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RPV Long Term Operation: Open Issues

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Актуальные проблемы обеспечения долговременной работы корпусов АЭС

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Описаны актуальные проблемы обеспечения безопасной работы АЭС при продлении сроков эксплуатации, которые широко обсуждаются экспертами данной отрасли. К ним, в частности, относятся: эффекты запаздывания в сталях с низким содержанием меди; влияние Cu, Ni, Mn и P на микроструктуру, упрочнение и охрупчивание облученных сталей; применимость результатов испытаний, полученных в исследовательском атомном реакторе, к промышленным реакторам, включая эффекты флакса и спектра; сопоставление Master-кривой с унифицированной кривой, а также особенности разрушения высокооблученных материалов; охрупчивание материалов в зонах корпусов реакторов вне традиционных участков; построение трендовых кривых охрупчивания для высокого флюенса нейтронов при малом объеме данных; повторное охрупчивание после отжига.

Ключевые слова: долговременная эксплуатация, реакторный сосуд давления, облученная сталь, охрупчивание, Master-кривая, унифицированная кривая.

Introduction. The lack of new build of plants over the last twenty years has resulted in a switch within the industry from design, construction and development of new systems to the strengthening of safety systems and to the life extension, or long term operation (LTO), of existing reactors. The most relevant component of any nuclear power plant (NPP) is the reactor pressure vessel (RPV). This is because currently the RPV is still considered irreplaceable or prohibitively expensive to replace. A RPV operational life of 60 years is being considered frequently by many utilities in their plant life management programmes. Consideration is given also to extending that further to possibly 80 years.

There are several scientific and technical open issues which are critical for a safe plant operation to 60 years and beyond. Several of these issues are considered old, in the sense that they have been debated by experts in the field since long time ago. For instance, the "neutron flux effects" or the "re-embrittlement after annealing." Other issues are relatively more recent, since they arise directly from the need to get a more accurate picture of the material behavior after long exposure times. That is the case of the "expanding beltline" or the development of "embrittlement trend curves at high fluence."

The following sections describe in detail the relevant open issues.

1. **Old Open Issues**.

1.1. ***Chemical Composition***. A more precise analysis of the nickel-manganese effect is needed. In addition, it may be strong synergistic interactions at high fluences between copper, nickel, manganese and phosphorus. The role of silicon should be clarified. Its presence in clusters should indicate an increase in embrittlement with increasing silicon concentration, but there are results indicating the opposite influence [1].

The RPV wall material of the WWER-440 (15Kh2MFA) is alloyed with Cr, Mo, and V. The vanadium alloying may increase the radiation resistance, but phosphorus segregation to vanadium carbonitride interfaces has been observed [2].

1.2. ***Late Blooming Effects***. Models suggest and increasing experimental evidence shows that clusters rich in Ni and Mn may form in low Cu steels and may or may not contribute to hardening and embrittlement until relatively high fluences – called "late blooming effect" (LBE).

A late blooming effect on both the yield stress increase and the magnetic scattering cross section of SANS data has been observed for low-Cu RPV steels irradiated at a relatively low temperature of 255°C [3].

SANS, APT and electrical resistivity-Seebeck coefficient measurements all show large volumes of Mn and Ni rich clusters and high hardening in two Cu-free, high Ni steels irradiated at 270°C and intermediate flux to $\approx 1.7 \cdot 10^{19}$ n/cm^2 [4]. Other investigations (e.g., [5]) indicate that there is no such late-blooming effect in several RPV steels irradiated at relatively high fluxes in the temperature range from 265 to 300°C.

1.3. ***Flux, Spectrum, and Irradiation Temperature Effects***. Whether or not the same magnitude of "damage" would be exhibited by materials irradiated under "fast" versus "slow" fluence accumulation conditions is considered an open issue. Early investigations of flux effects, using test reactor experiments, did not reveal a significant influence of this exposure variable on steel property changes. In most instances, the data bank information does not offer a 1:1 comparison for a specific material.

A further impediment to testing for flux effects is the general tie between flux level and neutron spectrum. Decoupling these two factors experimentally is difficult.

Temperature irradiation effects seem to be more important for higher neutron doses representative of long term operation conditions. Experimental data on studies of JRQ steel under irradiation at different temperatures (265 and 300°C) show that there is significant difference in hardening as the irradiation dose growth. After irradiation to the dose of $5 \cdot 10^{19}$ n/cm^2 the difference in hardening is

~ 60 MPa, and at irradiation to $1.5 \cdot 10^{20}$ n/cm^2 it is ~ 150 MPa [6]. Similar result was obtained in the modelling studies of [7].

1.4. ***MTR versus Power Reactor***. In general, surveillance data correspond to "low fluences." There are insufficient surveillance data to cover service life prolongations. Typical problems are:

(i) insufficient number of surveillance capsules initially inserted;

(ii) longer exposures needed for reinserted capsules;

(iii) insufficient lead factors in some plants.

The use of high fluence material test reactor (MTR) data is a preliminary step to life extension, but still high controversy exists on the use of MTR data to support life extension, in particular related to the "flux effects" issue.

1.5. ***Thermal Ageing***. Thermal ageing is not considered, in general, a problem for Western European RPV steels since the Ni content is relatively low. It is known that nickel enhances thermal embrittlement as a result of activation of segregation mechanisms.

For WWER-1000 RPV welds with high Ni the embrittlement dependency can be determined on the basis of tests results of thermal surveillance sets. If the time of thermal exposure is around 100,000 h, the DBTT shift amounts to approximately 20 K [8], however, a more pronounced thermal embrittlement cannot be excluded for exposure times typical for LTO (e.g., 450,000 h).

1.6. ***Master Curve and Unified Curve***. Currently there are two advanced approaches of fracture toughness evaluation, the Master Curve (MC) and the Unified Curve (UC), represented by the following equations:

$$K_{Jc(med)}^{MC} = 30 + 70\exp[0.019(T - T_0)],$$

$$K_{Jc(med)}^{UC} = 26 + \Omega\left(1 + \tanh\left(\frac{T - 130}{105}\right)\right).$$

The prediction of $K_{Jc}(T)$ curve for the RPV end of life may be non conservative when the MC is applied. One of the main differences between the MC and the UC is the shape of the curve. The MC is not affected by irradiation and the shape parameter is constant and equal to 0.019/°C, while for the UC the shape is changing with irradiation. When the degree of embrittlement increases the parameter Ω decreases. According to [9], the MC can be seen as a particular case of the UC.

1.7. ***Re-Embrittlement after Annealing***. The traditional models (lateral shift, vertical shift, etc.) on re-embrittlement after annealing are not able to describe the peculiar behavior of high phosphorus steels, as it is the case of WWER-440 high P welds. More general validation of re-embrittlement models based on studies of mechanical properties, as well as on microstructural investigations, is still needed. A better understanding of re-embrittlement mechanisms is essential for an accurate prediction. An attempt of integrated approach to this problem was made in [10].

Results of the PRIMAVERA project on "WWER-440 Welds Re-Embrittlement Assessment" show that current evaluation methods for embrittlement after annealing are adequate or conservative. Nevertheless some open issues remain: e.g., verification of PRIMAVERA results for low flux and high fluence irradiation and possible flux effects.

SANS investigations at a WWER-440 weld material revealed that re-irradiation after annealing causes clusters in the same size range as for the original irradiation, however, their formation strongly decelerates or saturates at a smaller volume fraction. The new clusters differ in composition from the original ones. The observed hardness change due to re-irradiation indicates that the obstacle strength of the re-irradiation-induced clusters is higher than that for the original irradiation [11].

2. **New Open Issues**.

2.1. ***Embrittlement Trend Curve at High Fluence***. There is a lack of embrittlement data at high fluence. 90% of existing data (75% of surveillance data) are for irradiation times of less than 15 years. In addition, some well known embrittlement trend curves, as for R.G. 1.99 Rev. 2 and 10CFR50.61a, have a tendency to under-predict more as fluence increases, and the same outcome is valid for test reactor irradiations.

It is not clear whether it is appropriate the direct use of high flux test reactor data to predict ΔT for high fluence – low flux conditions.

On the positive side it is worth to mention the trend curve model called "Charpy Master Curve," which has been developed recently by EPRI using a method of fitting raw Charpy data in a manner consistent with the Master Curve approach [12].

The "Coordinated PWR Reactor Vessel Surveillance Programme" is in progress in US and it intends to generate high-fluence surveillance data needed to develop embrittlement correlation for fluences representative through 80 years of operation.

2.2. ***The Expanding Beltline***. For 80 years or longer operation times some regions outside the beltline can accumulate nonnegligible neutron fluence. The chemical content of embrittling elements (Cu, Ni, P) may be higher than in the beltline, or unknown. In addition, materials from regions outside the traditional beltline may not be available for irradiation and testing. Sharing of data between plants of similar design and vendor is vital to address this issue.

Lack of material data may lead to a need to assign generic properties for extended beltline materials, and therefore lead to more restrictive pressure–temperature limit curves.

2.3. ***Monitoring Embrittlement during Life Extension***. The issue of monitoring embrittlement during life extension is directly related to the availability or non-availability of surveillance material. The use of miniature specimens and reconstitution techniques can help to solve or mitigate the situation. Other tools are the use of tailored or surrogate material or the participation of the plant in an Integrated Surveillance Programme.

Different surveillance strategies can be applied to increase the number of surveillance data at high fluence:

(i) testing a different capsule (with higher lead factor) than planned;

(ii) irradiate the standby capsules, if available, in positions with higher lead factor;

(iii) retain surveillance capsules in vessel for longer period of time, then increasing the neutron fluence accumulated by the capsule;

(iv) move the surveillance capsule to higher lead factor position in vessel;

(v) reinsert previously removed capsule for additional irradiation (using specimen reconstitution if needed);

(vi) manufacture new capsule if there exists an archive material.

3. **Research Needed for LTO**. European coordinated research on RPV embrittlement and LTO issues is addressed in the Euratom projects PERFORM-60 and LONGLIFE, which are key research projects of the NUGENIA Association (www.nugenia.org). NUGENIA is an association dedicated to the research and development of nuclear fission technologies, with a focus on Generation II and III nuclear plants. This research is complemented with several national programmes, as the Enhanced Surveillance Strategy (Belgium), the CARISMA and CARINA projects (Germany), the revision of embrittlement trend curves (France), etc.

The primary motive in US for reactor pressure vessel integrity is to ensure that plants can safely and efficiently operate through 80 years without significant operational constraints or mitigation of RPV embrittlement. The RPV integrity programme roadmap includes among others the following activities: late blooming phase embrittlement testing, development of surveillance database, develop coordinated surveillance capsule programme for PWRs, evaluate the impact of the extended beltline, etc.

Recommendations for future research were elaborated during the general assembly of the last IAEA-JRC specialists meeting on RPV embrittlement held in Znojmo in October 2010 [13]. The following is a non-exhaustive list:

(i) establish the relationship of microstructural variability and fracture toughness;

(ii) collection and analyses of the worldwide existing research and surveillance data;

(iii) use of RPV material data from decommissioned reactors for supporting LTO (low flux – high fluence);

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Open Issues for LTO

Issue	Importance for long term operation		
	Low	Medium	High
Chemical composition		×	
Late blooming effects			×
Flux effects			×
Spectrum effects	×		
Irradiation temperature effects	×		
MTR versus power reactor			×
Thermal ageing	×		
Master curve versus Unified curve			×
Re-embrattlement after annealing		×	
Embrittlement trend curve at high fluence			×
Expanding beltline		×	
Monitoring embrittlement during life extension		× →	

(iv) link nano-, micro-, and mesoscales and to study initiation and propagation of microcracks, including the mechanisms behind transgranular and intergranular propagation;

(v) develop procedure for construction of a design fracture toughness curve using concepts of Master Curve and Unified Curve focused on small specimens.

Table 1 lists the RPV issues discussed in the previous sections.

Conclusions. The RPV open issues are classified according to the importance for long term operation. Ongoing research is needed to ensure that the appropriate analytical tools and correlations are developed to analyse and model vessel integrity for safe and efficient operation through 60 years and beyond.

Резюме

Описано актуальні проблеми забезпечення безпечної роботи АЕС при продовженні термінів експлуатації, які широко обговорюються експертами даної галузі. До них, зокрема відносяться: ефекти запізнювання в сталях із низьким вмістом міді; вплив Cu, Ni, Mn і P на мікроструктуру, зміцнення і окрихчування опромінених сталей; використання результатів випробувань, отриманих у дослідном атомному реакторі, до промислових реакторів, включаючи ефекти флакса і спектра; зіставлення Master-кривої з уніфікованою кривою, а також особливості руйнування високоопромінених матеріалів; окрихчування матеріалів у зонах корпусів реакторів поза традиційними участками; побудова трендових кривих окрихчування для високого флюенса нейтронів за малого об’єму даних; повторне окрихчування після відпалу.

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