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Integrated surveillance specimen programme for WWER-1000/V-320 reactor pressure vessels

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ABSTRACT

Surveillance specimen programmes play nonreplaceable role in reactor pressure vessel lifetime evaluation as they should have to monitor changes in pressure vessel materials mainly their irradiation embrittlement. Standard surveillance programmes in WWER-1000/V-320 reactor pressure vessels have some deficiencies resulting from their design – nonuniformity of neutron field and even within individual specimen sets, large gradient in neutron flux between specimens and containers, lack of neutron monitors in most of containers and no suitable temperature monitors. Moreover, location of surveillance specimens does not assure similar conditions as the beltline region of reactor pressure vessels. Thus, Modified surveillance programme for WWER-1000/V-320C type reactors was designed and realized in two units of NPP Temelin, Czech Republic. In this programme, large flat type containers are located on inner wall of reactor pressure vessel in the beltline region that assures their practically identical irradiation conditions with critical vessel materials. These containers with inner dimensions of 210x300 mm have two layers of specimens; using inserts (10x10x14 mm) instead of fully Charpy size specimens allows irradiation of materials from several pressure vessels at once in one container. This design advantage has been used for the creation of the Integrated Surveillance Programme for several WWER-1000 units – Temelin 1 + 2, Belene (Bulgaria), Rovno 3 + 4, Khmelnick 2, Zaporozhie 6 (Ukraine) and Kalinin 3 (Russia). Irradiation of these archive materials together with the IAEA reference steel JRQ (of ASTM A 533-B type) and reference steel VVER-1000 will allow to compare irradiation embrittlement of these materials and to obtain more reliable and objective results as no reliable predictive formulae exist up to no due to a higher content of nickel in welds. Irradiation of specimens from cladding region will help in the evaluation of resistance of pressure vessels against PTS regimes.

INTRODUCTION

Reactor pressure vessels (RPV) are components with the highest importance for the reactor safety and operation as they contain practically whole inventory of fission material but they are damaged/aged during their operation by an intensive reactor radiation.
Surveillance specimen programmes are the best and nonreplicable method for monitoring changes in mechanical properties of reactor pressure vessel materials if they are designed and operated in such a way that they are located in conditions close to those of the vessels. Reactor Codes and standards usually included requirements and conditions for such programmes to assure proper vessel monitoring [2,3,4].

WWER reactor pressure vessels are designed according to former Russian Codes and rules with somewhat different requirements using different materials comparing e.g. with ASME Code.

Standard surveillance programmes in WWER-1000/V-320 reactor pressure vessels have some deficiencies resulting from their design – nonuniformity of neutron field and even within individual specimen sets, large gradient in neutron flux between specimens and containers, lack of neutron monitors in most of containers and no suitable temperature monitors. Moreover, location of surveillance specimens does not assure similar conditions as the beltline region of reactor pressure vessels.

Prediction of radiation damage/embrittlement in weld metals of these type of vessels has been put into great interest when first results from Standard surveillance programmes (SSP) were obtained – it looks that some of these weld metals showed higher irradiation embrittlement than was predicted with the use of the standard [1]. One of the reasons could be a fact that weld metals in most of these vessels contain higher content of nickel as it was tested within the Qualification tests of this vessel material – 15Kh2NMFA(A). In these tests nickel content was lower than 1.5 mass % but later Technical specification for the weld metal was changed and some of weld have as much as 1.9 mass % of nickel while no representative irradiation tests were performed. This situation can be seen in Figure 1 where results from some first tests of SSP specimen are summarized.

![Figure 1 Shift of ductile-to-brittle transition temperature of WWER-1000 RPV weld material due to irradiation. Results of surveillance specimen investigation. Full red line represents prediction in accordance with [1]](image)
1. STANDARD SURVEILLANCE PROGRAMME

Standard surveillance programme (SSP) design was based on the experience with WWER-440 RPVs (design of cylindrical containers) but tried to decrease their high lead factor. Thus, new location of containers was put into design – over the reactor active core.

Containers
Specimens are put in stainless steel containers identical to the ones in the SSP of WWER-440 type, i.e. either two Charpy type (impact of pre-cracked), or six tensile, resp. six fatigue type specimens. Six, resp. twelve (in two floors) these containers are accumulated into assemblies with one or two floors. Containers are pressed together by a special spring but they can practically free rotate within an assembly.

Location of containers
Five assemblies create one neutron embrittlement set. One set of assemblies was planned to be withdrawn at the same time. These sets are located in the upper part above the active core shroud near its outer diameter, i.e. above reactor active core – see Fig.2.

The neutron field in the location of neutron embrittlement assemblies in the RPV as well as containers within assemblies is very complicated. Due to their location above the reactor core, neutron flux gradient is substantial not only between upper and lower floor in assemblies but also between individual assemblies within one set. Moreover, half of sets contains assemblies only with upper floor of containers where neutron flux is even lower than in RPV beltline, i.e. lead factor is lower than one.

Fig.2. Scheme of location of containers and containers assemblies of the SSP in WWER-1000/320 RPVs
2. TECHNICAL ISSUES OF A STANDARD SURVEILLANCE PROGRAMME

The review of the existing surveillance programme of the WWER-1000/320 units confirmed the following facts:

**General design**
Design of assemblies and their positioning above the core result in nonuniform irradiation conditions and the number of specimens irradiated to similar neutron fluence is not sufficient for a reliable determination of the transition temperature shift.

**Irradiation temperature**
Irradiation temperature of the surveillance is higher (by about 10 to 15 °C) than the RPV wall temperature.

**Temperature monitoring**
Temperature monitoring by diamond powder is not adequate for determination of the irradiation temperature since the results show far too large scatter and mostly even unrealistic results (lower temperature than inlet water temperature).

**Neutron dosimetry**
The quantity of neutron fluence monitors (3 sets) and variety in individual assemblies is insufficient to characterize fully the distribution of the neutron flux within the assembly and in individual surveillance specimens.
The choice of neutron activation monitors does not enable to monitor fluences on surveillance specimens properly throughout the entire reactor lifetime.
The lead factor in surveillance specimens is in upper floors lower than one and therefore the results cannot be used for prediction of irradiation embrittlement of RPV.
The design of surveillance assemblies and containers inside of the assemblies does not allow clear determination of their orientation (moreover, they can rotate during reactor operation) with respect to reactor core centre which, together with small number of neutron monitors, cannot ensure a proper determination of neutron fluence in individual surveillance specimens without direct autodosimetry (gamma-scanning) on each specimen.

3. MODIFICATION OF THE STANDARD SURVEILLANCE PROGRAMME

Main disadvantage of the original SSP is that it is not capable to provide the monitoring of RPV material properties in a reliable way. Therefore, a modification of the programme was elaborated in SKODA Nuclear Machinery, Plzen, Czech Republic for NPP with WWER-1000/V-320C type reactors for Belene (Bulgaria) and Temelin (Czech Republic).

Main principles of the design were chosen in such a way to solve problems of the Standard Surveillance Programme, mainly:
- location of containers should well monitor the conditions of reactor pressure vessel wall in beltline region, i.e. specimens temperature should be as close as possible (containers must be washed by a cold inlet water) and lead factor should be less than 5,
- whole set of specimens for one testing curve should be located in identical neutron fluence position,
- as much as possible sets of specimens should be located in similar/close neutron fluence to be able to compare behaviour of different materials,
- withdrawal scheme of containers should assure monitoring pressure vessel material as well as neutron fluence during the whole RPV lifetime,
- neutron monitoring should assure determination of neutron fluence to each of test specimens for every container,
- temperature monitoring should be performed using melting temperature monitors with an appropriate range of melting temperatures,
- cladding materials should be also included in the containers,
- reference material should be added for an objective comparison of results,
- spare containers should be added to monitor vessel annealing as well as further re-embrittlement if necessary.

Design of such a programme was performed and supported by a set of calculations (neutron physics, thermal-hydraulics) as well as experiments in a scale 1:1 (thermal-hydraulic characteristics measured in a hydraulic channel of a pressure loop in SKODA, thermal fatigue tests of container holders on pressure vessel wall).

Main characteristics of this Modified Surveillance Programme are as follows:

**Containers**

Containers are of flat type with inner dimensions approx. 200 x 300 x 25 mm and are made from austenitic stainless steels plates welded on a frame. They contain special holders for location on pressure vessel wall – see Fig.3.

All specimens for one withdrawal time are located in one irradiation container – specimens are in two layers, specimens of the same type and one set are touched each other in layer, only.

*Fig.3 Container of the Modified/Integrated Surveillance Programme in NPP Temelin*
Fig. 4. Location of containers of the Modified Integrated Surveillance Programme

**Location of containers**

Containers are located in special holders that are welded on inner surface of reactor pressure vessel wall approx. 400 mm below the centreline of beltline region – see Fig.4.

Containers are located symmetrically in maximum neutron fluence on vessel wall, i.e. in hexagonal corner positions.

Two additional identical containers are located between upper nozzles for monitoring possible thermal ageing effects.
Neutron monitors

Two types of monitors are used:
- 5 spectrometric sets of monitors in each container located close to both surfaces of the container and in different ends for absolute dosimetry of the container
  activation monitors - Co, Nb, Ni, Fe, Ti, Cu and Mn as foils and
  fission monitors $^{237}$Np and $^{238}$U with and without Gd shielding,
- two sets of wires – Cu and Fe – located on both surfaces in diagonal directions for relative dosimetry of each specimen,
- scanning of specimens is prepared to check the neutron dosimetry,
- continuous measurement of neutron fluences on outer pressure vessel wall (in the cavity) is a mandatory part of the programme,
- detailed calculation of neutron fields within assemblies and the reactor.

Temperature monitors

Several sets of melting temperature monitors are located either in specimens or in container filling:

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition</th>
<th>Melting Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb - 10% In</td>
<td></td>
<td>291°C</td>
</tr>
<tr>
<td>Pb - 8% In</td>
<td></td>
<td>300°C</td>
</tr>
<tr>
<td>Pb - 2.5% Ag</td>
<td></td>
<td>304.5°C</td>
</tr>
<tr>
<td>Pb - 1.75% Ag - 0.75% Sn</td>
<td></td>
<td>309°C</td>
</tr>
<tr>
<td>Pb</td>
<td></td>
<td>327°C</td>
</tr>
</tbody>
</table>

Withdrawal schedule

The following scheme is proposed:
2, 6, 10, 18, 26 + x years for radiation damage containers,
14, 34 years for thermal ageing containers,
one container for thermal annealing effect,
one container for re-embrittlement rate effect.

This programme has been loaded into both pressure vessels on NPP Temelin, and was also prepared for the pressure vessel of unit 1 in NPP Belene, Bulgaria.

4. INTEGRATED SURVEILLANCE PROGRAMME FOR WWER-1000/320 TYPE RPVs

In principle, it exists a possibility to use this reactor of WWER-1000/V-320C as a “host” reactor for those V-1000 units that are supplied by the Standard Surveillance Programme and thus reliability of obtained results is not very high. Possibility of incorporation materials also from other reactors is given by the fact that containers of flat type are sufficiently large as they were designed for full size Charpy type specimens but now, application of reconstitution technique allows to include practically four times more specimens if inserts of dimensions 10x10x14 mm are used- see Fig.5.
Integrated surveillance programme for several similar reactors can be realized in accordance with the [2] if the following main requirements are fulfilled:
- reactors are similar in design and operation,
- neutron fluence determination on all RPV wall is assured for the whole reactor lifetime,
- operation of the “host reactor” is assured for the whole operation of reactors within the family.

A proper and reliable monitoring radiation damage in materials for WWER-1000/320 units is now under high study and interest as it was determined that in some welds with high nickel content (in some cases up to 1.88 mass %) radiation embrittlement can be much larger than that obtained from predicted formula given in [1]. Qualification tests for materials of WWER-1000 RPVs were performed on welds with nickel content below 1.5 mass %, but later the nickel content was increased (in most of V-1000 units) to get better fracture toughness properties but no further study of radiation embrittlement was performed.

Thus, using the opportunity that NPP Temelin was delayed in its start-up due to changes in I&C system, it was possible to modified content of some containers (for Unit 2) in such a way that specimens from archive materials of the following units were incorporated into the programme: Khmelnitsky Unit No. 2, Rovno Units No. 3 and No. 4, Zaporozhye Unit No.6 (Ukraine) and Kalinin Unit 3 (Russia), as nickel content in all these weldments is well over 1.5 mass %. In this first part of the programme only weld metals from these RPVs were included. From all materials, 12 specimens for impact notch toughness and 12 specimens for static fracture toughness tests are included. It is necessary to mention that all these RPVs contain still their original Standard surveillance programme.

In this time, second part of this Integrated surveillance programme is under final realization. New six containers have been manufactured that will replace containers from the first part in both units in NPP Temelin (design of container holders and containers itself allows inserting of new containers during reactors shut down where reactor internals are
removed) – one container was already replaced last year in Unit 1. Base metals from all abovementioned RPVs will be included in these containers together with base and weld metals from the NPP Belene. Moreover, standard IAEA reference material JRQ as well as IAEA reference V-1000 materials are also included for mutual comparison with results of the first part as well as for better and more objective evaluation of results (there exist a large database of the behaviour of JRQ steel, e.g. within the IAEA Co-ordinated programmes and its database).

Realization of such Integrated Surveillance Programme will substantially improve knowledge about behaviour of WWER-1000 RPV materials during their operation, i.e. about radiation damage – embrittlement. Comparison of results from different RPVs also allows to assess the behaviour of materials from other RPVs with only Standard surveillance programme – based on comparison of chemical composition and operational conditions. It also allows comparison and analysis of results from testing their SSP and to propose a correction coefficients (taking into account different irradiation conditions) if necessary. Results from this Integrated Surveillance Programme also will enlarge existing database of radiation embrittlement data of this type of materials in a more objective manner.

CONCLUSION

Modified Surveillance Programme for reactor pressure vessels of NPP Temelin with WWER-1000/V-320C type reactors is used for the Integrated Surveillance Programme for several RPVs of NPPs in Ukraine, Russia, Bulgaria and Czech Republic as the Standard Surveillance Programmes in WWER-1000/V-320 type reactors do not fulfil requirements given by codes and standards.

Such Integrated Surveillance Programme allows to obtain reliable information about radiation embrittlement of materials in tested reactors pressure vessels that will be also correlated with the IAEA reference steel JRQ to get more objective results.

Realization of this Integrated Surveillance Programme increases information about the behaviour of RPV materials of this type of reactors that have only Standard Surveillance Programme. Moreover, it allows correlation of results from these Standard Surveillance Programmes with those from other vessels not included in this Programme that also increase reliability of such results. Generally, this Integrated Surveillance Programme will increase safety of operating WWER-1000/V-320 type reactors operated in these countries.
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[1] „Нормы расчета на прочность оборудования и трубопроводов атомных энергетических установок“: ПН АЭ Г-7-002-86, Москва 1989 (Standards for Strength Calculations of Components and Piping in NPPs, PN AE G-7-002-86, Moscow 1989)

