Hot Laboratory Work for the CARINA project to Extend the Data Base for Fracture Mechanical Characteristics of Irradiated German RPV Materials – Status and Outlook

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Abstract

In the frame of the already completed project CARISMA "Determination of Fracture Mechanics Values on Irradiated Specimens of German PWR Plants" a data base was created for pre-irradiated original RPV steels of the four construction lines of German PWRs, which allowed to examine the consequences if the Master Curve (T_0) approach instead of the RT_{NDT} concept is applied to the RPV safety assessment. In the ongoing research project CARINA the experimental date base will be extended by additional representative materials irradiated under different conditions and with respect to the accumulated neutron fluences and specific impact parameters (neutron flux, chemical composition, manufacturing effects). Moreover, some of the specimen materials will be provided for microstructural examinations to get a complete picture of the irradiation behavior of the materials concerned. After a brief introduction of the objectives of the CARINA project an overview on the requirements of the hot laboratory work in terms of transport, specimen manufacturing and material testing is given and examples for realization are shown. Finally an outlook is given for future work.

Keywords: reactor pressure vessel steel, neutron irradiation, irradiation embrittlement, fracture toughness, crack arrest, master curve, RT_{NDT}, RT_{T0}, microstructure

1. Introduction

The proof of a sufficient safety margin against brittle fracture of the Reactor Pressure Vessel (RPV) is essentially for the safety of a Nuclear Power Plant. In Germany, usually the RT_{NDT} concept is applied for the RPV safety assessment according to the current set of rules of the German Nuclear Safety Standards Commission (KTA). In this concept a lower bound fracture toughness – temperature curve which was determined deterministically by measured data is adjusted for the concerned material by the specific adjusted reference nil-ductility temperature RT_{NDTj} for the brittle fracture transition.

Beside the RT_{NDT} approach the German regulation accepts the use of measured fracture toughness values and the reference temperature RT_{T0} for establishing a fracture toughness – temperature curve. The RT_{T0} (Master Curve) approach allows a direct determination of reference temperature by fracture mechanics tests and a more realistic transfer of the test results to the component behavior.

In order to compare the safety assessment by the RT_{NDT} concept and the Master Curve concept an experimental data base by tensile, Charpy-V impact, fracture toughness and crack arrest testing was created in the project CARISMA "Determination of Fracture Mechanics Values on Irradiated Specimens of German PWR Plants" [1] which was finished in 2008. This data base was obtained from 7 pre-irradiated materials being representative for the four German PWR construction lines. The materials have been irradiated at temperatures from 283 °C to 288 °C and fast neutron fluences from 6×10^{18} to 4×10^{19} n/cm^2 (E>1 MeV).

Finally, CARISMA revealed some remaining issues and the need of more data leading to the initiation of the follow-up project CARINA in 2008.

2. CARINA Overview

The research project CARINA "Extension of the Data Base for Fracture Mechanical Characteristics of Irradiated German RPV Materials - Application of the Master Curve Approach for Neutron Fluences in the Upper Bound" [2] has a duration of 4 years. The project is funded by the VGB (German utilities), the German Ministry of Economics and Technology (sponsorship number 1501357), NPP Gösgen (Switzerland) and NPP Ringhals/Vattenfall (Sweden).

The main objectives are:

- Extension of already existing CARISMA data base by additional materials irradiated to higher neutron fluences and different irradiation conditions (beyond 5×10^{19} n/cm², E > 1 MeV).
- Study of possible specific irradiation effects such as Late Blooming Phases and neutron flux by specimens irradiated in gradient capsules.
- Application of Master Curve approach to RPVs with longer operation times and beyond EoL, respectively.

Moreover, some of the specimen materials will be provided for additional microstructural examinations to get a complete picture of the irradiation behavior of the materials concerned.

Table 1 contains the specimen materials used for testing. The specimens were irradiated in the VAK test reactor and in a PWR, respectively.

Project	Material	Code	Type	Cu [%]	P [%]	Ni [%]
CARINA	22NiMoCr3-7 JSW (3rd generation, Pre Convoy)	P150	BM	0.05	0.008	0.83
CARINA	22NiMoCr3-7 JSW (3rd generation, Pre Convoy)	P150	HAZ	0.05	0.008	0.83
CARINA	22NiMoCr3-7 Klöckner (1st and. 2nd generation)	P151	BM	0.09	0.007	0.97
CARINA	22NiMoCr3-7 Klöckner (1st and. 2nd generation)	P151	HAZ	0.09	0.007	0.97
CARINA	Molytherme Electrode Sulzer (1st generation)	P152	WM	0.03	0.015	0.08
CARINA	20MnMoNi5-5 JSW (4th generation)	P142	BM	0.06	0.009	0.8
CARINA	S3NiMo1/OP41TT GHH (4th generation)	P142	WM	0.06	0.012	0.9
CARINA	S3NiMo3/OP41TT Udcomb (3rd generation)	P16	WM	0.08	0.012	1.69

Table 1: List of specimen materials

3. Hot Cells Laboratory AREVA NP GmbH

The Hot Cells Laboratory is part of the Radiochemical Laboratory consisting of following units:

- Radiochemistry
- Analytical chemistry
- Radiation metrology
- Hot Cells

The Hot Cells Laboratory is DAP (German German Accreditation System for Testing) accredited according to DIN EN ISO/IEC 17025:2005 and is well equipped for many kinds of material testing, specimens manufacturing, metallographic examinations, and other services:

Material Testing: Irradiation surveillance programs for LWR and research reactors, post irradiation examinations, failure analysis, radiation resistance (e.g. cables).

Specimens manufacturing: Tensile, Charpy, fracture mechanics (with mechanical and fatigue cracks) specimens, test pieces from tested specimens, reconstituted specimens with Electron Beam Welding (EBW), dimension measurements by digital phototechnique.

Metallographic examinations: Failure analyses, e.g. SG tubes, springs, screws, center ring pins, microstructure examinations on metallic materials and nuclear fuel, material development (e.g. for spacer grids) with examination of oxide layer, hydrogen content distribution and geometric change of components, specimen preparation for SEM and TEM examinations.

All-included Service: Provision of transport packages for highly radioactive specimens, organization and execution of transports, performance of examinations, evaluation and documentation, return/disposal of waste.

4. CARINA Hot Lab Work

<u>Disassembling of capsules and radiochemical analyses</u>

In order to make the specimens, the temperature monitors and neutron detectors available for testing, for visual inspection and for radiochemical analysis, respectively, the VAK capsules and the surveillance capsules were opened in the Hot Cells laboratory of AREVA NP GmbH in Erlangen (Figure 1).

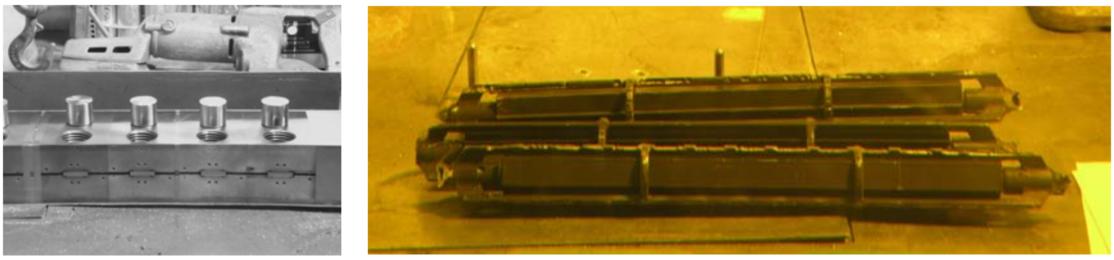

Figure 1: Dismantled VAK capsule and the surveillance capsules at state of delivery

As far as necessary the activity of the neutron fluence detectors was then determined by radiochemical analysis.

<u>Manufacture and testing of specimens</u>

An important part of the Hot Cells work is the preparation and manufacture of specimens, in particular the PCCV specimens used for T_0 testing and specific specimens used for crack arrest testing.

If necessary the PCCV specimens are manufactured by EDM from WOL specimens or by reconstitution technique from broken specimen halves. The fatigue crack is introduced by a high-frequency vibration load using a resonance testing machine.

Beside Compact Crack Arrest (CCA) specimens so-called Duplex specimens [3] are planned for crack arrest testing.

All welded seams are manufactured by Electron Beam Welding (EBW).

The testing of the specimens is another central point of the Hot Cells work with following material tests:

- Tensile tests according to DIN EN 10002
- Instrumented Charpy-V tests according to DIN EN 10045
- Fracture toughness (crack initiation) PCCV tests according to ASTM E-1921 (Figure 2)
- Crack arrest CCA tests according to ASTM E-1221 (or Duplex, ongoing qualification)

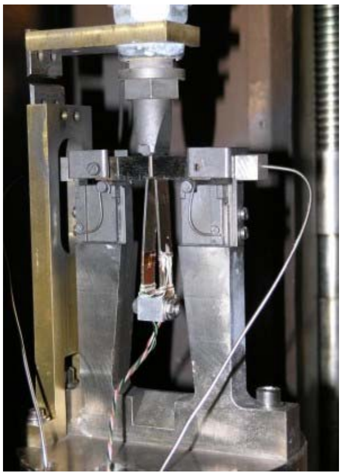

Figure 2: Testing of PCCV specimens

<u>Analytical examinations</u>

Due to the unexpected low irradiation embrittlement of P15X materials at 1.2×10^{19} n/cm^2 (E > 1 MeV) some analytical examinations have been performed with the aim to exclude some possible reasons for this behavior.

- Activity measurements (Co-60 in P150 BM) with the result that the activity follows the neutron fluence accumulated in the specimens
- Chemical analyses by Spark Emission Spectroscopy with the result of no significant deviations in chemical compositions of specimens

<u>Metallographic examinations</u>

Some metallographic examinations have been performed for the broken surfaces of the tested unirradiated P150 BM and P151 BM specimen materials made of 22NiMoCr3-7 steel. In Figure 3 is shown that the P151 BM (Klöckner) is more coarse-grained than the P150 BM (JSW) that underlines the impact of the manufacturing process on the microstructure.

P151 BM 140B ***P150 BM 71A***

Figure 3: Broken surfaces of the tested unirradiated P150 BM and P151 BM specimen materials

Moreover, the impact of non-metallic inclusions, found on surfaces of the unirradiated broken P150 BM PCCV specimens (Figure 4), on fracture toughness data was studied by reconstituted specimens. However no significant impact on fracture toughness was found.

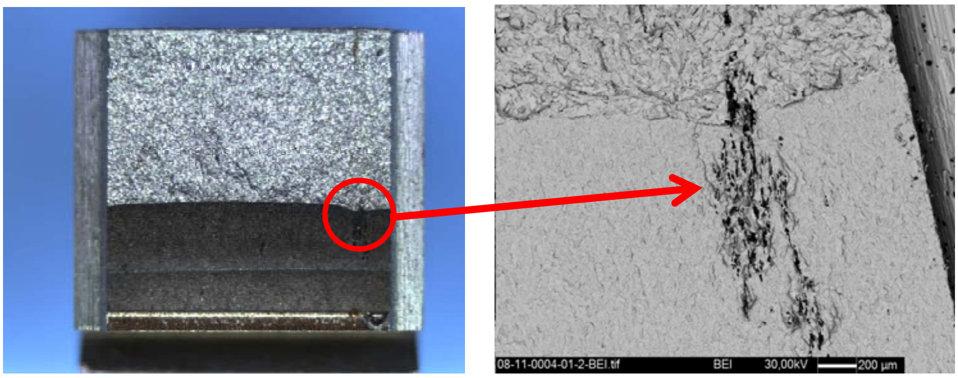

Figure 4: Broken surfaces of the tested unirradiated P150 BM and P151 BM specimen materials

<u>Microstructural examinations</u>

In order to better understand the mechanisms behind the irradiation embrittlement in RPV steels insights into the microstructure are important. Therefore, some of the specimen materials will be provided for microstructural examinations to get a complete picture of the irradiation behavior of the materials concerned. In particular three techniques are planned for application to assess the microstructural material changes caused by fast neutrons:

- Small Angle Neutron Scattering (SANS) in cooperation with German Research Center Dresden (FZD) and within EU FP7 project LONGLIFE
- Atom Probe Tomography (APT) within EU FP7 project LONGLIFE
- Transmission Electron Tomography (TEM) within EU FP7 project LONGLIFE (FP7) and by own R&D

In addition a dual-beam focused-ion-beam (FIB) microscope will be used if appropriate.

5. Status and Outlook

First results from fracture toughness testing and T_0 data from specimens irradiated in PWR standard surveillance capsules are available and indicate a low irradiation embrittlement. The CARINA specimens irradiated in the VAK reactor will be tested next. Moreover, the qualification of Duplex specimens for crack arrest testing is ongoing. In general progress of the work is on schedule to finish the project by 2012.

In the near future the activities for microstructural studies (SANS, APT, TEM) will be enhanced, the possibilities to use the FIB facility will be checked, and the installation of a new EBW machine is also planned.

6. Summary

In the research project CARINA the experimental data base for both the safety concepts RT_{NDT} and Master Curve will be extended by additional representative materials irradiated under different conditions and with respect to “Upper Bound” accumulated neutron fluences and specific impact parameters (neutron flux, chemical composition, manufacturing effects). The Hot Cells work is a focal point of the project, in particular capsule opening, radiochemical analysis, specimen manufacture, material testing, and analytical, metallographic and microstructural examinations.

In general the progress of the work is on schedule to finish the project by 2012.

7. References

[1] H. Hein, E. Keim, H. Schnabel, T. Seibert, A. Gundermann
"Final results from the CARISMA project on fracture mechanical assessments of pre-irradiated RPV steels used in German PWR", 24th ASTM Symposium on Effects of Radiation on Nuclear Materials and the Nuclear Fuel Cycle, June 24-26, 2008, Denver, Colorado

[2] H. Hein, J. Ganswind, A. Gundermann, E. Keim, H. Schnabel
PVP2009-77035: CARINA: A new project to extend the data base for fracture mechanical characteristics of irradiated German RPV materials at high neutron fluences
PVP 2009 ASME Pressure Vessels and Piping Division Conference, July 26-30, 2009, Prague, Czech Republic

[3] A. Gundermann, E. Keim, H. Hein, H. Schnabel
PVP2009-77025: Development of Duplex specimens for potential application in testing of highly irradiated weld metals
PVP 2009 ASME Pressure Vessels and Piping Division Conference, July 26-30, 2009, Prague, Czech Republic