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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Introduction

RPV safety assessment in Germany

- Beside RT\textsubscript{NDT} approach, German regulation accepts use of measured fracture toughness values and RT\textsubscript{T0} for establishing a $K_{IC}$, $T$-curve
- RT\textsubscript{T0} (Master Curve) approach allows direct determination of reference temperature by fracture mechanics tests
- More realistic transfer to the component behavior

CARISMA “Determination of Fracture Mechanics Values on Irradiated Specimens of German PWR Plants” finished in 2008

- Data base on 7 pre-irradiated materials being representative for the four German PWR construction lines
- Irradiation at 283 °C to 288 °C and 6×10\textsuperscript{18} to 4×10\textsuperscript{19} n/cm\textsuperscript{2} (E>1 MeV)
- Application of RT\textsubscript{NDT} and Master Curve based reference temperature RT\textsubscript{T0}
- Determination of Crack Arrest characteristics, some remaining issues

Initiation of follow-up CARINA due to need for more data
Follow-up 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”

- 2008 to 2012
- Support by VGB (German utilities), the German Ministry of Economics and Technology (sponsorship number 1501357), NPP Gösgen (Switzerland) and NPP Ringhals/Vattenfall (Sweden)

Objectives

- Extension of already existing CARISMA data base by additional materials irradiated to higher neutron fluences and different irradiation conditions (beyond $5 \times 10^{19}$ 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
### CARINA Overview

#### Materials

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

*CARINA 22NiMoCr3-7 JSW (3rd generation, Pre Convoy)
CARINA 22NiMoCr3-7 JSW (3rd generation, Pre Convoy)
CARINA 22NiMoCr3-7 Klöckner (1st and 2nd generation)
CARINA 22NiMoCr3-7 Klöckner (1st and 2nd generation)
CARINA Molytherme Electrode Sulzer (1st generation)
CARINA 20MnMoNi5-5 JSW (4th generation)
CARINA S3NiMo1/OP41TT GHH (4th generation)
CARINA S3NiMo3/OP41TT Udcomb (3rd generation)*
## CARINA Overview

### Test Matrix

<table>
<thead>
<tr>
<th>Code</th>
<th>Type</th>
<th>Estimated fluence [n/cm²] (E&gt; 1 MeV)</th>
<th>Tensile test irradiated</th>
<th>Charpy-V irradiated</th>
<th>KJc = f(T), T₀ unirradiated</th>
<th>KJc = f(T), T₀ irradiated</th>
<th>Crack Arrest Kᵢa</th>
</tr>
</thead>
<tbody>
<tr>
<td>P142</td>
<td>BM</td>
<td>4.3×10¹⁹</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
| P150  | BM     | 4.6×10¹⁸  
1.1×10¹⁹  
2.6×10¹⁹ | data available                      | data available          | yes               | yes                         | yes             |
|       |        |                                     |                         |                     |                             |                             |                 |
| P150  | HAZ    | 4.6×10¹⁸  
1.1×10¹⁹  
2.6×10¹⁹ | data available                      | data available          | yes               | yes                         | yes             |
|       |        |                                     |                         |                     |                             |                             |                 |
| P151  | BM     | 4.6×10¹⁸  
1.1×10¹⁹  
2.6×10¹⁹  
~3×10¹⁹ | data available                      | data available          | yes               | yes                         | yes             |
|       |        |                                     |                         |                     |                             |                             |                 |
| P151  | HAZ    | 4.6×10¹⁸  
1.1×10¹⁹  
2.6×10¹⁹  
~3×10¹⁹ | data available                      | data available          | yes               | yes                         | yes             |
|       |        |                                     |                         |                     |                             |                             |                 |
| P142  | WM     | 4.7×10¹⁹                           | yes                     | yes                 | yes                         | yes                         | yes             |
| P152  | WM     | 4.6×10¹⁸  
1.1×10¹⁹  
2.6×10¹⁹  
~3×10¹⁹ | data available                      | data available          | yes               | yes                         | yes             |
| P16   | WM     | 4.62×10¹⁹  
5.22×10¹⁹ | data available                      | data available          | yes               | yes                         | yes             |
Detailed project description and first results presented on PVP 2009 ASME Pressure Vessels and Piping Division Conference, July 26-30, 2009, Prague, Czech Republic

- PVP2009-77035: CARINA: A NEW PROJECT TO EXTEND THE DATA BASE FOR FRACTURE MECHANICAL CHARACTERISTICS OF IRRADIATED GERMAN RPV MATERIALS AT HIGH NEUTRON FLUENCES
  H. Hein, AREVA NP GmbH, Erlangen, Germany; J. Ganswind, VGB PowerTech e. V., Essen, Germany; A. Gundermann, E. Keim, H. Schnabel, AREVA NP GmbH, Erlangen, Germany

- PVP2009-77025: DEVELOPMENT OF DUPLEX SPECIMENS FOR POTENTIAL APPLICATION IN TESTING OF HIGHLY IRRADIATED WELD METALS
  A. Gundermann, E. Keim, H. Hein, H. Schnabel, AREVA NP GmbH, Erlangen, Germany
Hot Cell Laboratory
AREVA NP GmbH

- Radiochemical Laboratory
  - Radiochemistry
  - Analytical chemistry
  - Radiation metrology
  - Hot Cells

- Hot Cells Laboratory
  - Material Testing
  - Specimens manufacturing
  - Metallographic examinations
  - All-included Service
  - DAP accreditation according to DIN EN ISO/IEC 17025:2005

AREVA NP GmbH

Hot Laboratory Work for the CARINA project – Hieronymus Hein
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Hot Cell Laboratory
AREVA NP GmbH

» Hot Cells Laboratory

◆ 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 EBW
  • Dimension measurements by digital phototechnique
Hot Cell Laboratory
AREVA NP GmbH

Hot Cells Laboratory

- 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
CARINA Hot Lab Work
Disassembling of Capsules

- Opening of Capsules
  - VAK and surveillance capsules
  - Temperature monitors
  - Fluence detectors

- Radiochemical analysis
  - Activity of neutron fluence detectors

Dismantled VAK capsule

Surveillance capsules, state of delivery
CARINA Hot Lab Work
Manufacture of Specimens

- **PCCV specimens used for \( T_0 \) testing**
  - Manufactured by EDM
  - Fatigue crack introduced by a high-frequency vibration load using a resonance testing machine

- **Compact Crack Arrest (CCA) and Duplex specimens for Crack Arrest testing**

Manufacture of PCCV specimen
CARINA Hot Lab Work
Manufacture of Specimens

- Reconstitution technique
CARINA Hot Lab Work
Testing of Specimens

- Tensile
  - DIN EN 10002

- Charpy-V
  - Instrumented DIN EN 10045

- Crack initiation
  - PCCV according to ASTM E-1921

- Crack Arrest
  - CCA according to ASTM E-1221
  - Duplex (ongoing qualification)

Testing of PCCV specimens
Unexpected low irradiation embrittlement of P15X materials at 1.2×10^{19} \text{n/cm}^2 (E > 1 \text{ MeV})

- Activity measurements (Co-60 in P150 BM) → activity follows the fluence
- Chemical analyses by Spark Emission Spectroscopy → no significant deviations
Metallographic Examinations

- 22NiMoCr3-7 steel: Broken surfaces of the tested unirradiated P150 BM and P151 BM specimen materials
  - P151 BM (Klöckner) is more coarse-grained than the P150 BM (JSW)
  - Underlines the impact of the manufacturing process on the microstructure
Impact of non-metallic inclusion (found on surfaces of the unirradiated broken P150 BM PCCV specimens) on $K_{jc}$ data studied by reconstituted specimens ➔ no significant impact
CARINA Hot Lab Work
Microstructural Examinations

- **SANS**
  - CARISMA materials (by FZD)
  - CARINA materials planned (by FZD)

- **APT**
  - Planned in LONGLIFE (FP7)

- **TEM**
  - Planned in LONGLIFE (FP7) and by own R&D

- **FIB**
  - Dual-beam focused-ion-beam (FIB) microscope
  - Feasibility study
Status and Outlook

Status

- First results from fracture toughness testing and $T_0$ data from specimens irradiated in PWR standard surveillance capsules are available (low irradiation embrittlement)
- CARINA specimens irradiated in the VAK reactor will be tested next
- Ongoing qualification of Duplex specimens for crack arrest testing
- In general progress of the work is on schedule to finish the project by 2012

Outlook

- Enhanced activities for microstructural studies (SANS, APT, TEM)
- FIB
- Installation of a new EBW machine
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).

Focal point on Hot Cells work

- Capsule opening
- Radiochemical analysis
- Specimen manufacture
- Material testing
- Analytical, metallographic and microstructural examinations

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