016 many of the uncertainties are now addressed, guided by the experience of EKK and Rolls-Royce. Just a few uncertainties remain to be finalized before testing begins in summer 2016. The currently agreed specification for hold time tests, including remaining uncertainties still to be addressed is:

- Cycling at 300°C
- Strain-control
- Air and water environments
    - Whilst testing will be initially in both air and water, it is acknowledged that the limited available data for these environments suggests there may be no discernible effect of PWR water environment on hold time sensitivity. If, after initial testing, this is confirmed, the project may modify test plans to make more efficient use of test resources, this may involve concentrating resources on the simpler testing in air.
- Strain amplitude = 0.3% and 0.6%, but with the bulk of tests at 0.3%
    - Hold time effects are expected to be greatest at low strain amplitude. 0.3% is considered the highest strain amplitude for which a significant effect of hold time can be expected. This is in effect a compromise between extended test durations at lower strain amplitudes and data requirements to support subsequent modelling activities.
- Strain rate = 0.01%/s (air and water)
- Hold temperature = 300°C; also some at 400°C (air)
- Hold time
    - Long holds (for increased plant relevance)
    - 16 hours (a maximum practical time, to be confirmed through dialogue with plant operators)

  - Possibly include different hold times to assess the importance of strain hardening
- Hold frequency
  - Holds will be imposed after 'packages' of cycles. The number of cycles per 'package' will be different for the two strain amplitudes of 0.3% and 0.6% (proposed to be greater number of cycles at 0.3% than at 0.6%).
  - To be confirmed through dialogue with operators
- Waveform = sawtooth (faster load drop to aid test efficiency)
- Hold strain = zero (low strain holds are most plant relevant)
- Hold position = after positive strain rate

6. Mean stress/Strain Considerations

For mean stress/strain the issues affecting choice of testing parameters are particularly complex and significant effort has been expended by the project to create a test programme that is a) practical, and b) likely to deliver information useful for plant assessments. The choices of test conditions and their relative merits are:

- Mean stress combined with strain control.
  - This is agreed to be the most plant-relevant type of test for components (e.g. pipework) subject to both thermal transient loading and static loading due to pressure.
  - It is also a complex test to implement. There is some experience of this type of test (EDF and CEA) upon which a campaign could be based. However, the investment in test capability would likely be significant.
- Mean stress combined with stress control.
  - Practical test to perform.
  - Mean stress is plant-relevant, e.g. to components such as pipework subject to pressure loading.
  - Experience to date from PSI suggests high cycle fatigue is required before significant mean stress effects are apparent.
- Mean strain with strain control.
  - Practical test to perform.
  - Strain control is more relevant to the LCF regime (which is the main focus of INCEFA-PLUS).
  - Strain controlled test results are directly comparable with data already available.

Another consideration is the strain or stress level to which the mean strain or mean stress should be applied. Based on the inputs from the in-kind contributions from the INCEFA project, it was concluded that the testing would be carried out at low strain/stress amplitudes, i.e. in the high-cycle fatigue domain. It is noted that the effect of mean strain/stress is very limited in the LCF domain as a mean strain/stress contribution tends to redistribute through the component thickness.

Based on these considerations, a practical, and useful, program has been developed as follows:

- Phase 1 of the program will involve a limited number of mean stress with stress control tests but focus on mean strain with strain control tests.
  - These tests can be performed by all partners without the need to develop test techniques.
  - Testing will be in both air and water environments.
  - The tests will enable available limited data for these conditions to be challenged and confirmed or refined.
  - For the strain controlled tests, 0.5% mean strain combined with 0.3% strain amplitude has been chosen. The strain amplitude provides for comparison with other data being obtained by the project, whilst the mean strain is approximately equivalent to a plant-relevant mean stress.

  - Test parameters for the stress control tests will be determined by PSI as these tests form part of the Swiss National program being contributed to the project.
- Phase 2 of the project is expected to begin in 2017 and comprise exploratory testing using mean stress with strain control.
  - It is planned to develop the scope for this program during 2016.
  - Given likely test control complexities, testing will commence first in air.
  - The scope and direction for the program will depend firstly on sensitivities to mean strain revealed by the exploratory tests, and secondly test constraints because of practicality.

7. Summary

This paper introduces the INCEFA-PLUS project to the ICMFM community. It presents the objectives and organization of the project. It also summarizes the current status of the project, including current challenges. It is anticipated that this paper will be updated throughout the course of the project for continued dissemination to the wider community as opportunity arises.

Acknowledgments

This project has received funding from the Euratom research and training program 2014-2018 under grant agreement No 662320. The significant contributions of all partners in the INCEFA-PLUS project are also acknowledged.

References

[1] US-NRC Regulatory Guide 1.207, "Guidelines for Evaluating Fatigue Analyses Incorporating the Life Reduction of Metal Components due to the Effects of the Light-Water Reactor Environment for New Reactors", March 2007.

[2] O.K. Chopra and W.J Shack, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials": U.S. Nuclear Regulatory Commission. NUREG/CR-6909 and ANL-06/08, February 2007

[3] D. R. Tice, D. Green and A. Toft, "Environmentally Assisted Fatigue Gap Analysis and Roadmap for Future Research – Gap Analysis Report", EPRI 1023012, December 2011

[4] Environmentally-Assisted Fatigue Assessment – The European view of the State of the Art for stainless steels in LWR environments. NUGENIA position paper available at www.nugenia.org.

[5] CEN Workshop on Standards Compliant Formats for fatigue Test Data – FATEDA. Information available at www.cen.eu/Pages/resultsearch.aspx?k=FATEDA.

[6] M. Bruchhausen , K. Mottershead , C. Hurley , T. Métais , R. Cicero , M. Vankeerberghen and J.-C. Le Roux, "Establishing a multi-laboratory test plan for environmentally assisted fatigue", Symposium on Fatigue and Fracture Test Planning, Test Data Acquisition and Analysis, May 04 2016 - May 05 2016, San Antonio, TX, USA