**AMP 114 FLOW ACCELERATED CORROSION AND EROSION (Version 2021)**

**Programme Description**

The objective of this programme is to ensure that the risk of wall thinning due to flow accelerated corrosion (FAC) and erosion so the risk of pipe rupture is adequately managed. The AMP ensures that the structural integrity of all lines containing high-energy fluids, two-phase as well as single phase, is maintained.

FAC is a complex phenomenon that is a function of several parameters of water chemistry, hydrodynamics, material composition and the type of component [1-4]. FAC involves the electrochemical aspects of general corrosion plus the effects of mass transfer and momentum transfer. FAC is characterized by the constant removal of protective oxide films, ranging from thin invisible passive films to thick visible films of corrosion products, from the metal surface. Typical general corrosion kinetics involves the formation of a protective oxide that slowly thickens with time [5]. The thickening of the protective film makes subsequent corrosion reactions at the solution/oxide or oxide/metal interface more difficult since the reactants have to pass through every increasing film thickness.

FAC is influenced by chemical parameters (pH, dissolved oxygen concentration, ferrous ion concentration, secondary water conditioning), hydrodynamic parameters (fluid velocity, wall roughness, geometry), temperature, and metallurgical parameters (mainly chromium and also molybdenum, vanadium, copper are beneficial).

The corrosion rate kinetics in this situation is typically parabolic [i.e. the change in thickness is proportional to root time (√t)]. In the case of FAC, only a limited thin protective film is established due to constant flow-induced mass transport removal/dissolution of the oxide. This results in linear corrosion kinetics where the change in wall thickness is proportional to time. Local attack occurs in the region where the film has been removed. This corrosion can be further accelerated if the solution contains solid particles that have an abrasive action.

The programme includes performing (a) an analysis to determine critical locations, (b) limited baseline inspections to determine the extent of thinning at these locations, and (c) follow-up inspections to confirm the predictions or repairing or replacing components as necessary. Additional mandatory requirements for FAC ageing management and inspection may be specified by applicable national regulatory and code requirements [6-13].

With appropriate considerations, this programme may also manage wall thinning caused by mechanisms other than FAC, in situations where periodic monitoring is used in lieu of eliminating the cause of various erosion mechanism(s).

**Evaluation and Technical Basis**

***1. Scope of the ageing management programme based on understanding ageing:***

The scope of the FAC ageing management programme includes procedures or administrative controls to assure that the structural integrity due to corrosion of all carbon steel lines containing high-energy fluids (two-phase as well as single phase) is maintained. Valve bodies retaining pressure in these high-energy systems and other components e.g., Feedwater Heater Shells [14] are also covered. The programme also includes components that are subject to wall thinning due to erosion mechanisms such as cavitation, flashing, droplet impingement, or solid particle impingement in various water systems.

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

Effective preventive actions in reducing FAC and erosion mechanisms include careful monitoring of water chemistry [15-16] to control pH (high pH values) and dissolved oxygen content, design of piping configurations and hydrodynamic conditions to reduce bulk-flow velocity effects from turbulence and impingement effects, and selection of FAC-resistant materials (e.g. with higher chromium content, in some Member States those materials are applied in which the chromium content is greater than 0.15 %).

***3. Detection of ageing effects:***

The principle ageing effect from FAC is wall thinning of piping and components. The ageing management programme monitors the effects of loss of material due to wall thinning on the intended function of piping and components by measuring wall thickness. Visual inspection (VT) of the affected surface is a good tool to identify locations where FAC occurs when practical. Ultrasonic and radiographic inspection techniques are used to detect and quantify wall thinning. This programme includes identification of susceptible locations, as indicated by operating conditions or special considerations. A representative sample of components is selected based on the most susceptible locations for wall thickness measurements at a frequency in accordance with industry guidelines to ensure that degradation is identified and mitigated before the component integrity is challenged. The extent and schedule of the inspections assure detection of wall thinning before the loss of intended function or before code allowable limits are exceeded. Industry standards and guidelines, such as NSAC-202L-R4 developed by the Electric Power Research Institute [17], provide recommended approaches for (a) conducting an analysis to determine critical locations, (b) performing limited baseline inspections to determine the extent of thinning at these locations, and (c) performing follow-up inspections to confirm the predictions, or repairing or replacing components as necessary.

For erosion mechanisms, the programme includes the identification of susceptible locations-based on the extent-of-condition reviews from corrective actions in response to plant-specific and industry operational experience. EPRI provides guidance for identifying potential damage locations [18].

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

FAC is a complex phenomenon, and so it is necessary to accurately, yet conservatively, predict and monitor the susceptible locations and the rate of metal loss to ensure that the wall-thickness does not fall below the minimum allowable.

* Predictive computer codes, such as CHECWORKS [19, 20], COMSY [21, 22], BRT CICERO [23], ToSPACE [24] and RAMEC, can be used to predict component degradation in the systems susceptible to FAC, as indicated by specific plant data, including material, hydrodynamic, geometry and operating conditions (pH, temperature, pressure...), provided all those parameters are known with sufficient precision. The computer code is considered to be validated and benchmarked, using data obtained from many plants. The inspection schedule developed on the basis of the results of such a predictive code then provides reasonable assurance that structural integrity will be maintained between inspections. Feedback from operating experience is used to continuously validate the computer codes.
* For FAC susceptible lines, valve bodies and other components for which it is impossible to perform predictive calculations because the operating conditions are uncertain, or the geometry cannot be modelled, components to be inspected are selected on the basis of operational experience, risk analysis or engineering judgment. For components that have been inspected at least once, predictability of the extent of degradation is obtained through trending which means that the next inspection date is determined based on the observed wall thinning.
* The programme includes trending of wall thickness measurements to adjust the monitoring frequency and to predict the remaining service life of the component for scheduling repairs or replacements. Inspection results are evaluated to determine if assumptions in the extent-of-condition review remain valid.

In all cases, inspection results are evaluated to determine if additional inspections are needed to assure that the extent of wall thinning is adequately determined, assure that intended function will not be lost, and identify corrective actions.

Previous wall thinning rate predictions may change after a power uprate is implemented or any other change that can affect the hydrodynamic or operating conditions. Wall thinning rates are updated in the predictive computer code according to the power uprate conditions or other new conditions. Subsequent field measurements are used to calibrate or benchmark the predicted wall thinning rates.

***5. Mitigating ageing effects:***

Where practical, effective mitigation methods and technology for FAC and erosion include:

1. Controlling water chemistry pH and dissolved oxygen content (however, this may not always be effective and changing the pH for the purpose of reducing the loss of material rate could affect another component's performance);
2. Repair or replacement of affected piping and parts with materials less susceptible to FAC such as increasing minimum chromium content in the replacement steel; and
3. Possible changes in operating parameters or design of the component to control ageing degradation of the structure or component.

***6. Acceptance criteria:***

Inspection results are input to a predictive computer code or to a trending analysis (see Attribute 4) to calculate the number of operating cycles or time remaining before the component reaches the minimum allowable wall thickness. If calculations indicate that an area will reach the minimum allowed wall thickness before the next scheduled inspection, the component is to be repaired, replaced, or re-evaluated [25].

***7. Corrective actions:***

Prior to service, components for which the acceptance criteria are not satisfied are re-evaluated, repaired, or replaced. Long-term corrective actions could include adjusting operating parameters or selecting materials resistant to FAC (see attribute 5).

However, if the wear mechanism has not been identified, then the replaced components remain in the inspection programme because FAC-resistant materials do not protect against all erosion mechanisms. Furthermore, when carbon steel piping components are replaced with FAC-resistant material, the susceptible components immediately downstream will be monitored to identify any increased wear due to the ‘entrance effect‘.

For erosion mechanisms, long-term corrective actions to eliminate the cause may include adjusting operating parameters and/or changing components’ geometric designs; however the effectiveness of these corrective actions will be verified. Periodic monitoring activities will continue for any component replaced with an alternate material, since a material that is completely resistant to erosion mechanisms is not available.

***8. 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.

Pipe ruptures due to wall-thinning have occurred in single-phase systems (feed-water and condensate systems). Wall-thinning problems have also occurred in two-phase piping in extraction steam lines, and moisture separation reheater and feed-water heater drains, and CANDU/PHWR outlet feeders.

In India for the first time in 1998, wall thickness reduction of feeder elbows was observed in Rajasthan Atomic Power Station-2 (RAPS-2) after 15 full power years of the reactor. This was predominantly observed in extrados of the elbows at the outlet feeders after Grayloc joint. The wall thickness reduction was localized and was attributed to FAC. Subsequently wall thinning was observed in many reactors. Cause of thinning was attributed to FAC by researchers (see AMP 140).

Observed wall thinning can be due to FAC, erosion (solid particle impingement, liquid drop impingement, flashing and cavitation) or less commonly, due to a combination of mechanisms [26]. The degradation mechanism are identified and attributed to particular damage and assessed as part of an AMP feedback, particularly when an ageing effect (wall thinning) can be caused by several degradation mechanisms (FAC, erosion, etc.), to prevent misleading use of operating experience.

The ageing management programme for FAC and erosion includes a mechanism that ensures timely feedback of operating experience and provides objective evidence that the operating experience is taken into account in this programme. Operating experience shows that FAC and erosion ageing management practices, when properly implemented, is effective in managing FAC and erosion in high-energy carbon steel piping and components [27].

Operational Experience exchange is a vital part of the AMP and can be realized by participation at operating experience exchange forums such are e.g. CHUG (CHECWORKS USERS GROUP) organized by EPRI or COMSY USERS GROUP organized by FRAMATOME.

Several R&D activities are conducted to enhance prediction codes (CHECWORKS – EPRI [20], BRT Cicero – EdF [23]) or to address particular aspect of FAC and erosion management.

***9. Quality management***

Site quality assurance procedures, review and approval processes, and administrative controls are implemented in accordance with the different national regulatory requirements (e.g., 10 CFR 50, Appendix B [28]).

**References**

1. UNITED STATES NUCLEAR REGULATORY COMMISSION, Erosion/ Corrosion-Induced Pipe Wall Thinning in U.S. Nuclear Power Plants, NUREG-1344, USNRC, 1989
2. INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment and management of ageing of major nuclear power plant components important to safety: BWR pressure vessel internals, IAEA-TECDOC-1471, IAEA, Vienna 2005
3. INTERNATIONAL ATOMIC ENERGY AGENCY, Generic safety issue for nuclear power plants with pressurized heavy water reactors and measure for their resolution, IAEA- TECDOC – 1554, IAEA, Vienna, 2007
4. INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear power plant life management processes: Guidelines and practices for heavy water reactors, IAEA- TECDOC – 1503, IAEA, Vienna, 2006
5. ELECTRIC POWER RESEARCH INSTITUTE, Flow-Accelerated Corrosion in Power Plants: Revision 2. EPRI, Palo Alto, CA: 2016. 3002008071
6. JAPAN SOCIETY OF MECHANICAL ENGINEERS, JSME technical rules of the pipe-wall-thinning management for BWR,JSME S NH1-2006, JSME
7. JAPAN SOCIETY OF MECHANICAL ENGINEERS, JSME technical rules of the pipe-wall-thinning management for PWR, JSME S NG1-2006, JSME
8. JAPAN NUCLEAR ENERGY SAFETY ORGANIZATION, Review Manual for Aging-Related Technical Evaluation Piping Wall Thinning, JNES-SS-0510, JNES
9. ATOMIC ENERGY REGULATORY BOARD, Life Management of Nuclear Power Plants, AERB Safety Guide, AERB/NPP/SG/O-14, AERB, India, 2005
10. AMERICAN SOCIETY OF MECHANICAL ENGINEERS, Code Case N-480 on examination requirements for pipe wall thinning due to single phase erosion corrosion, ASME Section XI Div. 1, ASME, New York, NY
11. STATE OFFICE FOR NUCLEAR SAFETY OF CZECH REPUBLIC, Aging Management Programme FAC in nuclear power plants of WWER type, National safety guide BN-JB-5.6, January 2021.
12. Normative Technical Documentation of Association of Mechanical Engineers of Czech Republic for Design and Life Time Assessment of Components and Piping in WWER NPPs, Section IV, Annex XVII, 2020.
13. Korea Hydro & Nuclear Power, Wall Thinning Management Procedure for Carbon Steel Piping, STANDARD MAINTENANCE-9144, Revision 6, 2019
14. CHUG Position Paper No. 4: Recommendations for Inspecting Feedwater heater Shells, Revision 4, 2013, EPRI
15. INTERNATIONAL ATOMIC ENERGY AGENCY, Data processing technologies and diagnostics for water chemistry and corrosion control in nuclear power plants (DAWAC), IAEA TECDOC-1505, IAEA, Vienna 2006
16. INTERNATIONAL ATOMIC ENERGY AGENCY, Chemistry Programme for Water Cooled Nuclear Power Plants, Specific Safety Guide, IAEA SSG-13, IAEA, Vienna, 2011
17. ELECTRIC POWER RESEARCH INSTITUTE, Recommendations for an Effective Flow Accelerated Corrosion Program (NSAC-202L-R4). EPRI, Palo Alto, CA: 2013. 3002000563
18. ELECTRIC POWER RESEARCH INSTITUTE, Recommendations for an Effective Program Against Erosive Attack. EPRI, Palo Alto, CA: 2015. 3002005530
19. ELECTRIC POWER RESEARCH INSTITUTE, CHECWORKS™ Steam/Feedwater Application Guidelines for Plant Modelling and Evaluation of Component Inspection Data, Revision 1. EPRI, Palo Alto, CA: 2017. 3002010594
20. CHECWORKS™ Steam/Feedwater Application (SFA), Version 4.2, EPRI, Palo Alto, CA: 2017. 3002010583
21. A. Zander, The COMSY – code for the Detecting of Piping Degradation due to Flow-accelerated Corrosion, IAEA - Workshop on FAC and EAC; April 21- 23, 2009, Moscow
22. COMSY Condition Oriented ageing and plant life Monitoring System Manual, Version 1.07, August 2001, by Framatome ANP GmbH Dept. NT31
23. BRT-CICERO, Un logiciel pour maîtriser la corrosion-érosion, Manuel Utilisateur Indice B, Janvier 2000, Copyright EDF EQT 200
24. ToSPACE, Development of ToSPACE for Pipe Wall Thinning Management in Nuclear Power Plants, World Journal of Nuclear Science and Technology, Vol.9, pp.1-15, 2019
25. AMERICAN SOCIETY OF MECHANICAL ENGINEERS, Code Case N-597-2 Requirements for Analytical Evaluation of Pipe Wall Thinning,ASME Section XI, Division 1, ASME, New York, NY, November 18, 2003
26. UNITED STATES NUCLEAR REGULATORY COMMISSION, NUREG–2191, Generic Aging Lessons Learned for Subsequent License Renewal (GALL-SLR) Report, Final Report, 2017
27. NEA/CSNI/R(2014)6, CODAP Topical Report Flow Accelerated Corrosion (FAC) of Carbon Steel and Low Alloy Steel Piping in Commercial Nuclear Power Plants, June 2014
28. 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