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POSITION PAPER ON RPV IRRADIATION EMBRITTLEMENT ISSUES BASED ON THE OUTCOME OF THE EURATOM FP7 PROJECT LONGLIFE

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ABSTRACT

A position paper on Reactor Pressure Vessel (RPV) irradiation embrittlement is introduced which was prepared on the initiative of the Nuclear Gen II & III Association (NUGENIA) and based on the outcome of the EURATOM FP7 project LONGLIFE from the perspective of Long Term Operation (LTO). As starting point an overview is given on the current state of knowledge with respect to the existing database, the most important embrittlement mechanisms, the irradiation induced change of mechanical properties, the impact of chemical composition, and to the flux affect. Following this, the scope of work, the most important microstructural and material testing results, and the final outcome of the LONGLIFE project are presented. In this context, relevant issues such as flux effects, high fluence behaviour, late irradiation effects, macroscopic heterogeneity, thermal aging, correlation of microstructure with mechanical properties, essential insights in microstructure, and the use of Embrittlement Trend Curves (ETC) are addressed. Appropriate measures for monitoring RPV irradiation embrittlement during LTO are also suggested and elucidated by practical applications. Finally, some open issues and the derived main research needs are presented, and the overall conclusions of the LONGLIFE project are summarized.

INTRODUCTION

During service RPV steels are exposed to neutron irradiation, which causes microstructural changes and a degradation of the mechanical properties. As the ages of existing NPPs are increasing and lifetime extensions and EOL up to 80 years for existing and new NPPs are on the agenda, some existing open issues regarding the understanding and prediction of RPV irradiation embrittlement need to be addressed. Especially for materials with higher contents of Cu, P, or Ni, irradiation embrittlement effects resulting from long irradiation times and high neutron fluences must be adequately considered in RPV irradiation surveillance and safety assessment. Up to now, high fluence data for original RPV materials are largely used in national research programs but the RPV surveillance database for long irradiation times (>20 years) and low neutron flux is sparse. Consequently, the treatment of long term irradiation effects is often afflicted with large uncertainties, requiring the assessment of appropriate data. In this context, the availability of microstructural data is essential for an improved understanding of the underlying mechanisms. The application of appropriate safety concepts, such as Master Curve, and of well-developed and validated prediction tools for irradiation embrittlement is also important for the implementation of any dedicated safety assessment approach and for making decisions with respect to the remaining economic lifetime of nuclear power plant (May et al. 2012). The position paper on RPV irradiation embrittlement was issued by NUGENIA Technical Area 4 “System and Component Integrity”.

OVERVIEW ON CURRENT STATE OF KNOWLEDGE

Database

The essential mechanisms of RPV irradiation embrittlement are well known and confirmed by experimental data obtained from RPV surveillance programs in which representative steels are irradiated in capsules, retrieved and then tested. Those capsules are located on the inside of the RPV near the core where the neutron flux is ideally several times higher than in the RPV beltline itself. In this way early estimates of RPV embrittlement can be provided in terms of material property data measured by tensile, Charpy-V and fracture toughness testing. Accelerated test-reactor irradiation programs have also been conducted to study irradiation embrittlement of RPV steels. Over decades, the test data have provided an increasingly large database for assessing and predicting irradiation embrittlement and for studying the underlying mechanisms. This notwithstanding, the data base for long irradiation times well beyond 40 operational years and high neutron fluences is sparse.

Embrittlement Mechanisms

The most important embrittlement mechanisms are matrix damage (lattice point-defects and their clusters, such as dislocation loops and vacancy clusters which may grow to nanovoids), formation of Cu-rich precipitates (CRP, with Ni, Mn, Si, …), formation of MnNi-rich precipitates (MNP, with Cu, Si, …) and P segregation on grain boundaries. According to Odette and Lucas (2001) the primary mechanism of embrittlement is the hardening produced by nanometer features that develop as a consequence of irradiation. The key embrittlement processes are illustrated in Figure 1.

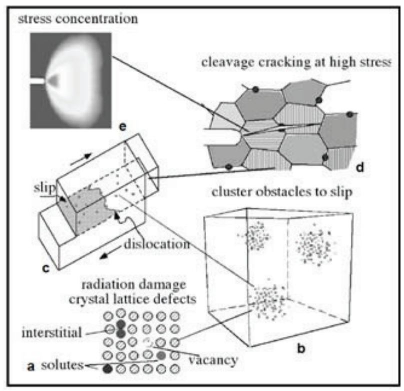


Figure 1: Basic embrittlement processes: (a) creation of primary radiation damage defects: (b) formation of nanoscale solute and defect clusters; (c) pinning of dislocations and hardening by nanofeatures; (d) hardening enhanced cleavage fracture; at a (e) stress concentration, Odette and Lucas (2001).

The above embrittlement mechanisms become significant for neutron fluences exceeding $1 \cdot 10^{17}$ n $\cdot$ cm^{-2} (E > 1 MeV) for which an irradiation surveillance program is required.

Irradiation induced change of mechanical properties

The above key embrittlement mechanisms are responsible for the increasing hardening and embrittlement with increasing neutron fluence, which results in higher DBTT (ductile brittle transition temperature, e.g. T_{41} from Charpy tests) as shown in Figure 2.

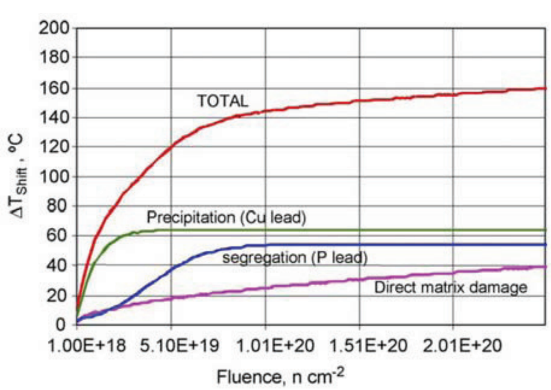


Figure 2: Scheme of irradiation embrittlement mechanisms calculated by a semi-mechanistic analytical model, Debarberis et al. (2002).

The relative importance of the three different mechanisms depends significantly on the chemical composition of the steel.

In a typical Light Water Reactor (LWR), the neutron flux ranges between approximately 10^9 and 10^{12} $n \cdot cm^{-2} \cdot s^{-1}$. For Western LWRs, neutron energies greater than 1 MeV are used for correlations, while 0.5 MeV is used as the threshold for WWER (Water-Water Energetic Reactor). RPV temperatures are usually in the range between ~260 to 300 °C. Regarding their effects on material properties, the ultrafine (nanometer) microstructural features (so-called nanofeatures) act as effective obstacles which require increased stress to move dislocations through or around them. As radiation exposure increases, the volume fraction of ultrafine scale obstacles increases and higher stresses are required for dislocation motion with a resulting increase in the yield strength of the material. In this context the efficiency of different kinds of obstacles that contribute to the total hardening, the correct interaction model, and the rule of superposition are the issues of interest; all these issues can nowadays receive valuable support from physical models and computational physics modelling tools. The increase in yield strength means that higher temperatures are necessary to keep the yield strength below the cleavage fracture strength, especially near the tip of a crack where large stress and strain concentrations exist. Thus, the DBTT is increased, which is the measure used to describe the radiation-induced embrittlement (shifts ΔT_{41} and ΔT_0 usually). For some steels, non-hardening embrittlement can be caused by radiation-induced solute segregation to grain boundaries. This type of embrittlement, frequently associated with segregation of phosphorous, can manifest itself as intergranular (grain boundary) fracture, rather than the usual transgranular cleavage fracture, IAEA (2009).

Concerning the development of predictive models, the synergistic effects of neutron fluence, flux and spectrum, irradiation temperature, chemical composition and the initial microstructure of the steel must be understood in order to minimize uncertainties. Some variables play a more important role than others, e.g. composition and temperature play a first order role to determine embrittlement versus fluence, and neutron spectrum and initial microstructure play, if any, a second order role, whereas neutron flux is a key variable to be understood due to its importance in order to transfer data from Material Test Reactor and surveillance to LTO.

The most common mechanical properties and their measured quantities are summarized in IAEA (2009). In addition to those mechanical properties, there are common reference fracture toughness indices used for RPV steels such as RT_{NDT}, RT_{T0} and T_k which are used in various ways to normalize fracture toughness of RPV steels. Changes in the physical properties of RPV steels are minimal, IAEA (2009).

Impact of chemical composition

Copper has the greatest effect on irradiation sensitivity, but nickel and phosphorus are also strong contributors, IAEA (2009):

- Copper is one of the elements that has the most deleterious effects on the irradiation-induced embrittlement of RPV steels. This effect appears from a copper content of about 0.04% (when the solution is supersaturated at RPV operating temperatures) and becomes very strong above 0.1%.
- Nickel effects have been extensively studied from the beginning of the 1980s. This element has a strong, and so far not fully explained, deleterious impact on irradiation-induced embrittlement of RPV steels. This impact may become very significant for nickel contents higher than about 1 or 1.2% and increases with the copper content in a synergetic way.
- Phosphorus has a well known deleterious effect on thermal ageing of ferritic steels due to its propensity to intergranular segregation. The phenomenon is known as thermal equilibrium segregation and is particularly significant in the temperature range 350 to 600°C. To limit or avoid this phenomenon, chemical compositions of ferritic steels have been optimized for many years (specification for P content, addition of Mo, etc.).
- Manganese has not yet been the subject of many dedicated experimental studies. Consequently, its impact on irradiation-induced embrittlement is not so well characterised. Thermodynamics and experimental studies have shown that, in operation, manganese can integrate with copper-rich

precipitates. It also participates in the Ni/Mn rich clusters that might or not be precursors for late blooming phases if any. The effect of Mn was thoroughly reviewed by Jones (2011).

Most of the irradiation predictive formulas around the world variously include copper, nickel and phosphorus contents, IAEA (2009).

Flux effect

Many experiments have been carried out to assess flux effects on irradiation-induced embrittlement of RPV steels. The interpretation of available data is not straightforward due to a large variety of experimental conditions (ranges of flux, chemical composition, etc.). For NiMnMo steels containing standard levels of Ni and Mn, it was agreed that three different scenarios are of interest, IAEA (2009):

- For steels containing a low level of copper (Cu less than about 0.1%), there is no significant flux effect in a range of flux below a threshold value (about 10^{12} n · cm^{-2} · s^{-1}, E > 1 MeV at 290°C) and irradiation temperatures between 150 and 300°C;
- For steels containing a significant amount of copper and irradiated to relatively low fluence (before the saturation of copper-related hardening), three regimes are expected according to the range of flux. One can expect a flux dependence at high (≥7 · 10^{10} n · cm^{-2} · s^{-1}, E > 1 MeV at 290°C) and low (no consensus on the threshold) flux regions, and a regime of flux independence at intermediate fluxes;
- For steels containing a significant amount of copper and irradiated to relatively high fluence (after the saturation of copper-related hardening), results support the flux independence of the copper-related hardening in the saturation region. If the flux is not too high (lower than approximately 10^{12} n · cm^{-2} · s^{-1}, E > 1 MeV at 290°C), the total hardening should be dose independent.

For steels containing high levels of Mn and Ni (>1.2%), results are too sparse to draw conclusions. However, it is noteworthy that results yielded by Williams and co-workers show that the embrittlement of low copper steels (Cu < 0.1%) with 1.6% Ni and 1.2–1.7% Mn is flux independent, IAEA (2009).

SUMMARY OF THE LONGLIFE PROJECT

Scope of work

The 4-year project LONGLIFE (Treatment of long-term irradiation embrittlement effects in RPV safety assessment) was initiated under the EURATOM 7th Framework Programme of the European Commission in 2010 as an umbrella project of NULIFE (Network of Excellence for Nuclear Plant Life Prediction), later integrated in NUGENIA, with the purpose of assessing the relevance of high neutron fluence and flux effects in RPV steels, in connection with the envisaged extension of NPP lifetimes from 40 up to 80 years. The consortium consisted of 16 European research organizations and industrial companies. The project aimed at improved knowledge of LTO phenomena relevant for European LWRs, the assessment and proposed improvements of prediction tools, codes and standards, and the elaboration of best practice guidelines on RPV irradiation surveillance.

The experimental investigations in terms of material testing and microstructural analyses were based on 16 pre-selected materials classed into various RPV material groups with both base and weld materials chosen for their significant sensitivity to specific long term irradiation effects, including one RPV steel from a decommissioned plant (EDF-1), see Table 1 and Table 2. Most of the pre-selected materials are representative of Western LWRs and WWER reactors in operation, Hein et al. (2013).

The technical work comprised the analysis of LTO boundary conditions, microstructural investigations and supplementary mechanical tests on RPV steels, training activities, and elaboration of recommendations for RPV materials assessment and embrittlement surveillance under LTO conditions.

Table 1: LONGLIFE materials and experimental matrix, Altstadt [1] (2014).

ANP-2 P60	WM S3NiMo1	MTR	AP, SANS, TEM FT	Representative Western LWR
ANP-6 / RAB1	WM S3NiMo	MTR	AP, SANS, TEM, PAS	
ANP-5	WM 22NiMoCr3-7	MTR (evidence for flux effect)	SANS, PAS	
ANP-4 P60	BM 22NiMoCr3-7	MTR	SANS, TEM	
SCK-6	BM 22NiMoCr3-7	MTR	TEM, PAS Tensile	
EDF-1	BM 16MND5	Surveillance	AP, TEM	
EDF-2 P60	BM 16MND5	Surveillance	AP, SANS, TEM	
EDF-3 P60	WM 16MND5	Surveillance	AP, SANS, TEM	
FZD-1a	BM A533B high P (JPB)	MTR (evidence for LBE at T_{irr}=255°C)	AP, SANS, TEM, AES Tensile	Western LWR Special Effects
FZD-1b	BM A533B low P (JPC)	MTR (evidence for LBE at T_{irr}=255°C)	AP, SANS, TEM, AES Tensile	
FZD-2	WM 10KhMFT	Decomm. (Greifswald 4)	SANS, AES FT, SPT, Tensile, HV	VVER-440/230
VTT-1	WM 10KhMFT	Surveillance	SANS, TEM FT	
AEK-1	BM 15Kh2MFA	MTR Decomm. (Greifswald 8, unirr)	AP, SANS, TEM FT, HV	VVER-440/213
NRI-6	BM+WM 15Kh2MFA	Surveillance	TEM	
NRI-1	WM 5Kh2NMFAA	MTR	AP, TEM Impact, Tensile, HV	VVER-1000

Table 2: LONGLIFE materials and chemical composition.

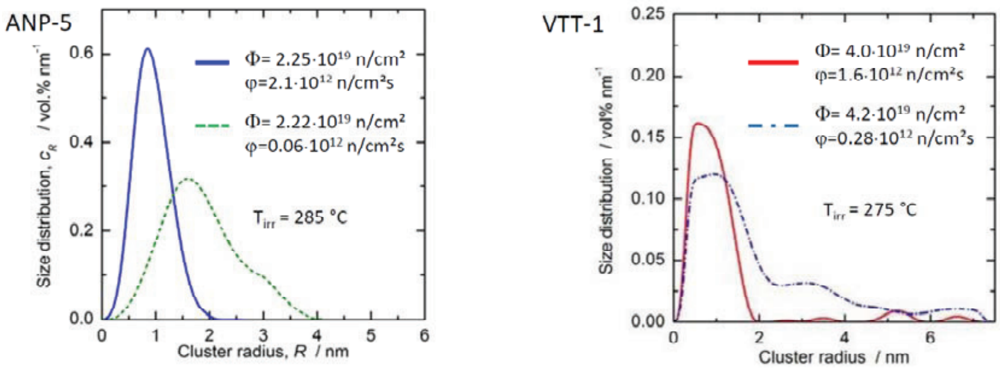
Code	Material	Chemical Composition [wt.%]									
		C	Si	Mn	P	S	Cr	Mo	Ni	Cu	V
ANP-2	WM S3NiMo1	0.05	0.12	1.08	0.019	0.009	< 0.10	0.62	1.01	0.03	0.01
ANP-6	WM S3NiMo	0.05	0.15	1.41	0.012	0.007	0.07	0.46	1.69	0.08	0.004
RAB-1	WM S3NiMo	0.052	0.21	1.46	0.009	0.006	0.07	0.5	1.58	0.08	0.002
ANP-5	WM NiCrMo1	0.08	0.15	1.14	0.015	0.013	0.74	0.6	1.11	0.22	0.01
ANP-4	BM 22NiMoCr3-7	0.21	0.22	0.85	0.006	0.006	0.39	0.55	0.84	0.05	<0.010
SCK-6	BM 22NiMoCr3-7	0.21	0.24	0.82	0.003	0.004	0.003	0.56	0.79	0.05	<0.010
EDF-1	BM 16MND5	0.169	0.31	1.27	0.01	0.005	0.15	0.39	0.65	0.09	0.02
EDF-2	BM 16MND5	0.138	0.22	1.32	0.006	0.006	0.2	0.54	0.69	0.064	<0.005
EDF-3	WM 16MND5	0.054	0.35	1.41	0.009	0.011	0.02	0.57	0.64	0.033	0.004
FZD-1a	BM A533B	0.2	0.24	1.3	0.020	0.004	0.17	0.57	0.74	0.027	0.005
FZD-1b	BM A533B	0.19	0.24	1.32	0.005	0.005	0.16	0.55	0.73	0.029	0.006
FZD-2	WM 10KhMFT	0.04	0.44	1.13	0.043	0.007	1.39	0.45	0.14	0.11	0.17
VTT-1	WM 10KhMFT	0.04	0.6	1.06	0.02	0.026	1.57	0.46	0.13	0.2	0.2
AEK-1	BM 15Kh2MFA	0.16	0.29	0.54	0.018	0.013	2.65	0.68	0.07	0.09	0.28
NRI-6	WM 15Kh2MFA	0.031	0.6	1.13	0.01	0.015	1.31	0.52	0.05	0.06	0.19
NRI-1	WM 5Kh2NMFAA	0.07	0.37	0.74	0.006	0.008	1.86	0.68	1.67	0.04	-

Discussion of results

Flux effect

A significant flux effect on microstructure was observed for high copper weld materials, however not in material properties (Figure 3). The SANS results indicated that the larger sizes and slightly higher volume fraction are consistent with the observed lower number density of clusters at the lower flux.

wt%	C	Si	P	V	Cr	Mn	Ni	Cu	Mo
ANP-5 (WM)	0.08	0.15	0.015	0.001	0.74	1.10	1.11	0.22	0.60
VTT-1 (WM)	0.04	0.6	0.02	0.2	1.57	1.06	0.13	0.2	0.46



Bergner et al. J. Phys. Cond. Matt. 20 (2008)
Reported flux effect confirmed in a 2nd SANS exp.
Flux ratio ≈ 35
No effect on T_{CVN} nor R_{p02}

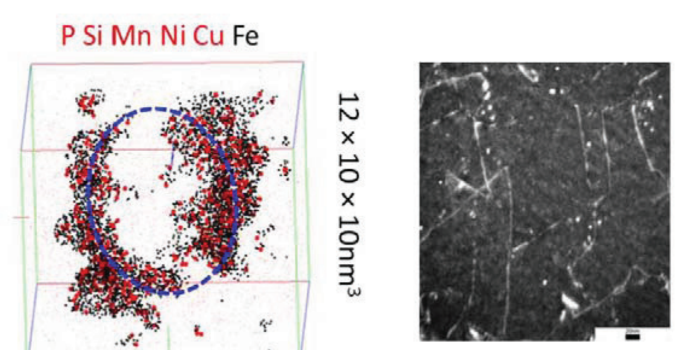
Flux effect on size distribution, but less pronounced than in ANP-5
Flux ratio ≈ 6

Figure 3: Flux effect on microstructure of high Cu weld materials, Altstadt et al. [1] (2014).

High fluence behaviour

With respect to the irradiation behaviour at high fluences, the following common trends have been observed in terms of microstructure (Figure 4):

- Irradiation damage comprises of a relatively low number density of heterogeneously distributed dislocation loops, a high number density of Mn, Ni, Si, Cu, P rich clusters and segregation of the same solutes along dislocation lines and dislocation loops. Voids are detected at high fluence.
- The chemical composition of the solute clusters seems to be independent of the fluence.
- There is an increase of cluster size (very slow growth) and number density with increasing dose, resulting in an increase of their volume fraction.
- No observation of saturation of the clustering process at high fluence.



Solute atoms EDF 2 irradiated at 6.95×10^{19}n.cm^{-2}. *[B. Radiguet LONGLIFE D3.3]*

Dislocation loops. TEM images EDF 2 irradiated at 6.95×1019n.cm-2. *[E. Meslin LONGLIFE D3.9]*

Figure 4: Different features observed by microstructural examinations, Altstadt et al. [1] (2014).

The mechanical test data (T_{41}) of the LONGLIFE materials confirms that no saturation of the irradiation embrittlement was observed at high fluence (Figure 5).

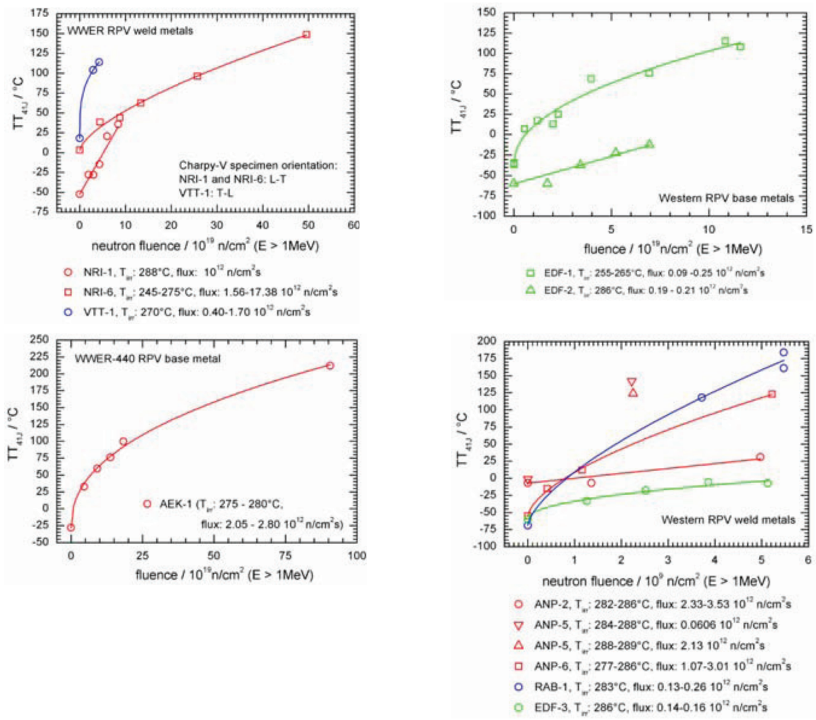


Figure 5: T_{41} data measured for LONGLIFE materials.

Late irradiation effects

There are controversial viewpoints on the existence or not of "Late Blooming Effects" (LBE) and whether they are really "Blooming" or not. For low-Cu steels it is not clear if the reason for LBE is the formation of clusters accelerating at high fluence or a delayed formation (incubation time). A visible LBE in terms of higher than expected irradiation embrittlement at higher fluences was measured for the material ANP-2 (low Cu, medium Ni/Mn content) in both microstructure and mechanical properties (Figure 6).

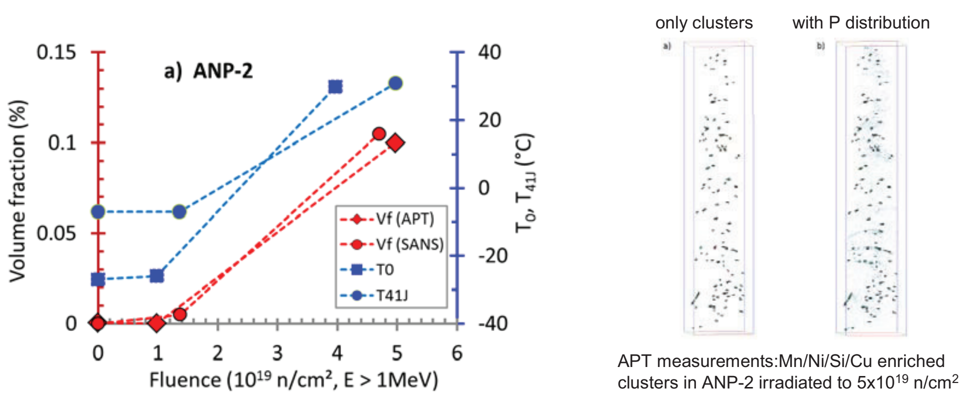


Figure 6: Volume fraction (by Atom Probe Tomography (APT) and Small-Angle Neutron Scattering (SANS) left) and cluster measurements (by APT, right) for LONGLIFE material ANP-2, Hein (2014), Altstadt et al [2] (2014).

Possible explanations for this unexpected material behaviour of ANP-2 are given in Hein (2014):

- Late Blooming Phases (may occur at high fluences, high Ni/Mn, low Cu, low T)
- Late irradiation effect (late acceleration but no new features)
- Scattering of data (inherent scatter of the Charpy and FT toughness test results)
- Impact of different take out locations of specimens used ("material variability")

With respect to LTO it is worth mentioning that a similar pattern of behaviour has been observed in surveillance measurements, as shown in Soneda (2014).

Macroscopic heterogeneity

An effect of macroscopic heterogeneity was observed in fracture mechanics testing of FZD-2 weld. In this case material inhomogeneities in the multi-layer weld are dominant over irradiation effects, Altstadt et al. [1] (2014).

Thermal aging

Concerning thermal aging appropriate data representative of 60–80 years of operation (range of 500,000 h) are still missing and no additional thermally aged RPV steels were available for the investigation in the LONGLIFE project.

Correlation of microstructure with mechanical properties and insights in microstructure

Further findings from the microstructural examinations in LONGLIFE are, Barthelmes and Hein (2014):

- Higher Cu, Ni, Mn and possibly Si contents will increase the number density and volume fraction of solutes clusters induced during neutron irradiation
- CRPs in Cu-rich materials (ANP-5, VTT-1)
- Materials with low alloying elements and impurities
    - Change in material properties mainly caused by matrix defects
    - Low number of precipitates/clusters (e.g. ANP-4, AEK-1)
- Volume fraction v_f and shift in T_{41} are correlated (approx.: $\Delta T_{41} \sim A^*\sqrt{v_f}$, where deviations from the correlation can be explained in terms of loops and nanovoids, e.g. in material AEK-1)

The high Ni (and Mn) content of weld material ANP-6 is responsible for the higher number density and volume fraction measured for this material where NiMnSi-rich clusters were found. More irradiation induced clusters with significant higher Ni and higher Mn, Si and Cu concentration were measured for ANP-6 compared to materials with lower Ni contents (see Figure 7).

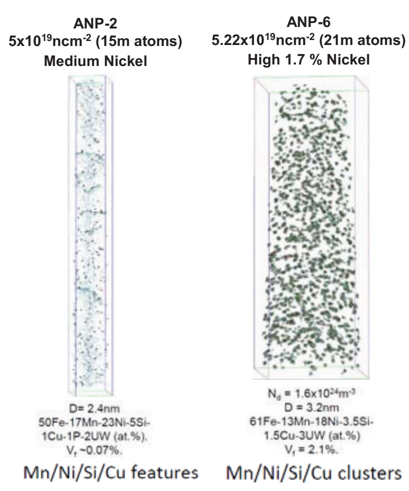


Figure 7: NiMnSi-rich clusters measure by APT for a low (left) and high (right) nickel weld, Barthelmes and Hein (2014).

Embrittlement Trend Curves (ETC)

Another point of interest is the application of Embrittlement Trend Curves (ETC). None of the existing ETCs predicts the temperature shift sufficiently for all materials with a clear tendency of underprediction of the irradiation embrittlement at higher fluences as can be seen in Figure 8. Beside the large scatter of the data there are limitations of the ETC models, e.g. all relevant chemical elements and the effect of microstructure are not explicitly considered, Altstadt et al. 1 (2014). Whilst, for example, existing trend curves such as 10 CFR 50.61a and Reg.-Guide 1.99 Rev. 2 represent well their databases, these do not extrapolate accurately the irradiation behaviour at high fluence and for low Cu materials, Kirk (2010).

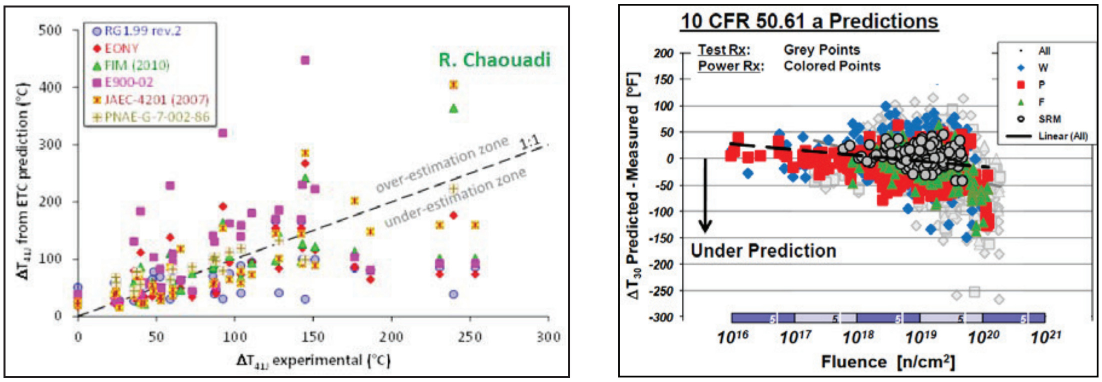


Figure 8: Application of ETCs to all LONGLIFE materials (left, Altstadt et al. [1] (2014)) and 10 CFR 50.61a predictions for RPV steels (right, Kirk (2010)).

Monitoring irradiation embrittlement during LTO

Finally, guidelines for monitoring irradiation embrittlement during LTO have been developed in LONGLIFE (Altstadt et al. [1] (2014), Hein (2014), Ballesteros et al. (2014)) including following issues:

- Reconstitution of specimens and further irradiation
- Use of miniature specimens
- Use of surrogate material
- Additional capsules with higher lead factors
- RPV dosimetry and temperature monitoring
- Withdrawal schedules
- Integrated surveillance programs
- Mitigation measures (if required and based on monitoring results)

CONCLUSION

The overall conclusions of the LONGLIFE project are, Altstadt et al. [1] (2014), Altstadt [2] (2014):

- Indications of LBE seem to exist in some cases, however clear criteria for occurrence/exclusion in terms of irradiation conditions and chemical composition could not be defined.
- Flux effects were observed on microstructure in some cases (high-Cu materials). However these were not accompanied by significant effects on mechanical properties.
- An effect of Phosphorus on hardening was observed.
- Experimental embrittlement and hardening curves do not show saturation at high fluences.
- In real welds, irradiation effects on mechanical behaviour can be swamped by the influence of inhomogeneous mesoscopic structural effects.
- The master curve shape validity issue is not relevant for most RPV applications.
- None of the existing trend curve models predicts accurately the entirety of LONGLIFE database (FIM, RG 1.99, E900-02, EONY, JAEC, PNAE-G7).
- Appropriate surveillance guidelines for LTO have been developed.

Some still open issues arising from LONGLIFE are the flux effect, the conditions of presence or absence of LBE, and the critical assessment of existing embrittlement trend curves. The so-called extended beltline issue should also be addressed for LTO because at longer operation times higher fluences are expected not only for the core beltline but also for an extended area where the fluence might exceed $1 \cdot 10^{17}$ n·cm^{-2} (E > 1 MeV). Moreover, the impact of the as delivered microstructure and of metallurgical macroscopic heterogeneities at initial state on the irradiation embrittlement should be clarified as well.

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REFERENCES

Altstadt, E. [1] (2014). "Welcome and overview of LONGLIFE," *LONGLIFE Final International Workshop*, Dresden, Germany.

Altstadt, E. [2] (2014). „Treatment of long term irradiation embrittlement effects in RPV safety assessment," Final publishable summary report, LONGLIFE D1.9 Final Report.

Altstadt, E., Serrano, M., Gillemot, F., Brumovsky, M., Hein, H., O'Donnell, I., Marcelles, I. [1] (2014). "Conclusions from LONGLIFE," *LONGLIFE Final International Workshop*, Dresden, Germany.

Altstadt, E., Keim, E., Hein, H., Serrano, M., Bergner, F., Viehrig, H.-W., Ballesteros, A., Chaouadi, R., Wilford, K. [2] (2014). "FP7 Project LONGLIFE: Overview of results and implications," *Nuclear Engineering and Design,* 278 753–757.

Ballesteros, A., Altstadt, E., Gillemot, F., Hein, H., Wagemans, J., Rouden, J., Barthelmes, J., Wilford, K., Serrano, M., Brumovsky, M., Chaouadi, R., Ortner, S. (2014). "Monitoring radiation embrittlement during life extension periods," *Nuclear Engineering and Design,* 267 197– 206.

Barthelmes, J., Hein, H. (2014). "RPV materials behaviour: Lessons learned from microstructural results and implications regarding optimized material design," *LONGLIFE Final International Workshop*, Dresden (Germany).

Debarberis, L., Kryukov, A., Gillemot, F., Acosta, B., Sevini, F. (2005). "Semi-mechanistic analytical model for radiation embrittlement and re-embrittlement data analysis," *International Journal of Pressure Vessels and Piping,* 82 195-200.

Hein, H. (2014). "Practical issues of RPV irradiation surveillance for LTO," *LONGLIFE Final International Workshop*, Dresden, Germany.

Hein, H., Keim, E., May, J., Schnabel, H. (2013). "Some recent research results and their implications for RPV irradiation surveillance under long term operation," *IAEA Technical Meeting on Degradation of primary components of Pressurised Water Cooled Nuclear Power Plants: current issues and future challenges*, Vienna, Austria.

IAEA (2009). Integrity of Reactor Pressure Vessels in Nuclear Power Plants: Assessment of Irradiation Embrittlement Effects in Reactor Pressure Vessel Steels. *IAEA Nuclear Energy Series No. NP-T-3.11*, Vienna.

Jones, R.B. (2011). "Influence of manganese on mechanical properties, irradiation susceptibility and microstructure of ferritic steels, alloys and welds," *International Materials Reviews 56* 167-206.

Kirk, M. (2010). "Comparison of Different Embrittlement Trend Curves," *IAEA Specialists' Meeting on Irradiation Embrittlement*, Znojmo, Czech Republic.

May, J., Hein, H., Altstadt, E., Bergner, F., Viehrig, H. W., Ulbricht, A., Chaouadi, R., Radiguet, B., Cammelli, S., Huang, H., Wilford, K. (2012). "FP7 project LONGLIFE: Treatment of long-term irradiation embrittlement effects in RPV safety assessment," *3rd International Conference on Nuclear Power Plant Life Management (PLiM) for Long Term Operations*, Salt Lake City.

Odette, G., Lucas, G. (2001). "Embrittlement of Nuclear Reactor Pressure Vessels,"*JOM* 53 (7) 18-22.

Soneda, N., Nakashima, K., Nishida, K., Dohi, K. (2013). "High Fluence Surveillance Data and Recalibration of RPV Embrittlement Correlation Method in Japan," PVP2013-98076, *Proceedings of the ASME 2013 Pressure Vessels and Piping Conference PVP2013*, Paris, France.