## AMP 112 THERMAL AGEING EMBRITTLEMENT OF CAST AUSTENITIC STAINLESS STEEL (VERSION 2020)

**Programme Description**

Thermal ageing embrittlement decreases the fracture toughness of cast austenitic stainless steel (CASS) reactor coolant pressure boundary components that are exposed to temperatures above 250 °C. However, not all CASS material has the same susceptibility to experiencing a “significant” loss of fracture toughness due to thermal ageing embrittlement. A significant loss of fracture toughness is a decrease that could potentially challenge the structural integrity of a component or exceeds a generic bounding value established by requirements or guidance documents for the plant. A CASS component that retains adequate fracture toughness to ensure its intended function(s) will be performed, after experiencing thermal ageing embrittlement, can be screened out as not susceptible to a “significant” loss of fracture toughness. If it is determined that a CASS component is not susceptible to a significant loss of fracture toughness, then the additional inspection or evaluations contained in this AMP are not needed (i.e., screened out).

This ageing management programme (AMP) provides guidance on (a) a process to screen out components that are not susceptible to significant loss of fracture toughness and (b) inspections and flaw tolerance evaluations for components that are susceptible to significant loss of fracture toughness. A screening method is used to determine the susceptibility of CASS piping, piping components, pump casing, and valve bodies to experiencing a significant loss of fracture toughness due to thermal ageing embrittlement. The screening criteria used to determine if the CASS material is susceptible to a significant loss of fracture toughness due to thermal ageing embrittlement is based on the casting method, molybdenum (Mo) content, chromium equivalent value (Creq), and percent ferrite [1, 2]. CASS components determined to be susceptible to a significant loss of fracture toughness are subjected to additional ageing management actives, as described in this AMP.

The reactor coolant system components are inspected in accordance with the pertinent governing requirements or guidance documents for the plant (e.g. [2, 3]). Because the effects of loss of fracture toughness due to thermal ageing embrittlement of CASS piping components can decrease the critical flaw size in susceptible components, augmented inspection maybe necessary to confirm the absence of flaws which could approach the critical flaw size. For components determined to be susceptible to a significant loss of fracture toughness, ageing management is accomplished through either: (a) qualified visual inspections, such as enhanced visual examination (EVT-1); (b) a qualified ultrasonic testing (UT) methodology; or (c) a component-specific flaw tolerance evaluation in accordance with the pertinent governing requirements or guidance documents for the plant. Additional inspection or evaluations to demonstrate that the material has adequate fracture toughness are not required for components that are not susceptible to a significant loss of fracture toughness due to thermal ageing embrittlement.

Based on the results of the assessment documented in [1], screening for a significant loss of fracture toughness due to thermal ageing embrittlement is not required for valve bodies in the United States. The existing ASME Code, Section XI inspection requirements are adequate for valve bodies [3]. Ageing management of CASS reactor internal components of PWRs are discussed in AMP 113 and BWRs in AMP 109.

### Evaluation and Technical Basis

1. ***Scope of the ageing management programme:***

This programme manages loss of fracture toughness in Class 1 piping and piping components made from CASS. The programme includes screening criteria to determine which CASS components are susceptible to experiencing a significant loss of fracture toughness due to thermal ageing embrittlement and require augmented inspection. The screening criteria are applicable to all primary pressure boundary components constructed from CASS with service conditions above 250 °C.

The potential to experience a significant loss of fracture toughness due to thermal ageing embrittlement of CASS materials is determined in a manner consistent with the pertinent governing requirements or guidance documents for the plant.

In the United States, the potential significance of thermal ageing embrittlement of CASS materials is determined using criteria based on the casting method, Mo content, and ferrite content. The screening criteria are set forth in the May 19, 2000, NRC letter [1]. For low-molybdenum content steels (SA-351 Grades CF3, CF3A, CF8, CF8A or other steels with less than or equal to 0.5 weight percent [wt.%] Mo), only static-cast steels with greater than 20 % ferrite are susceptible to a significant loss of fracture toughness due to thermal embrittlement. Static-cast low-molybdenum steels with less than or equal to 20 % ferrite and all centrifugal-cast low-molybdenum steels are not susceptible to a significant loss of fracture toughness (i.e., screens out). For high-molybdenum content steels (SA-351 Grades CF3M, CF3MA, and CF8M or other steels with 2.0 to 3.0 wt.% Mo), static-cast steels with greater than 14 % ferrite and centrifugal-cast steels with greater than 20 % ferrite are susceptible to a significant loss of fracture toughness. Static-cast high-molybdenum steels with less than or equal to 14 % ferrite and centrifugal-cast high-molybdenum steels with less than or equal to 20 % ferrite are not expected to experience a significant loss of fracture toughness (i.e., screens out). The screening criteria are summarized in Table 1 below. This screening criteria is not applicable to niobium-containing steels; such steels require evaluation on a case-by-case basis.

In the United States, the ferrite content is calculated by using the Hull’s equivalent factors (as described in NUREG/CR-4513, Revision 1 [4]) or a staff-approved method for calculating delta ferrite in CASS materials. An ambient temperature fracture toughness value of 255 kilojoules per square meter (kJ/m2) (1,450 inch-pounds per square inch) at a crack extension of 2.5 millimeters (0.1 inch) is used to differentiate between CASS materials that may potentially experience a significant loss of fracture toughness and those that are not susceptible to a significant loss of fracture toughness due to thermal embrittlement. Extensive research data indicate that the saturated lower-bound fracture toughness is greater than 255 kJ/m2 for CASS materials not susceptible to a significant loss of fracture toughness due to thermal ageing embrittlement [5].

Screening for susceptibility to a significant loss of fracture toughness is not needed for valve bodies, in the United States. For valve bodies greater than 100 millimeters (4 inches) nominal pipe size (NPS), the existing inspection requirements from the pertinent governing requirements or guidance documents for the plant are adequate. If the pertinent governing requirements or guidance documents require only surface examinations for valve bodies less than 100 millimeters (4 inches) NPS, the adequacy of inservice inspection (ISI) according to these requirements or guidance has been demonstrated by a bounding integrity analysis [1].

Table 1. Screening criteria used to determine whether CASS is susceptible to a significant loss of fracture toughness due to thermal ageing embrittlement.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Molybdenum (Mo) Content | Casting Method | Ferrite Content (wt.%) | Loss of Fracture Toughness | |
| Potentially Significant | Not Significant (Screens Out) |
| Low or ≤ 0.5 wt.% | Static | > 20 | X | -- |
| ≤ 20 | -- | X |
| Centrifugal | Any | -- | X |
| High or 2.0-3.0 wt.% | Static | > 14 | X | -- |
| ≤ 14 | -- | X |
| Centrifugal | > 20 | X | -- |
| ≤ 20 | -- | X |

1. ***Preventive actions to minimize and control ageing degradation:***

This programme is a condition monitoring programme and contains no preventive actions.

1. ***Detection of ageing effects:***

The programme monitors the effects of loss of fracture toughness on the intended function of the Class 1 CASS components by (a) identifying the CASS materials that are susceptible to a significant loss of fracture toughness due to thermal ageing embrittlement and (b) performing inspections or a flaw tolerance evaluation.

The programme does not directly monitor for the loss of fracture toughness that is induced by thermal ageing; instead, the impact of loss of fracture toughness on component integrity is indirectly managed by using visual or volumetric examination techniques to monitor for cracking in the components. For components that have been determined not to be susceptible to a significant loss of fracture toughness and have screened out, no additional inspection or evaluations are needed to assess the impact of thermal ageing embrittlement, beyond those implemented consistent with the pertinent governing requirements or guidance documents for the plant.

In France, the development of formulas for toughness, as described in attribute 8, can estimate the loss of fracture toughness induced by thermal ageing.

For piping components that may potentially experience a significant loss of fracture toughness, the AMP provides for inspections of the base metal, such as EVT-1, qualified UT, RT and PT techniques, with the scope of the inspection covering the portions determined to be limiting from the standpoint of applied stress, operating time, and environmental considerations. Examination methods meet the criteria of the pertinent governing requirements or guidance documents for the plant. Alternatively, a plant-specific or component-specific flaw tolerance evaluation, using specific geometry, stress information, material properties, and provisions of the pertinent governing requirements or guidance documents for the plant, is used to demonstrate that the thermally-embrittled material has adequate toughness. For CASS piping, UT may be performed in accordance with a qualified methodology that meets the criteria of the pertinent governing requirements, such as the methodology of Code Case N-824 [6], as conditioned by 10 CFR 50.55a in the United States. A description of EVT-1 is found in Boiling Water Reactor Vessel and Internals Project (BWRVIP)-03 and Materials Reliability Program (MRP)-228 for PWRs [5, 7].

1. ***Monitoring and trending of ageing effects:***

Timely and reliable detection of cracks is provided by implementation of inspection schedules in accordance with the pertinent governing requirements or guidance documents for the plant, reliable examination methods, and qualified inspection personnel. If flaws are detected, the period of acceptability is determined from analysis of the flaw, depending on the crack growth rate and mechanism.

In France, a large testing programme is still performed on material samples from components in operation, from replaced components and on representative cast ingots (see attribute 8). All those materials can be thermally aged in laboratory furnaces at 300 °C, 325 °C, and 350 °C for holding time of up to 200,000 hours. These results provide information uses in the development of the estimation formulas discussed in paragraph 8. Monitoring techniques, such as Thermo electric Power (TEP) or Small Angle Neutron Scattering (SANS) [8-10] measurements, have been developed and applied to susceptible components. Additionally, direct toughness measurements have been made on specimen removed from leading components [11, 12]. Microhardness testing has also been used to assess the effects of thermal ageing embrittlement.

1. ***Mitigating ageing effects:***

This programme is a condition monitoring programme and does not mitigate thermal ageing embrittlement.

1. ***Acceptance criteria:***

Flaws detected in CASS components are evaluated in accordance with the applicable procedures of the pertinent governing requirements or guidance documents for the plant (e.g., [3, 13]). Flaw tolerance evaluation for CASS piping or components with ferrite levels exceeding those addressed in the pertinent governing requirements or guidance documents is performed on a case-by-case basis using the plant specific fracture toughness data. Methods for predicting the fracture toughness of thermally aged CASS materials with delta ferrite content up to 25 % are provided in NUREG/CR–4513, Revision 1 [4].

1. ***Corrective actions:***

Repair and replacement are performed in accordance with the pertinent governing requirements or guidance documents for the plant. Repair of defects that are deeply embedded in the metal is considered very difficult, so they are unlikely to be carried out. Components which are projected to be unacceptably degraded due to thermal ageing embrittlement may be replaced in a proactive manner (for instance susceptible primary elbows may be replaced at the same time as steam generators).

1. ***Operating experience feedback and feedback of research and development results:***

This AMP addresses the industry-wide generic experience. Relevant plant-specific operating experience is considered in the development of the plant AMP to ensure the AMP is adequate for the plant. The plant implements a feedback process to periodically evaluate plant and industry-wide operating experience and research and development (R&D) results, and, as necessary, either modifies the plant AMP or takes additional actions (e.g. develop a new plant-specific AMP) to ensure the continued effectiveness of the ageing management.

There is currently no operating experience associated with cracking in PWR and BWR CASS components.

In France, formulas were developed to predict the loss of fracture toughness due to the thermal ageing of all CASS components [11, 12]. This development was made possible due to the large experimental database built at EDF/R&D since the 1980’s. This database covers a large set of representative materials and various aging conditions up to 200,000 hours, between 285 °C and 350 °C. The prediction scheme relies on three steps [11]:

* Estimation of the Charpy impact test values at 20 °C and 320 °C using the chemical composition of the steel (Cr%, Mo%, Si%, C%, N%, Ni%), the ferrite content, the unaged Charpy impact test values and the aging conditions (temperature and duration);
* Estimation of the J-R curve at 20 °C and 320 °C – defined by a power law J = C.Δan – based on correlations between n and C and the Charpy impact test values;
* Estimation of the J-R curve at any temperature between 20 °C and 320 °C using interpolation formulas.

To validate these formulas, elbows were removed in the same time than the replacement of steam generators. These aged components were studied in hot cells [8-9] and their actual properties were compared to predictions.

EDF has developed an in-situ device to evaluate in a non-destructive way the ageing of components. This new portable device was developed in order to perform thermoelectrical power measurements in industrial conditions on large components (e.g. pipes and elbows). The principle of measurements is based on a thermal gradient generated in the material by two test prods of a reference metal, set at different temperatures, applied on the surface of the component to inspect. The differences of potential and temperature between the two prods are measured and the TEP of the heated area of the material is calculated.

To complement, laboratory studies have established a linear relationship (abacus) between the TEP of cast duplex stainless steels, the ferrite content, the mechanical properties and an Arrhenius-type aging parameter depending on aging time and temperature [14-16].

1. ***Quality management:***

Site quality assurance procedures, review and approval processes, and administrative controls are implemented (e.g. 10 CFR Part 50, Appendix B [17]).

### References

[1] UNITED STATES NUCLEAR REGULATORY COMMISSION, Letter from Christopher I. Grimes, USNRC License Renewal and Standardization Branch, to Douglas J. Walters, Nuclear Energy Institute, License Renewal Issue No. 98-0030, Thermal Ageing Embrittlement of Cast Stainless Steel Components, May 19, 2000, (ADAMS Accession No. ML003717179), USNRC

[2] JAPAN NUCLEAR ENERGY SAFETY ORGANIZATION, Review Manual for Aging-Related Technical Evaluation Thermal Aging of two phase stainless steel, JNES-SS-0812-01, JNES

[3] AMERICAN SOCIETY OF MECHANICAL ENGINEERS, Rules for Inservice Inspection of Nuclear Power Plant Components, The ASME Boiler and Pressure Vessel Code, ASME Section XI, as approved in 10 CFR 50.55a, ASME, New York, NY

[4] UNITED STATES NUCLEAR REGULATORY COMMISSION, NUREG/CR-4513, Rev. 1, Estimation of Fracture Toughness of Cast Stainless Steels during Thermal Aging in LWR Systems, USNRC, August 1994

[5] ELECTRIC POWER RESEARCH INSTITUTE, BWR Vessel and Internals Project, Reactor Pressure Vessel and Internals Examination Guidelines, BWRVIP-03, (EPRI Technical Report 3002005571), EPRI, Palo Alto, CA, December 2015

[6] AMERICAN SOCIETY OF MECHANICAL ENGINEERS, ASME Code Case N-824, Ultrasonic Examination of Cast Austenitic Piping Welds From the Outside Surface, Section XI, Division 1, ASME, New York, NY

[7] ELECTRIC POWER RESEARCH INSTITUTE, Materials Reliability Program: Inspection Standard for Pressurized Water Reactor Internals – 2018 update (MRP-228, rev. 3), EPRI Technical Report 3002010399, EPRI, Palo Alto, CA, 2018

[8] Massoud J.P. and al.: Thermal Aging of PWR duplex stainless steel components – Development of a Thermoelectrical Technique as a NonDestructive Evaluation Method of Aging, 7th International Conference on Nuclear Engineering - ICONE 7

[9] Coste, J.F., Kawaguchi, Y.: Non-Destructive Monitoring of the Thermal Aging of Cast Duplex Stainless Steels Using Thermopower Measurements, 8th International Conference on Nuclear Engineering - ICONE 8

[10] Massoud J.P. and al.: "Evaluation of the thermal ageing of duplex stainless steels. Proceedings of the 6th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems, TMS publication, San Diego, 1993

[11] Le Delliou P. et Saillet S. Recent improvements in toughness prediction of cast duplex stainless steel components. PVP2018-84707. Pressure Vessels and Piping Conference PVP2018 July 15-20, 2018, Prague, Czech Republic. PVP2018-84707

[12] Thermal aging of cast duplex stainless steels of PWR: material assessment on removed cast elbows, Fontevraud 6, Report Number INIS-FR--08-0343, 2006

[13] UNITED STATES NUCLEAR REGULATORY COMMISSION, Regulatory Guide (RG) 1.147, Inservice Inspection Code Case Acceptability, ASME Section XI, Division 1, USNRC, 2014

[14] Thermal Ageing of Cast Duplex Stainless Steels of PWR: Material Assessment on Removed Cast Elbows, Fontevraud 6, Report Number INIS-FR--08-0343, 2006

[15] Faidy C, Ageing Management of Cast Stainless Steel Components in French PWRs, Pressure Vessels and Piping Conference PVP2012 July 15-19, 2012, Toronto, Ontario, Canada. PVP2012-78843

[16] Saillet S. and Le Delliou, Prediction of J-R Curves and Thermoelectric Power Evolution of Cast Austenitic Stainless Steel after Very Long-term Ageing (200,000 h) at Temperatures below 350°C, Journal of Nuclear Materials 540 (2020) 152328

[17] UNITED STATES NUCLEAR REGULATORY COMMISSION, 10 CFR Part 50, Appendix B, Quality Assurance Criteria for Nuclear Power Plants, Office of the Federal Register, National Archives and Records Administration, USNRC, Latest Edition