## AMP 118 REACTOR PRESSURE Vessel Surveillance (VERSION 2020)

### Programme Description

Reactor vessel beltline materials are exposed to a high-energy neutron flux which results in embrittlement (i.e., increase in yield strength, increase in brittle-ductile transition temperature, decrease in upper shelf energy and tensile elongation). The irradiation embrittlement effects are described in detail in IAEA Nuclear Energy Series Report NP-T-3.11 [1]. This change in the materials properties is monitored by a surveillance programme.

This AMP describes the general principles of reactor pressure vessel surveillance programmes. Practical implementation is made consistent with the applicable regulation in each Member State of the IAEA. Examples of codes, standards and regulations applicable in the Member States may be found in the reference list [2-13]. A related AMP addresses reactor vessel surveillance for WWER plants (AMP 152).

The reactor beltline is typically considered to be the region of the reactor vessel adjacent to the active height of the core. It is more precisely defined as the area of the reactor vessel which receives a fluence exceeding a specified value (depending on the national regulation) at the end of the operating period being considered (design lifetime or extended operation). The surveillance programme in operating plants were designed based on a given design life of the plant and additional surveillance capsules or a change to the withdrawal schedule may be needed in case of long-term operation.

The objective of the reactor vessel material surveillance programme is to provide sufficient material data and dosimetry to:

1. Monitor irradiation embrittlement until the end of the period of operation;
2. Determine the need for operating restrictions (e.g. operating pressure and temperature limits, and the fluence limit for continued operation).

Operating restrictions are to be established to ensure that the plant is operated under the conditions to which the surveillance capsules were exposed.

The programme is a condition monitoring programme that measures the increase in Charpy V-notch transition temperature at an established reference level of impact energy (as specified in the applicable national regulation) and the drop in the upper shelf energy as a function of neutron fluence and irradiation temperature. The programme may also include use of additional specimen types (tensile, fracture mechanics, or low-cycle fatigue), depending on the national codes, standards and regulations, and individual plant needs. The data from the surveillance programme is used to monitor neutron irradiation embrittlement and to justify the acceptability of the embrittlement level in the safety analyses involving time-limited assumptions. All capsules in the reactor vessel that are removed and tested must meet the test procedures and reporting requirements specified in the applicable national regulatory documents and standards.

The reactor vessel surveillance programme is a plant-specific programme, or in some circumstances an integrated programme covering several plants [9], which considers the composition of the representative limiting materials, availability of surveillance capsules, and projected fluence levels for each reactor vessel. The proposed withdrawal schedule is approved by the regulatory authorities and any changes to this schedule, including spare capsules, are approved by the regulatory authorities prior to implementation. Untested capsules placed in storage are maintained for possible future use consistent with national requirements.

### Evaluation and Technical Basis

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

The programme considers all reactor vessel beltline materials which receive a fluence exceeding a specified value (as specified in the applicable national regulation) at the end of the operating period being considered. In most existing plants, the representative limiting materials of the surveillance programme are the welds, heat affected zone, and the base material (plate or forging) from one or two shells, which are located in the beltline region. Materials originally monitored within the scope of the existing surveillance programme will continue to serve as the basis for the reactor vessel surveillance ageing management programme for the period of extended operation unless safety or material availability considerations for this period would require the monitoring of additional or alternative materials.

1. ***Preventive actions:***

The programme is a surveillance programme and no preventive actions are identified.

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

The reactor vessel surveillance programme monitors the embrittlement of the representative limiting materials for the reactor. In the programme, surveillance capsules are withdrawn from the reactor vessel after several years of irradiation and tested in accordance with the applicable national standard and regulatory guidance, which describe the methods for selecting limiting materials, establishing the withdrawal schedule for capsules, and monitoring irradiation embrittlement. The regulatory requirements in different countries are reviewed in references [1, 12]. Since the existing surveillance programmes are generally based on plant operation during the initial design lifetime, additional surveillance capsules may be needed for long term operation.

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

The programme monitors and trends the reduction of fracture toughness of reactor vessel beltline materials due to neutron irradiation embrittlement and the long term operating conditions of the reactor vessel (cold leg operating temperature and neutron fluence) that could affect the reactor vessel embrittlement. This programme provides reactor vessel material property data for the safety analyses involving time-limited assumptions on neutron irradiation embrittlement (e.g., upper-shelf energy, pressurized thermal shock and pressure-temperature limits evaluations for PWRs, pressure-temperature limits evaluations for water level instrument nozzles for BWRs, etc.) for the intended period of operation. The programme is designed to remove and test capsules for monitoring and trending purposes according to a predefined schedule.

The programme uses two parameters to monitor the effects of neutron irradiation:

1. The increase in the Charpy V-notch transition temperature measured at an established reference level of impact energy;
2. The drop in the Charpy V-notch upper shelf energy.

In addition, the programme uses neutron dosimeters to benchmark neutron fluence calculations. Low melting point elements or eutectic alloys may be used as a check on peak specimen irradiation temperature. Preferably, irradiation temperature will be monitored from cold leg operating temperatures in PWRs*.* The Charpy V-notch specimens, neutron dosimeters, and temperature monitors are placed in surveillance capsules that are located within the reactor vessel. The capsules are withdrawn according to a predefined schedule to monitor the reduction in fracture toughness due to neutron irradiation.

Additional specimens (for tensile, fracture mechanics or low-cycle fatigue tests) may be included in the surveillance programmes and may provide additional information on the reactor vessel material embrittlement. The Master Curve approach is used to monitor fracture toughness in reactor pressure vessels and is described in several IAEA and industry documents [13-20] but is generally used as a complement to the existing regulatory surveillance programme to demonstrate the conservatism of the regulatory approach.

An effective programme includes the following considerations:

* Surveillance capsules are located near the inside vessel wall in the beltline region so that the specimen irradiation history conservatively represents, to the extent practicable within the physical constraints of the system, the temperature history, neutron spectrum, and maximum neutron fluence experienced by the reactor vessel inner surface. There is a sufficiently high “lead factor”, which is defined as the ratio of the neutron flux of the specimens in the surveillance capsule to the maximum flux of the vessel inside wall, to ensure that the programme will provide timely information on the embrittlement trends for the reactor vessel. A maximum “lead factor” is also specified to represent the actual neutron flux levels experienced by the reactor vessel. Applicable lead factors are in the range of 1.5 – 5 according to ASTM E185 [4] or 1.5 – 12 according to KTA 3203 [2].
* The plant-specific surveillance programme has at least one capsule with projected neutron fluence equal to or exceeding the maximum reactor vessel wall neutron fluence at the end of the planned period of operation. The programme plans to withdraw one of these capsules at an outage, in which the capsule receives a neutron fluence of between one and two times the peak reactor vessel wall neutron fluence at the end of the period of operation. The specimens of the withdrawn capsule are tested in accordance with the applicable national standard.
* It is recommended that the programme retain additional capsules within the reactor vessel to support additional testing if, for example, the data from the required surveillance capsule turn out to be invalid or the plant is in preparation for long term operation. If the projected neutron fluence for these additional capsules is expected to be excessive when left in the reactor vessel, the programme may propose to withdraw and place one or more untested capsules in storage for future reinsertion and/or testing, attaining relevant irradiation levels before testing in accordance with the applicable national regulation and guidance.
* It is recommended that the programme has as much unirradiated material (initial state) as needed to assess the initial properties with good precision and keep archived material for future testing or fabrication of additional surveillance capsules.
* Withdrawn and tested specimens and untested surveillance capsules are placed in storage to support future reconstitution and reinsertion if needed.
* Plant-specific and fleet operating experience is considered in determining the withdrawal schedule for all surveillance capsules. A revised withdrawal schedule is submitted as part of an application for long-term operation.
* If all surveillance capsules have been removed and tested, the programme can propose one of the following for the period of long-term operation:

1. An active surveillance programme with reconstituted specimens. This programme consists of reconstitution of specimens from tested capsules, capsules made from any available archival materials, or some combination of the two previous options.
2. An alternative neutron fluence monitoring programme. Programmes without in-vessel capsules may use alternative dosimetry (for example ex-vessel dosimetry) to monitor neutron fluence during the period of extended operation.
3. A plant may participate in an integrated surveillance programme as further described below.

* If all surveillance capsules have been removed, operating restrictions are established to ensure that the plant is operated under conditions to which the surveillance capsules were exposed. The exposure conditions of the reactor vessel are monitored to ensure that they continue to be consistent with those used to project the effects of embrittlement to the end of operation.
* If the reactor vessel exposure conditions (neutron flux, spectrum, irradiation temperature, etc.) are altered, then the basis for the projection to the end of operation is reviewed and, if deemed appropriate, modifications are made to the reactor vessel surveillance programme.
* Any changes to the reactor vessel surveillance programme are submitted to the regulatory authorities for approval in accordance with the applicable national regulation.

In some cases, where there is insufficient material to enable a plant-specific surveillance programme, the surveillance programme may incorporate use of an integrated surveillance programme [21-23] among similar plants, “sister plant” data, or surrogate materials, subject to the review and approval of the regulatory authorities. The results from these programmes should achieve similar goals to that of the plant-specific surveillance programme, including the implementation of adequate fluence monitoring for the reactor.

The safety analyses involving time limited assumptions use projections in accordance with the applicable regulatory embrittlement trend curve (or an appropriate trend curve in the absence of regulatory guidance) that predicts the reference temperature shift (or the absolute value of the reference temperature) as a function of the material chemistry and neutron fluence, and, in some cases, the neutron flux and temperature.

The surveillance results are compared to the trend curve projection to verify that the projection is conservative for the reactor vessel. Some regulations authorize the direct use of “credible” surveillance results (by fulfilling a number of requirements) to adapt the trend curve for a specific material.

Surveillance results exceeding the trend curve prediction are further evaluated in order to clarify the reasons for the observed behaviour and resolve potential associated issues as necessary. Appropriate measures are taken to ensure that the safety analyses use a conservative trend curve such that sufficient operating limits are established for the reactor and the embrittlement of the reactor vessel is maintained acceptable for the period of operation.

In the case where future plant operating conditions exceed the limitations or bounds of the surveillance programme, such as operating at a lower cold leg temperature or higher fluence, the impact of these operating conditions on the reactor vessel embrittlement are evaluated and the regulatory authorities are notified.

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

Since the objective of the reactor vessel surveillance programme is to monitor the irradiation embrittlement of the reactor vessel, the programme does not provide specific actions to mitigate the embrittlement. However, neutron irradiation embrittlement can be mitigated by flux reduction (fuel management implementing a low neutron leakage core or shielding elements) or by thermal annealing of the reactor vessel.

1. ***Acceptance criteria:***

There are no acceptance criteria that apply directly to the surveillance data, but the results of surveillance capsule testing are used for reactor vessel embrittlement projections to determine the increase in the reference transition temperature (RTNDT) which is used to index the reference fracture toughness curves for KIc and KIa as specified in the applicable national regulation. These fracture toughness curves are used to determine the pressure-temperature limits for heat-up and cool-down transients and to justify adequate protection of reactor vessel integrity against cold overpressure transients and a risk of non-ductile failure due to Pressurized Thermal Shock (PTS) [24-30].

The embrittlement projections from the surveillance data are also used to demonstrate that the reactor vessel retains adequate fracture toughness to prevent ductile failure, usually through comparison to a regulatory requirement on the Charpy upper shelf energy (e.g., §§IV.A.1 of Appendix G to 10 CFR Part 50 [31]).

***7. Corrective actions:***

There are no acceptance criteria that apply to the surveillance data, and hence there are no specific corrective actions. However, the results of surveillance capsule testing are used for projections of reactor vessel embrittlement during the period of extended operation, which may impose operational limits on the plant in accordance with the applicable national regulations.

In addition, if a capsule is not withdrawn as scheduled, the regulatory authorities are notified and a revised withdrawal schedule is submitted.

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.

All the anomalies detected in the surveillance programme are evaluated. Below are examples of anomalies that have been detected in some surveillance programmes:

* Variability of the chemical composition of the weld material;
* Weld Charpy specimens with the notch outside of the weld material;
* Irradiation temperature in capsules higher that in the pressure vessel wall;
* Build-up of Pu in 238U and 237Np dosimeters.

Temperature monitors can be included in the surveillance capsules for verification of the irradiation temperature of the specimens according to design. When possible, a reference steel or correlation monitor material is also included in the surveillance capsules. This will help to understand any anomaly in test results and will contribute to the credibility of the surveillance data. The IAEA reference steel JRQ has been used in some reactors[[1]](#footnote-1). It is a good practice to compare test results with those obtained in other reactors. For instance, to determine if the embrittlement results agree with the predictions of generic embrittlement trend curves. This will give credibility to the surveillance results.

Broken specimens of the tested surveillance capsules are kept in an appropriate place avoiding their deterioration by corrosion. Thus, the samples can be recovered at any time for further investigation.

An ex-vessel neutron measurement programme can provide additional data to support the intended period of operation. It allows long term monitoring, that permits continuous evaluation of the effect of changes in reactor operation and changing fuel management schemes on the reactor vessel exposure. With the addition of supplementary passive neutron sensors in the cavity annulus between the reactor vessel wall and the biological shield, the deficiencies in both surveillance capsule dosimetry and analytical prediction can be alleviated and the uncertainties associated with exposure estimates for the reactor vessel can be minimized.

The existing reactor vessel material surveillance programme provides sufficient material data and dosimetry to:

1. monitor irradiation embrittlement at the end of the period of operation;
2. determine the need for operating restrictions (e.g. operating pressure and temperature limits, and the fluence limit for continued operation).

IAEA has a database storing the results from reactor vessel surveillance programmes and collecting data of IAEA Coordinated Research Projects in the field of radiation damage in reactor vessel materials [32]. Specific databases are also established in different countries.

There are also numerous national and international research programmes providing improved understanding of radiation trends and mechanisms controlling neutron embrittlement at high fluence levels, so as to provide the bases for demonstrating safe plant operation for extended operating periods. Notably are the European projects LONGLIFE [33-34] and PERFORM60 [35].

Tested surveillance specimens may be removed from storage and used in research activities if the licensee determines that a sufficient number of specimens will remain to monitor reactor vessel integrity.

1. ***Quality management:***

Site quality assurance procedures, review and approval processes, and administrative controls are implemented in accordance with different national regulatory requirements (e.g., 10 CFR Part 50, Appendix B [36]).

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1. E.g. in Spain (corresponding reports are confidential) [↑](#footnote-ref-1)