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Monitoring radiation embrittlement during life extension periods

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HIGHLIGHTS

- Techniques and methods for monitoring radiation embrittlement are described.
- The life extension of the standard surveillance programmes is discussed.
- Guidance is given for the design of new surveillance capsules.
- Recommendations for Integrated and Coordinated Surveillance Programmes are given.

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ABSTRACT

This paper presents guidelines to monitor the radiation embrittlement of reactor pressure vessels (RPV) during life extension periods (to 60 or 80 years) or for the long term operation of nuclear power plants (NPPs). The guidelines were developed in 2012–2013 by a Task Group of the international project LONGLIFE. The work performed responds to the need for guidance to treat long term irradiation effects within the ageing management of NPPs, since the standard RPV surveillance programmes were designed only to cover a time period of 40 years. The guidelines are intended to support specialists in the field and managers in the plant to choose among the most adequate techniques and methods available today to extend the use of their current RPV surveillance programme beyond design life, or implement a new programme when needed. The study performed identifies weaknesses in the ability of the standard surveillance programmes to provide data needed for long term operation, and proposes solutions and tools to solve and/or mitigate the lack or scarcity of surveillance material for their use in life extension. Guidance is also given on methods and strategies to generate reliable surveillance data in the high fluence range.

1. Introduction

Neutron irradiation degrades the mechanical properties of reactor pressure vessel (RPV) steels. The extent of the degradation is governed by a number of factors such as neutron fluence, neutron energy, irradiation temperature, neutron flux and the concentration of deleterious elements in the steel. A RPV operational life of 60 years is being considered frequently by many utilities in their plant life management (PLIM) programmes, and even 80 years is mentioned often in the life extension plans of USA reactors. Guidelines are needed to treat long term irradiation effects within the ageing management plans of nuclear power plants (NPP), in particular for monitoring radiation embrittlement during life extension periods since the standard RPV surveillance programmes were designed only to cover a time period of 40 years. These guidelines should help specialists in the field and managers in plant to choose among the most adequate techniques and methods available today to extend their current RPV surveillance programme, or implement a new

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programme when needed, facing long term operation (LTO) of the plant.

This paper summarizes the guidelines for monitoring radiation embrittlement during life extension periods which were developed in 2012–2013 by a Task Group of the international project LONGLIFE. The LONGLIFE project (Project No. 249360 of the Euratom 7th Framework Programme of the European Commission) was designed to enhance knowledge of long term operation phenomena relevant to European Light Water Reactors (LWRs), to assess prediction tools, codes and standards including proposals for improvements, and to elaborate best practice guidelines for RPV irradiation surveillance. The following topics are covered in the guidelines:

- Tools and techniques for surveillance of RPV LTO.
- Extension of the standard surveillance programmes.
- Availability of surveillance material.
- Design of new surveillance capsules.
- Surveillance capsule location.
- Withdrawal schedule of surveillance capsules.
- Thermal ageing.
- Neutron dosimetry and Irradiation temperature monitoring.
- Use of reference materials.
- Use of surveillance data for embrittlement trend curves.
- Use of data from accelerated irradiations.
- Integrated and Coordinated Surveillance Programmes.
- Microstructural analysis techniques.
- Non-destructive techniques.

The guidelines for non-destructive techniques are not discussed in this paper in order to limit the length of this publication.

2. Tools and techniques for surveillance of RPV LTO

This section briefly describes several promising tools and techniques that can be used for embrittlement monitoring during life extension periods. Namely:

- reconstitution of broken specimens;
- use of miniature specimens;
- advanced fracture toughness approaches; and
- enhanced surveillance strategy.

2.1. Reconstitution of broken specimens

When plant life extension (PLEX) is required, additional surveillance data are also required, to improve the definition of the embrittlement trend curve (ETC) at the higher neutron fluence levels anticipated. Frequently, however, there is insufficient unirradiated material available to machine additional surveillance specimens for exposure to irradiation for monitoring material degradation during life extension. In addition, conventional (currently-running) surveillance schemes mostly do not include fracture toughness test specimens, even though the determination of a material's fracture toughness is necessary for a structural integrity assessment. Both of these problems may be addressed by the testing of reconstituted broken specimens in suitable specimen configurations. ASTM E1253-07 (2007), Bourdiliaua et al. (2011), Van Walle et al. (2001), and Planman et al. (2012) are important references than can guide in the selection of the most suitable method for specimen reconstitution.

In order to avoid the high costs and burden of long-term storage of irradiated materials, some plants may wish to discard broken Charpy specimens and other surveillance materials remaining from surveillance test programmes conducted years ago. However, broken Charpy specimens, particularly those from reactor vessels having radiation sensitive materials, may provide useful information (such as specific material embrittlement data), and should be stored in appropriate ways and places to avoid oxidation and permit easy retrieval for life extension studies.

2.2. Miniature specimens

Miniature specimen test techniques (Kumar et al, 2006) can significantly enhance the database for assessment of reactor pressure vessel integrity. They provide a means of obtaining material property information for situations in which extraction of samples from vessels (or other structural components) is not desirable or possible, or when the amount of available material is too limited to utilize conventional, standardized techniques. The ASTM books STP-1204 (Corwin et al., 1993), STP-1329 (Corwin et al., 1998) and STP-1502 (Sokolov, 2009) contain an extensive collection of papers on small specimen test techniques applied to nuclear reactor vessel embrittlement, thermal annealing and plant life extension.

Taking into account that the screening limits in the regulations are related to surveillance data from standard sized specimens, it is important to establish correlations between miniature and standard specimen testing results. ASTM E2248 (2009) presents the requirements for performing impact tests on miniaturized Charpy V-notch (MCVN) specimens fabricated from metallic materials. Nevertheless this standard considers that the comparison of the MCVN data with conventional Charpy V-Notch data or application of the MCVN data, or both, to the evaluation of ferritic material behaviour is the responsibility of the user of the test method and is not explicitly covered by ASTM E2248 (2009).

Perosanz (2002) includes an extensive overview of different types of mini-tensile and mini-Charpy specimens used in RPV material testing. Mini-Charpy specimens are grouped in three categories:

- Geometry 1/3: in which the specimen cross section is 3.33 mm × 3.33 mm.
- Geometry 2: in which the specimen cross section is 5 mm × 5 mm.
- Geometry DIN: where the specimen cross section is 3 mm × 4 mm.

Perosanz (2002) and Klausnitzer (1991) reviewed the different methodologies and correlations available to extrapolate results from miniature to standard sized specimens. The correlations should be taken with care since they might depend on the material and the irradiation conditions.

2.3. Advanced fracture toughness approaches

RPV integrity assessment can be performed using the Master Curve approach (IAEA-TEC-DOC-1631, 2009). In such a case, allowable stress intensity factor values are determined with the use of a reference temperature T_0 (based on static fracture toughness testing of surveillance specimens and/or specimens from template cut from RPV wall) instead of the critical brittle fracture temperature T_k, or adjusted reference temperature ART, derived from T_{41J} (based on Charpy V-notch impact testing). The transition temperature T_0 for the analyzed state of the RPV is determined using a single- or multiple-temperature method in accordance with the ASTM Standard E 1921.

The Master Curve approach is included in different design codes (ASME, KTA) and in the VERLIFE procedure, through the use of a new reference temperature RT_{T0}. ASME Code Case N-631 (Section 3) defines RT_{T0} for unirradiated reactor vessel material, while ASME