## AMP 152 WWER REACTOR PRESSURE VESSEL SURVEILLANCE (VERSION 2020)

### Programme Description

Reactor pressure vessel (RPV) beltline materials are exposed to a high-energy neutron flux which results in embrittlement and hardening (increase in yield strength, increase in brittle-ductile transition temperature determined from Charpy V-notch impact or fracture toughness tests, decrease in upper shelf energy, tensile elongation and reduction of area). The irradiation embrittlement effects are described in detail in IAEA document NP-T-3.11 [1]. This results in shifting of the initial critical brittleness temperature  to the higher values (). The changes in the materials properties are monitored by a surveillance programme.

According to WWER rules, the surveillance programme also considers the thermal embrittlement in RPV locations that are outside the irradiated part of the reactor vessel. Therefore, the WWER surveillance programmes also include specimens that are located in the reactor vessel, close to the reactor vessel wall but far from the active core, and that are subjected to the outlet water temperature [2-6].

This AMP describes the general principles of reactor pressure vessel surveillance programmes. Practical implementation is made consistent with the applicable regulation in each IAEA Member State. Examples of codes, standards and regulations applicable in the Member States may be found in the reference list [7-13]. The WWER surveillance programme also comprises the reactor dosimetry activities for verification and validation of the neutron fluence of the RPV.

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 given value (depending on the national regulation) at the end of the operating period being considered (design lifetime or extended operation). The surveillance programmes in operating plants were designed based on a given design life of the plant and additional surveillance capsules or a change in the withdrawal schedule may be needed in case of LTO.

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

1. Monitor irradiation and thermal embrittlement until the end of the operation period;
2. Determine the need for operating restrictions (e.g., operating pressure and temperature limits, and the neutron 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 specimens were exposed.

The programme is a condition monitoring programme that measures the shift of the critical brittleness 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, as well as the shift of the transition temperature determined from the results of fracture toughness testing or decrease in fracture toughness fluence dependence. 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 this surveillance programme are used to monitor neutron irradiation and thermal 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. Different types of capsules are included in the WWER surveillance specimen programmes - cylindrical type capsules that are either connected into chains (WWER-440/V-213), collected in special holders with two floors of containers (WWER-1000/V-320), or in flat containers that contain all specimens for one time withdrawal (WWER-1000/V-320). In this AMP, "capsule" means the full set of specimens to be withdrawn together, either a complete set of cylindrical capsules or a flat container.

The reactor vessel surveillance programme is a plant-specific programme which considers the composition of the representative limiting materials, availability of surveillance capsules, validation of neutron fluence of the RPV and surveillance specimens. The proposed withdrawal schedule is approved by the regulatory authorities prior to implementation, including any changes to this schedule or to the spare capsules. Untested capsules placed in storage are maintained for possible future use consistent with national requirements. Tested capsules can be reconstructed and reinsertion in RPV, if needed.

### 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 given 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 (as well as cladding materials, if possible) from one or two shells, which are situated 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.

This programme considers also other parts of the reactor pressure vessel which may be exposed to thermal ageing.

The WWER surveillance programme also comprises the reactor dosimetry activities for verification and validation of the neutron fluence of the RPV which is necessary for monitoring of the accumulated fluence at the RPV inner wall (maximal limit value given by the designer/ producer of the equipment) and at the surveillance specimens (maximal limit value according to the withdraw schedule).

1. ***Preventive actions:***

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

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

The surveillance programme monitors the embrittlement (and hardening, if possible) of the representative limiting materials of the reactor pressure vessel. 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 (and thermal ageing). The regulatory requirements in different countries are reviewed in reference [1]. Since the existing surveillance programmes are generally based on plant operation during the initial design lifetime, additional surveillance capsules may be needed for the long term operation period. Surveillance guidelines for long term operation are given in [14].

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

The programme monitors the reduction of fracture toughness of reactor vessel beltline materials due to both neutron irradiation embrittlement and thermal 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.

The programme uses two parameters to monitor the effects of embrittlement and loss of fracture toughness:

1. The increase in the Charpy V-notch transition temperature measured at an established reference level of impact energy and/or the increase in the transition temperature measured at an established reference level of static fracture toughness;
2. The drop in the Charpy V-notch upper shelf energy and/or the drop in the fluence dependence of fracture toughness values.

In addition, the programme uses neutron dosimeters to benchmark neutron fluence calculations. Ex-vessel dosimetry is strongly recommended for use simultaneously with in-vessel capsules to be able to determine more precisely the neutron fluence attenuation through the vessel wall. For example, some Member States operating WWER apply the Russian methodology of neutron control on external surface of reactor vessels [15], which is intended to experimentally verify the calculation methods used to determine the predicted data on the fluence of fast neurons at critical points in pressurized-water reactor vessels. 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*.* The Charpy V-notch specimens, fracture toughness specimens and tensile specimens, neutron dosimeters, and temperature monitors are placed in 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 (tensile or low-cycle fatigue) may be included in the surveillance programmes and may provide additional information on the reactor vessel material embrittlement. The use of the Master Curve approach to monitor fracture toughness in reactor pressure vessels is described in several IAEA and industry documents [10-11] and can be generally used as a substitution to the standard surveillance programme to decrease the conservatism of the regulatory approach using Charpy V-notch transition temperature.

An effective surveillance 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, the 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 fluence of the specimens in the surveillance capsule to the maximum fluence of the vessel inside wall, to ensure that the programme will provide timely information on the embrittlement trends for the reactor vessel. But, this "lead factor" is not larger than five; in such case, it is necessary to demonstrate that the "flux rate effect" cannot influence the radiation embrittlement values.
* 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 extended 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, observing the allowable time for capsule storage 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 a good precision and to keep archived material for future testing or additional surveillance capsules.
* Withdrawn and tested samples and untested 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 capsules. A revised withdrawal schedule is submitted as part of an application for extended operation. An integrated surveillance programme (ISP) can be established for a fleet of similar reactors if their design and operating conditions are similar (close to each other); in such case, one host reactor can use irradiated specimens from several reactors of the same fleet.
* If all surveillance capsules have been removed, the programme can propose one of the following options for the period of extended 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. New capsules can be loaded for a short irradiated time (two to four years) without archive materials but only with some reference material and neutron dosimeters or, if that is not possible, programmes without in-vessel capsules may use alternative dosimetry (for example ex-vessel dosimetry) to monitor neutron fluence during the period of extended operation.

* If all surveillance capsules have been removed, operating restrictions could be established to ensure that the plant is operated under conditions to which the surveillance capsules were exposed. Usually, the material embrittlement trend curve, based on results from surveillance specimen tests, can be extrapolated only by 10 % of the maximum neutron fluence received by the specimens. 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.
* Reactor dosimetry activities for verification and validation of the neutron fluence at the RPV and at the surveillance capsules. Ex-vessel detectors (e.g. copper, iron, manganese etc.) are placed at the belt region where the neutron exposure is higher. Neutron transport calculation codes and cross-section libraries used for neutron fluence and detector’s activity calculation are validated.

In some cases, where there is insufficient material to enable a plant-specific surveillance programme, the surveillance programme may incorporate use of an ISP 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.

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 WWERs, etc.) for the period of extended operation.

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.

In specific cases when no surveillance specimen tests are available (WWER-440/V-230) or surveillance tests were performed after irradiation to fluences lower than the projected neutron fluence, the applicable regulatory embrittlement trend curve is applied.

Reactors, that are planned to be annealed for decrease of radiation embrittlement of the beltline materials, ensure that plans for additional surveillance programme elements for monitoring these changes are prepared, with the plans submitted to the national regulatory body for approval and finally be implemented. Such programme elements monitor the effect of the annealing on restoration of properties (decrease of transition temperatures) as well as the re-embrittlement rate during further operation after annealing. For such a programme, archive materials are used, if possible. In other case, representative surrogate material can be used in the programme as a conservative alternative (this choice can be performed using "chemical factors" from the applicable regulatory embrittlement trend curve). This programme covers the whole extended operating life of the reactor after annealing.

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

Since the objective of the reactor vessel surveillance programme is to monitor the irradiation embrittlement of the reactor vessel (as well as the neutron fluence on the RPV wall), 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 (presently used only for WWER-440 reactor pressure vessels).

1. ***Acceptance criteria:***

There are acceptance criteria in national codes for the representativeness of irradiation conditions and reliability of obtained test data: irradiation temperature of the surveillance specimens cannot be more than 10 °C higher in comparison with the temperature of the inner RPV wall, and the maximum difference between neutron fluences of individual test specimens within one test group cannot be larger than 10 to 15 %, depending on national regulations. Then, the results of surveillance capsule testing are used for reactor vessel embrittlement projections to determine the increase in the transition temperature (Tk or Tk0, RTk or RT0), which is used to index the fracture toughness curves for KIC as specified in the applicable national regulation. The same parameters can be used for acceptance criteria in the case of thermal ageing. These fracture toughness curves are used to determine the pressure-temperature limits for heat-up and cool-down transients, for pressure and tightness tests 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).

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, and that its austenitic cladding has sufficiently high fracture toughness to ensure cladding integrity either during operation or during PTS regimes.

Regarding the neutron fluence validation, the conformity between the experimental and calculated results of the detector’s activities has to meet the requirements of the codes and standards, approved by the National Regulatory Body (for instance Regulatory Guide 1.190. “Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence. U.S. NRC, Washington DC, March 2001 [16], NP-089-15 “Rules for Design and Safe Operation of Equipment and Pipelines of Nuclear Power Installations” [5]).

1. ***Corrective actions:***

Surveillance results exceeding the trend curve prediction are further evaluated in order to clarify the reasons for the observed behaviour and resolve 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 case that 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.

The results of surveillance capsule testing are used for projections of reactor vessel embrittlement during the initial operating period (design) as well as extended operation, which are incorporated into operating limitations of the plant. In case of power uprating, the neutron fluence received by the RPV wall is re-evaluated and monitored if possible (e.g, using ex-vessel dosimetry).

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

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.

The IAEA has a database storing the results from reactor vessel surveillance programmes and collected data of IAEA Coordinated Research Projects in the field of radiation damage in reactor vessel materials [9]. 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.

There is a European Working Group on Reactor Dosimetry (EWGRD) which members can give more information about experience exchange and know-how in reactor dosimetry and connected programmes.

This programme includes provisions for continuing review of plant-specific and industry-wide operating experience, and research and development results, which may lead to the consideration of new actions or modifications to the existing programme as well as to its implementation.

1. ***Quality management:***

Site quality assurance procedures, review and approval processes, and administrative controls are implemented in accordance with different national regulatory requirements.

**References**

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