MANUFACTURING AND TESTING OF SPECIMENS OF THE PROJECT "CARISMA" AT FRAMATOME ANP HOT CELL LABoratory

***Hilmar Schnabel*, Hieronymus Hein, Elisabeth Keim, Reinhard Langer**

Framatome ANP GmbH, P.O. Box 3220, 91050 Erlangen, Germany
hilmar.schnabel@framatome-anp.com

ABSTRACT

A fracture mechanics database on irradiated materials of German PWR shall be developed for qualification of the production specific influences. Several original materials of the four generations of German nuclear power plants will be investigated. They have been irradiated in six large scale irradiation capsules in a German research reactor (the VAK plant) at corresponding plant conditions. The capsules contain regular tensile and Charpy impact specimens as well as Pellini and fracture toughness specimens up to a specimen thickness of 100 mm.

With the project CARISMA (Crack Initiation and Arrest of Irradiated Steel Materials) parts of these specimens will be used to create a data base of fracture toughness and arrest values with the original materials in different irradiated conditions.

The project also benefits from qualified experiences concerning the reconstitution technique for specimens, the T_0-test technique and the crack arrest test technology for reconstituted specimens in the hot cell test labs.

First examinations of the project have been completed like disassembling the capsules, taking out the specimens, activity measurements on fluence detectors, some fluence calculations, and some material tests.

An overview about the equipments, necessary for the manufacturing and the mechanical technological examinations of different kind of specimens and materials in the hot cells is presented.

KEY WORDS CRACK ARREST, FRACTURE TOUGHNESS, GERMAN PWR, IRRADIATION EMBRITTLEMENT, MASTER CURVE, MATERIAL TESTING, RT_{NDT} CONCEPT, RPV INTEGRITY

1. INTRODUCTION

For reasons of making provisions for the nuclear power plants built by Siemens/KWU six large capsules with specimens from original RPV base and weld materials were irradiated some years ago in the VAK reactor.

With the project CARISMA (Crack Initiation and ARrest of Irradiated Steel MAterials) parts of these specimens will be used to create a data base of fracture toughness and arrest values with the original materials in different irradiated conditions. They will allow for a direct comparison of two procedures for the proof of equivalent safety margin against brittle fracture of the RPV. The first procedure is based on rules-concurring Charpy tests, whereas the second one is related to brittle fracture characteristics derived from fracture mechanical tests. At present the current set of rules of the German Nuclear Safety Standards Commission (KTA) requires no determination of fracture mechanical characteristics.

Based on a comprehensive test matrix the database is created for un-irradiated and irradiated specimens for RPV base and weld materials of all four German PWR generations by tensile and Charpy tests and fracture toughness K_{Jc} testing to obtain the transition temperature T_0. The irradiated materials taken from original RPV base and weld materials were irradiated in the VAK reactor some years ago to neutron fluences of $6\ 10^{18}$ and $4\ 10^{19}\ cm^{-2}$.

The test data will allow for identifying manufacture conditioned parameters influencing the irradiation behaviour of RPV materials. The obtained results are assessed with respect to the effects of the T_0-concept (Master Curve) on the safety assessment of German RPV materials with un-irradiated and irradiated specimens including a comparison of the safety assessment by the RT_{NDT}-concept and by the T_0-concept. Moreover, it will be investigated to what extent crack arrest values can be provided for irradiated material.

CARISMA is financed by the VGB (association of German NPPs and NPP Gösgen), the German Ministry of Economy and Labour, NPPs Trillo (Spain) and Borssele (Netherlands) and Framatome ANP GmbH.

2. OBJECTIVE

The main objective of the CARISMA project is to create a comprehensive experimental data base for un-irradiated and irradiated specimens for real RPV base and weld materials of all four German PWR generations by tensile and Charpy-V tests and fracture toughness K_{Jc} testing to determine the transition temperature T_0. The original RPV materials covering all manufacturing lines and being representative for the plants in operation.
Finally, the project allows:

- to determine material and manufacture specific influences on fracture toughness properties
- to determine fracture toughness properties for both crack initiation and arrest
- to find a comparison of the safety assessment by the RT_{NDT}-concept and the Master Curve concept in the context with the present status in the KTA standard (Germany Nuclear Safety Standards Commission)
- to clarify some open issues like
  the identification of appropriate specimen shapes and sizes
  the proof of suitability of small pre-fatigued Charpy-specimens for T_0 determination

3. IRRADIATION FACILITY

Six large capsules have been irradiated in the German VAK reactor (Figure 1) in the years 1983 and 1985 in the frame of a research project for ensuring the RPV integrity considering possible changes in concept designs and plant life extension measures.

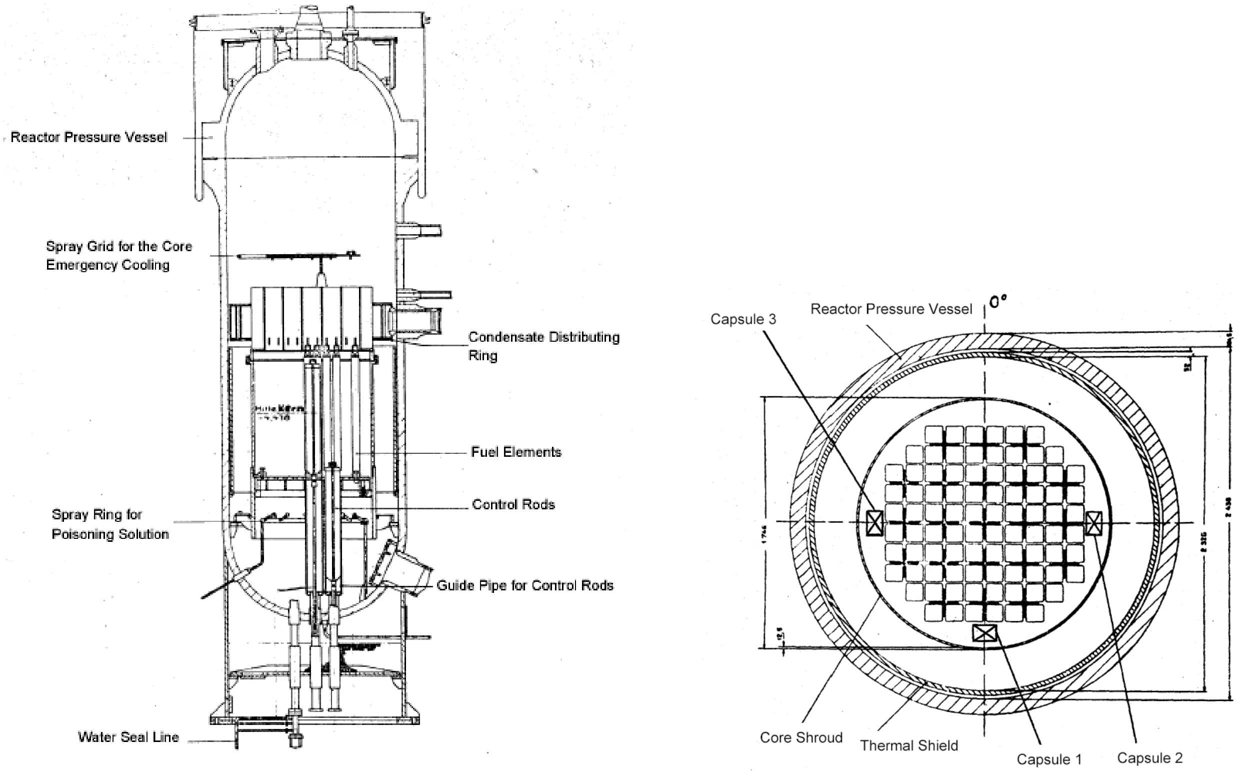


Figure 1. VAK reactor

The VAK reactor was operated by the German utility RWE. The reactor was used additionally from 1975 up to 1985 by Siemens/KWU (its nuclear group was the predecessor of Framatome ANP GmbH) as irradiation facility for different research and surveillance programmes. The VAK reactor which was closed in 1985 was a small Experimental Boiling Water Reactor with an electric power of about 15 MW.

The neutron spectrum of the VAK reactor was comparable to the other Siemens/KWU PWRs, but at the capsule positions (Figure 1) the neutron flux density of about $2{\cdot}10^{12}$ cm^{-2} s^{-1} (E>1 MeV) was higher than at the surveillance position of power reactors. The irradiation temperature in the reactor was about 285 °C.

The VAK RPV had three inner irradiation positions (90°, 180° and 270°) and the capability to irradiate large capsules of 965 mm length with a square of 100 mm x 146.5 mm corresponding to dimensions of WOL-100X specimens.

4. MATERIALS AND SPECIMENS

The six large capsules containing the original materials from the VAK irradiation programme are at present stored in the hot cell laboratory of Framatome ANP in Erlangen, Germany. Figure 2 shows an opened capsule with a row of WOL-100X (wedge opening load) specimens.

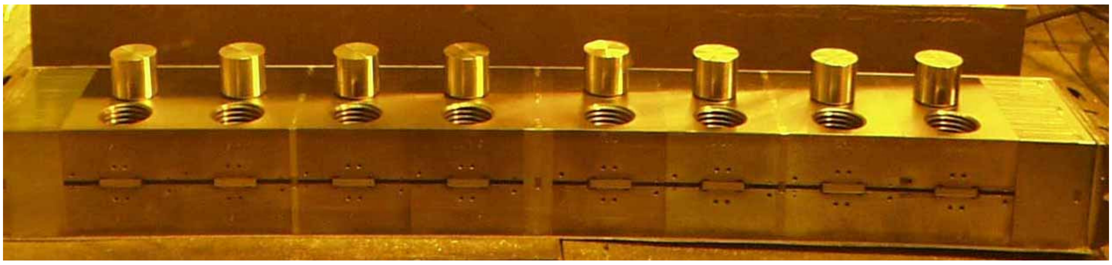


Figure 2. pened capsule with a row of WOL-100X specimens.

A large number of specimens is available mainly from the six large capsules as shown in Table 1 and also from former VAK irradiation programmes. The neutron fluences of the different irradiated base and weld materials were in the range of $6{\cdot}10^{18}$ and $4{\cdot}10^{19}$ n/cm^2 (E>1 MeV).

5. Experimental plan

At present 7 materials were selected for testing as shown in Table 1.

Table 1. Test matrix for the CARISMA project

Material data			Irradiated							Un-irradiated
			Basis data		Fracture toughness data					
					Crack initiation			Crack arrest		Crack initiation
Estimated fluence in cm^{-2}	Project	Material	Tensile test	Impact test	K_{Jc}	K_{Jc} T_0	K_{Jc} T_0	K_{Ia}		K_{Jc} T_0
6,00E+18	P141	Base	3 Tensile	12 Charpy-V	8 10x10 SE(B)	8 10x10 SE(B)		12 CCA		8 10x10 SE(B)
4,30E+19	P7	Base	3 Tensile	10 Charpy-V		8 10x10 SE(B)		12 CCA		8 10x10 SE(B)
1,20E+19	P147	Base			8 10x10 SE(B)	8 10x10 SE(B)	8 25x50 SE(B)	12 CCA		8 10x10 SE(B)
6,00E+18	P141	Weld	3 Tensile	12 Charpy-V		8 10x10 SE(B)		12 CCA		
6,00E+18	P16	Weld	3 Tensile	12 Charpy-V	8 10x10 SE(B)	8 10x10 SE(B)	6 WOL-25 X	12 CCA		
4,00E+19	KS05	Weld				8 10x10 SE(B)		12 CCA		
2,20E+19	P370	Weld			8 10x10 SE(B)	8 10x10 SE(B)	4 WOL-100 X			8 10x10 SE(B)

These materials are characterised by different kinds of base and weld materials. The material testing will be carried out on irradiated and un-irradiated specimens. The basic characterisation will comprise tensile and Charpy impact tests

The data of tensile, Charpy-V, fracture toughness and CCA (compact crack arrest) tests will be used for the RT_{NDT} and Master Curve concepts to get the following characteristic quantities:

- $T_{28,\ 41,\ 68}$: Transition temperature for the KV-T Charpy curve at an absorbed energy of 28J, 41J, 68 J
- RT_{NDT} : Reference Nil Ductility Transition Temperature
- K_{Jc}: Fracture toughness
- T_0: Reference temperature of the Master Curve (50 % mean value at 100 Mpa√m)
- T_{4kN}: Crack arrest temperature at F_a=4kN (crack arrest) from C_v instrumentation plots
- K_{Ia}: Crack arrest toughness value

Reconstituted specimens will be used where insufficient material for specimens is available. There are very good experiences with the reconstitution technique for broken C_v-specimens using electron beam welding at Framatome ANP. There is also no influence on the transition temperature T_0 obtained by full size and reconstituted specimens as was shown in the RESQUE project [1].

5.1. Experimental results Charpy-V and tensile specimens

All Charpy tests and tensile test were done and the relevant parameters calculated. With the results of the tested Charpy V specimens the KV-T curves of all relevant projects and materials were created according to KTA 1302.

The tensile specimens were examined by test temperatures in the area of the fracture toughness examinations. Therefore you have the associated yield stress value for all relevant test temperatures of the later T_0- and CCA examinations.

The KV-T curve and one part, the yield stess versus test temperature curve of the tensile tests is shown in shown in Fig. 3.

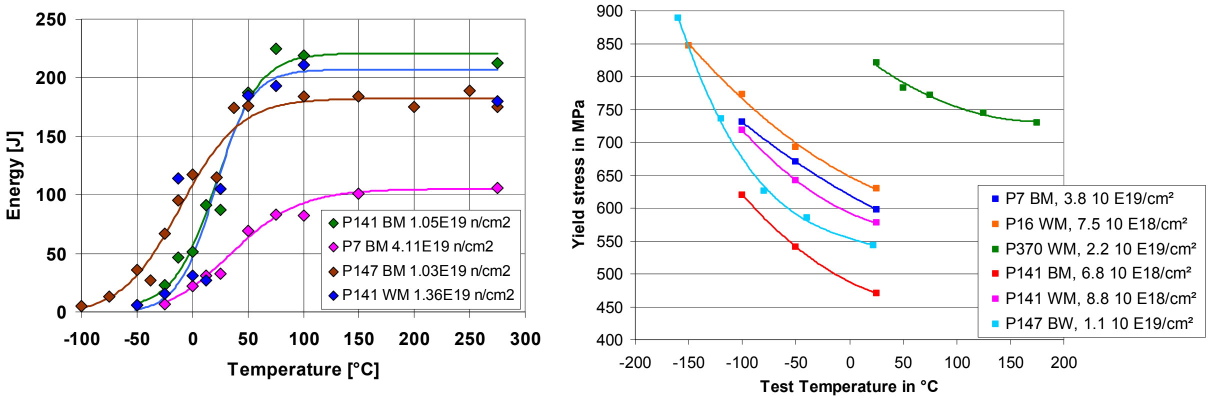


Figure 3. Results of the Charpy-V tests and the results of the yield stess versus test temperature curve of the tensile tests

5.2. Experimental results T_0 examination, project P370, WOL-100X specimens

The objective of the tests was the measurement of fracture toughness in the ductile to brittle regime and to determine the reference temperature T_0 according to the standard ASTM E1921-03. For this purpose results of existing measurements could be used as well as four new tests on 100 mm thick WOL 100X specimens.

The fracture toughness tests are shown in Figure 4. All results are normalized to a crack length of 25 mm. The old results of WOL X specimens with 50 mm thickness are marked with the small symbols and the new obtained results with the 100 mm thick specimens are the larger symbols. A T_0 of 103 °C is calculated for this weld material in the irradiated condition.

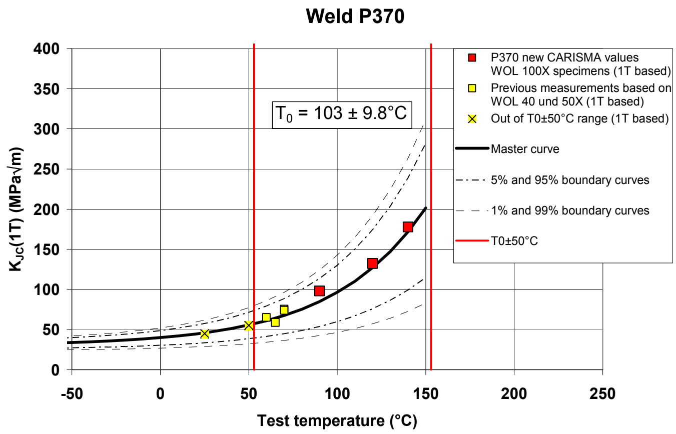


Figure 4. Fracture toughness curve of the irradiated weld material.

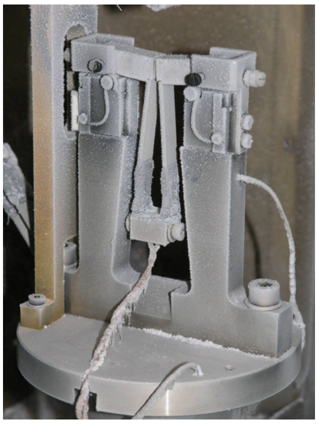
5.3. 10x10 SE(B) (single–edges notched bend bar) specimens

The objective of the tests was the measurement of fracture toughness in the ductile to brittle regime and to determine the reference temperature T_0 according to the standard ASTM E1921-05. For this examination standard 10x10 SE(B) specimens made from Charpy-V specimens und reconstituted 10x10 SE(B) specimens were used. EDM was used to create the following mechanical work:

- an 0.3 mm-deep crack starter notch in addition to the 2 mm Charpy-V notch by the standard specimens
- a 2 mm-deep crack starter notch by the reconstituted specimens

- and a 1.4 mm-deep 45° dovetail for the knife edge by both.

High-frequency loadings on a resonance testing machine was used to induce the fatigue crack to achieve a final crack length of appr. 5 mm. Two vertical 45° side grooves with a notch radius of 0.5 mm and each with a depth of 1 mm manufactured by EDM completed the SE(B) specimen.



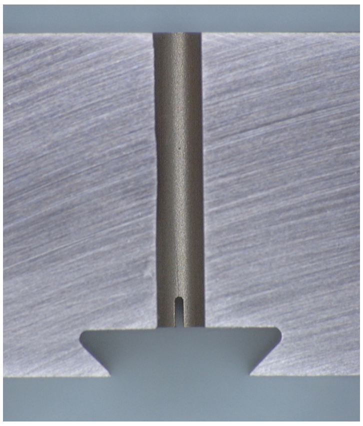


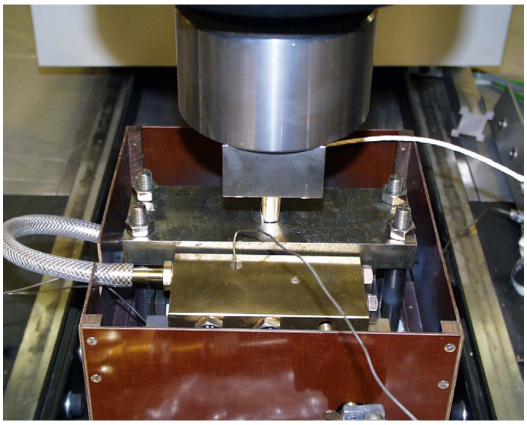
Figure 5 Test facility for 10x10 SE(B) specimens and detail side view of a 10x10 SE(B) specimen

5.4. Crack arrest examinations

Another important experimental task will be the measurement of crack arrest toughness values by the aid of crack arrest specimens according to ASTM E1221 standard. The appropriate CCA specimens will be manufactured out of test-ready WOL-100X specimens. The pre-fatigued crack of the WOL-100X will be removed and substituted by a brittle weld with an mechanical notch as crack starter notch. The weld is produced by electron beam welding.

Aim is, to produce CCA specimens with the maximum size. By means of EDM, 4 reconstituted CCA specimens will be manufactured out from one WOL-100X. Aim is, to produce CCA specimens with the maximum size.

In difference to the prior shown examinations these CCA specimens are made from un-irradiated material. These pre-tests on un-irradiated base material have been performed to qualify the test procedure. All work was done under hot cell conditions.



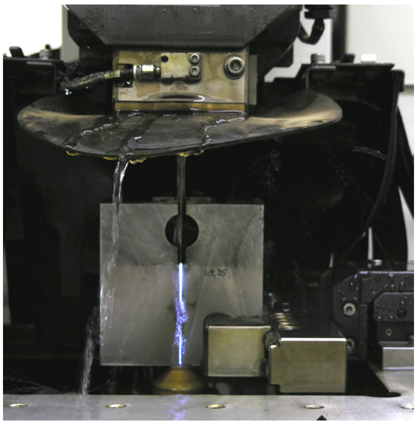


Figure 6. Test facility for CCA specimens and manufacturing of the side grove by EDM

6. Project status

- Activity measurements and fluence calculations are finished
- Existing data for un-irradiated materials have been collected
- Tensile and Charpy-V tests including KV-T curves for irradiated materials are completed
- K_{Jc}-testing and T_0 determination for irradiated WOL-100X specimens made by weld material is completed
- The K_{Jc} tests for T_0 determination with 10x10 SE(B) specimens have been started
- Successful pre-tests on reconstituted un-irradiated material to qualify crack arrest test facilities are done

The next step is the manufacturing of reconstituted CCA specimens from irradiated WOL-100X specimens and the K_{Jc}-testing and T_0 determination for irradiated WOL-25X specimens.

7. CONCLUSIONS

With the project CARISMA a data base will be created for a direct comparison of the two procedures RT_{NDT} concept and Master Curve concept for the proof of equivalent safety margin against brittle fracture of the RPV. The database is created for un-irradiated and irradiated specimens for RPV base and weld materials of all four German PWR generations by tensile and Charpy-V tests and fracture toughness K_{Jc} testing to obtain the transition temperature T_0. The materials taken from original RPV base and weld materials were irradiated in the VAK reactor some years ago to a fluence of $6{\cdot}10^{18}$ and $4{\cdot}10^{19}$ cm^{-2}.

Moreover, it will be investigated to what extent crack arrest values can be provided for irradiated materials. For that purpose, it is intended to determine crack arrest characteristics for the typical RPV materials and it will be checked if and how crack arrest can be integrated into the new safety concept based on T_0. The project also benefits from qualified experiences concerning the reconstitution technique for specimens, the T_0-test technique in both conventional and hot cell test labs, and the crack arrest test technology for reconstituted specimens with test inserts manufactured from irradiated WOL-100X specimens.

8. ACKNOWLEDGEMENT

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