Post Mortem Investigations of the NPP Greifswald WWER-440 Reactor Pressure Vessels

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ABSTRACT

The investigation of reactor pressure vessel (RPV) materials from decommissioned NPPs offers the unique opportunity to scrutinize the irradiation behaviour under real conditions. Trepans taken from the whole RPV wall enable a comprehensive material characterisation. The paper describes the trepanning technology applied to the decommissioned WWER-440/230 RPVs of the Greifswald NPP. The Greifswald RPVs represent different material conditions such as irradiated, irradiated and recovery annealed and irradiated, recovery annealed and re-irradiated. The working program is focussed on the characterisation of the RPV steels (base and weld metal) through the RPV wall. The key part of the testing is aimed at the determination of the reference temperature T_0 following the ASTM Test Standard E1921-05 to determine the fracture toughness of the RPV steel in different thickness locations. In a first step the material of the core welding seam was investigated. It could be shown that the Master Curve approach as adopted in E1921 is applicable to the investigated original RPV weld metal. The weld metal located in a distance of about 22 mm from the inner surface of the RPV wall yielded a T_0 of 50°C which is about 40K higher than T_0 close to the inner surface. This outcome is important for the assessment of results retrieved from so called boat samples taken directly from the RPV surface after the recovery annealing. It shows that boat samples do not represent the material with the lowest toughness.

INTRODUCTION

Nuclear plant operators must demonstrate that the structural integrity of a nuclear reactor pressure vessel (RPV) is assured during routine operations or under postulated accident conditions. The aging of the RPV steels is monitored with surveillance program results. Radiation loading, metallurgical and environmental histories, however, can differ between surveillance and RPV materials. Accordingly, the most realistic evaluation of the toughness response of RPV material to irradiation is done directly on RPV wall samples from decommissioned NPPs. Such a unique opportunity to evaluate the state of a standard RPV design and to assess the quality of prediction rules and assessment tools is now offered with material from the decommissioned Greifswald NPP (WWER-440/230). The four Greifswald NPP units were shutdown in 1990 after 11 – 17 years of operation [1,2]. Table 1 presents the operation characteristics of the units 1 to 4 and the expected neutron fluencies. RPVs in three different conditions are available:

- Unit 1 is irradiated, annealed and re-irradiated (IAI)
- Units 2 and 3 are irradiated and annealed (IA)
- Unit 4 is irradiated.

Table 1. Operation Characteristics and Expected Maximum Neutron Fluences of Greifswald Units 1 to 4

unit	operation period		effective days	annealed in	azimuthal maximum of $\mathbf{N}_{E>1MeV}$ in units of 10^{19} n/cm^2			
	date	cycles			inner wall axial maximum	inner wall weld 4	outer wall axial maximum	outer wall weld 4
1	1974-1988	15	4205.0	1988	3.8	2.6	0.7	0.38
1*	1988-1990	2	627.4	-	0.08	0.07	0.02	0.01
2	1975-1990	14	4067.4	1990	5.3	4.1	0.83	0.60
3	1978-1990	12	3581.8	1990	4.4	3.4	0.68	0.50
4	1979-1990	11	3207.9	not	4.0	3.1	0.62	0.45

* re-irradiated

The well documented different irradiation/annealing states of the four decommissioned Greifswald RPVs [2] allows the validation of material properties under long term, low flux irradiation, during industrial recovery annealing and during subsequent re-irradiation. In autumn 2005 the first trepans were extracted from Unit 1 of this NPP. This paper presents the results of the investigation of the first trepan taken from the RPV weld with the highest fast neutron load.

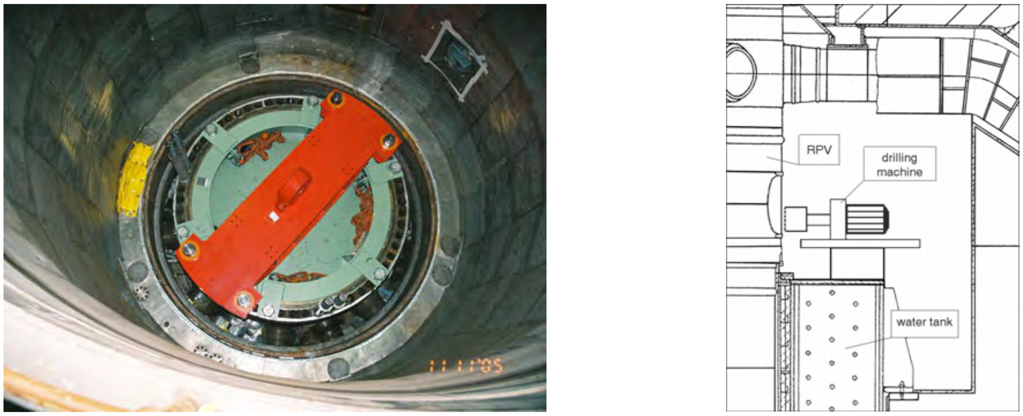
TREPANNING PROCEDURE

Trepanning Technology

The trepans were taken with a specially designed trepanning device which enables the following actions:

- labelling of the position and orientation of the trepan,
- drilling and ejection of the trepan into the RPV, and
- closing the hole in the RPV.

This trepanning device was mounted outside the RPV at the height of the coolant loops on the top of the water tank (Fig. 1). The water tank has a shielding function and additionally forms the fundament of the RPV. As the nozzles of the RPV had been cut off during the decommissioning, the RPV could be lifted and rotated by crane towards the predefined positions of the trepans. Before the actual drilling event, the selected position was marked by a vertical line (to identify/reassign orientation afterwards) and numbered (to distinguish the trepans from each other). The trepan was drilled using an air-cooled hollow milling tool featuring an extractor fan for drilling chip removal. Then, the trepan was pushed into the RPV. Finally, the remaining hole in the RPV wall was then sealed by a lead plug. All of the aforementioned actions were remote-controlled. The diameter of the trepan is 119 mm over the whole RPV wall thickness. By thermographic measurement it was proven that the maximum temperature never exceeded 190°C in vicinity of the drilling region and 80°C within the trepan itself.



a) **b)**

Fig. 1 RPV of Greifswald Unit 1: a) top view with biological cover and lifting beam; b) location of the trepanning device on the water tank

Location of the Trepans in the RPV of Greifswald Unit 1

The RPV of Unit 1 was recovery annealed at 475°C for 152 hours within the region of circumferential welding seam SN0.1.4 in 1988 and operated for another two years (Table 1). During the annealing treatment a belt region of 0.7 m above and below the welding seam SN0.1.4 was heated on 475°C. Fig. 2 shows the location of the trepans taken from the RPV of Greifswald Unit 1. Trepans were taken from the circumferential welding seam SN0.1.4., and the base metal ring 0.3.1. Table 2 contains the location, the estimated neutron fluencies of the trepans and the maximum temperatures during the annealing procedure in the location of the trepans. The neutron flux through the RPV was calculated [1] with TRAMO [3], which is a multi-group Monte Carlo code for neutron and gamma transport calculations.

Table 2 RPV Steels, Irradiation and Annealing Conditions of the Trepans Sampled from Greifswald Unit 1

code	RPV material	location		condition	inner wall fluence (E>1MeV) in 10^{18} n/cm^2	maximum annealing temperature in °C
		axial$^{)1}$ in mm	azimuthal in grd			
1-1	weld metal SN0.1.4	-6850	330	IAI	29.4	475
1-2	weld metal SN0.1.4	-6850	270	IAI	29.4	475
1-5	weld metal SN0.1.4	-6850	90	IAI	29.4	475
1-4	base metal ring 0.3.1.	-6430	330	IAI	>29.4	475
1-3	base metal ring 0.3.1.	-4440	300	U	<0.07	<300

IAI irradiated, annealed, irradiated after annealing
U unirradiated

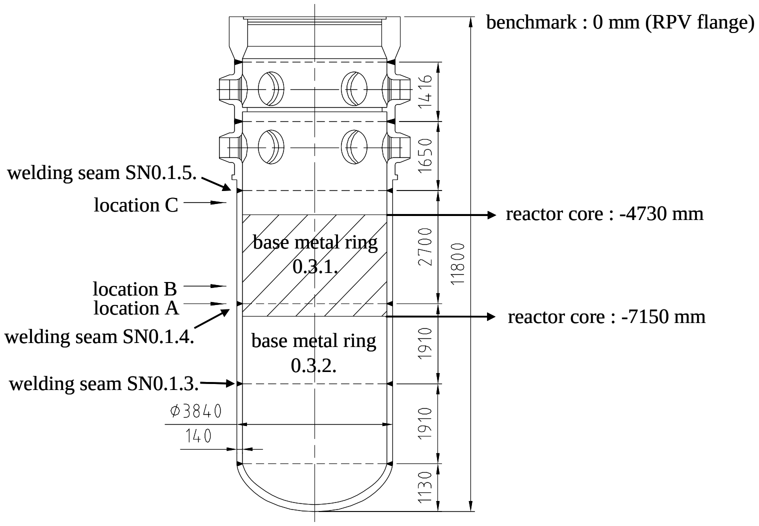


Fig. 2 RPV VVER 440 Greifswald Unit 1 and locations of the sampled trepans

MATERIAL AND SPECIMENS

At first the trepan 1-1 representing the IAI condition of the welding seam SN0.1.4. was investigated. The welding seam SN0.1.4. is a multilayer submerged weld. The welding seams of the WWER-440 RPVs consist of a welding root welded with an unalloyed wire Sv-08A and the filling material welded with the alloyed wire Sv-10KhMFT. Table 3 contains the chemical composition of the weld metal within trepan 1-1 in different thickness locations and the specifications of the manufacturing protocol [2]. The chemical compositions measured at the 3 locations of the welding seam belong to the alloyed filling material and generally agree with the information in the manufacturing protocol. The copper and phosphorus contents are within the range as specified in the manufacturing guidelines of the WWER-440 generation 1 (model 230), but both are clearly higher than in the specification of next generation (model 213) with maximum allowed P and Cu contents of 0.01% and 0.1%, respectively [4].

Table 3 Chemical Composition of Trepan 1-1 (Mass %)

No. disc	thickness location*1 mm	C	Si	Mn	Cr	Ni	Mo	V	P	Cu
protocol*2		0.05	0.47	1.22	1.48	0.23	0.41	0.16	0.037	0.103
1-1.1	8			1.06	1.49	0.22	0.40	0.14	0.044	0.125
1-1.3	22			0.97	1.35	0.19	0.43	0.14		0.141
1-1.12	94			0.93	1.23	0.22	0.40	0.09	0.028	0.141

*1 distance of disc centre from the inner surface
*2 manufacturing protocol of the RPV Unit 1 - welding seam SN0.1.4

The trepan 1-1 was cut in into discs with a thickness of 10 mm using a wire travelling electro-erosion discharging machine (EDM). From one disc 10 Charpy size SE(B) specimens were machined. Fig. 3 shows the trepan and Fig. 4 exemplifies the cutting scheme [of the disc 1-1.1]. The location of the welding seam within trepan 1-1 was metallographically examined and is schematically depicted in Fig. 3. The welding root is located within a distance of about 60 mm to 80 mm relative to the inner RPV wall.

The Charpy size SE(B) specimens were pre-cracked (a/W=0.5) and 20% side-grooved. As shown in Fig. 4 the orientation of the SE(B) specimen is TS (specimen axis axial and crack growth direction across the vessel wall) according to ASTM E399. The TS orientation is in correspondence with the surveillance specimens in Russian WWER-440/213 reactors. From the broken halves of the tested SE(B) specimens Charpy V-notch specimens according to DIN EN 10045-1 (1991) “Metallic Materials: Charpy Impact Test; Part 1: Test Method” and EN ISO 14556 (2000) “Steel – Charpy V-Notch Pendulum Impact Test – Instrumented Test Method” were manufactured by reconstitution technique.

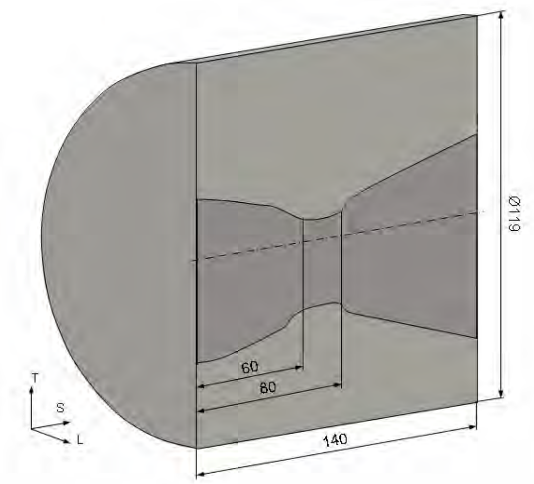


Fig. 3 Trepan 1-1 with the location of the welding seam

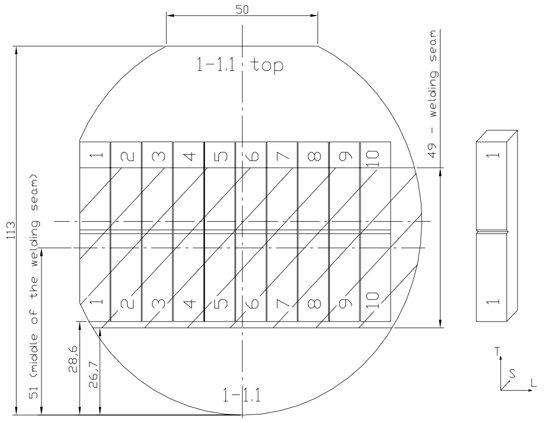


Fig. 4 Cutting scheme of disc 1-1.2 as an example

TESTING AND EVALUATION

The investigation of the trepans of base and weld metal comprises the following through-wall basic characterisation:

- cleavage fracture toughness values and Master Curve based reference temperatures (T_0),
- J-Δa curves and ductile initiation fracture toughness values,
- full Charpy-V transition curves,
- tensile properties,
- hardness HV10 properties,
- chemistry profiles, more in detail for weld than for base metal and
- metallographic characterization.

In a first step SE(B) specimens from five discs with thickness locations shown in Table 4 were tested and evaluated according to ASTM E1921-05 “Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range”. The pre-cracked and side-grooved Charpy size SE(B) specimens were monotonously loaded until they failed by cleavage instability. Standard MC reference temperatures T_0 were evaluated with the measured J integral based cleavage fracture toughness values, K_{Jc}, applying the multi temperature procedure of ASTM E1921-05. In addition, the “Structural Integrity Assessment Procedures for European Industry”, SINTAP, containing a modification of the MC analysis were used for the evaluation of the measured K_{Jc}- values. The SINTAP lower tail analysis contains three steps, and guides the user towards the most appropriate estimate of the reference temperature, T_0^{SINTAP}, describing the population having the lower toughness [5,6].

In addition J_R-curve testing was performed according to ASTM E1820-06 “Standard Test Method for Measurement of Fracture Toughness” and ESIS-P2 “ESIS Procedure for Determining the Fracture Behaviour of Materials”. Charpy size SE(B) specimens were partially unloaded to determine the crack extension. The J_R-curve and therefrom the engineering fracture toughness at 0.2 mm crack extension was evaluated according to ESIS-P2.

Instrumented Charpy V-notch impact tests on reconstituted specimens were performed according to DIN EN 10045-1 (1991). The impact energy, lateral expansion and fracture appearance temperature curves were fitted by tanh approach. Charpy-V parameters as transition temperatures and the upper shelf energy were evaluated. The Charpy-V tests have not been completed yet and only results of disc 1-1.1 are already available.

RESULTS AND DISCUSSION

Table 4 summarises the Master Curve (MC) and Charpy-V test results of the investigated discs of trepan 1-1. The table also contains the location of the discs within the trepan and the calculated neutron fluencies in the centre of the discs. The test results comprise the reference temperatures evaluated according to ASTM E1921-05 (T_0) and the SINTAP procedure (T_0^{SINTAP}), as well as the Charpy-V transition temperature at an impact energy of 41J (TT_{41J}) and upper shelf energy (USE). T_0 data presented in Table 4 and depicted in Fig. 5 vary through the thickness of the trepan 1-1 and, thus, the welding seam. Along the wall thickness, T_0 shows a wavelike behaviour. After an initial increase of T_0 from 10°C at the inner surface to 49°C at 22 mm distance from it, T_0 again decreases to -41°C at a distance of 70 mm, finally increasing again to 20°C at 94 mm from the centre. The lowest T_0 values were measured on SE(B) specimens from discs 1-1.6 and 1-1.9 located in the root region of the welding seam. Fig. 6 shows the K_{Jc} values versus the test temperature normalised to T_0 of the individual discs. The K_{Jc} values generally follow the course of the MC, though the scatter is large.

Nevertheless, the K_{Jc} values are close to or above the 2% fracture probability line. However, more then 5% of the K_{Jc} data fall below the 5% fracture probability lower bound ($K_{Jc(0.05)1T}$) curve. That strongly indicates that the material is not fully homogeneous, which is not unusual for the investigated multilayer weld metal.

Table 4 Location of the investigated discs within trepan 1-1, neutron fluences, MC test results according to ASTM E1921-05 and Charpy-V parameter

code disc	distance from inner surface (centre disc)	neutron fluence (E>1MeV)			ASTM E1921 - 05		SINTAP	Charpy-V	
		before*	after*	total	T_0	σT_0	T_0^{SINTAP}	TT_{41J}	USE
	mm	10^{18} n/cm^2	10^{18} n/cm^2	10^{18} n/cm^2	°C	K	°C	°C	J
1-1.1	8.3	24.23	0.71	24.93	10.3	6.4	32.5	51.4	130.8
1-1.3	21.9	21.47	0.64	22.11	49.1	6.3	49.1		
1-1.6	42.3	16.89	0.51	17.40	-5.0	6.4	-5.0		
1-1.9	69.9	11.63	0.36	11.99	-40.7	6.4	-13.6		
1-1.12	93.8	8.21	0.26	8.47	19.8	6.3	40.9		

* annealing

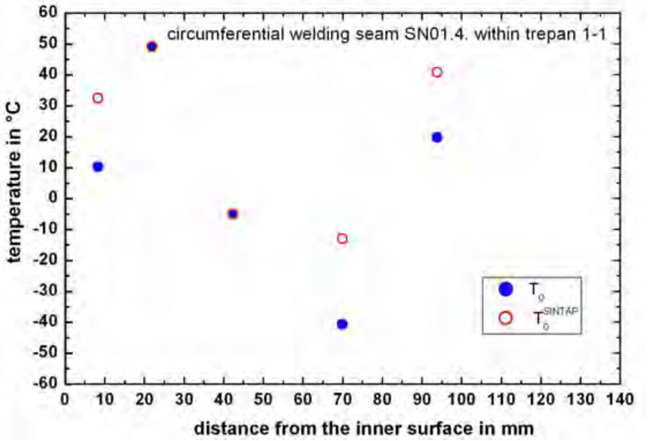


Fig. 5 Course of the reference temperatures T_0 and T_0^{SINTAP} through the welding seam SN0.1.4.

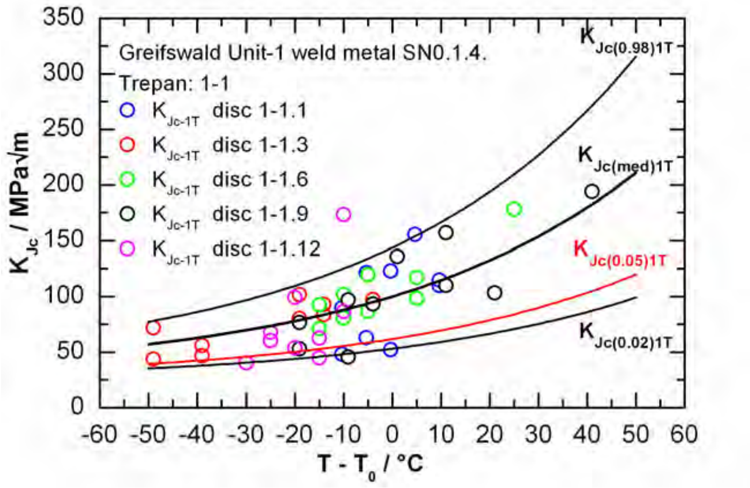


Fig. 6 K_{Jc} values measured on Charpy size SE(B) specimens, adjusted to 1T (25.4 mm) specimen size, versus the test temperature normalised to T_0 of the individual discs, and Master Curves

The SINTAP MC evaluation enables conservative lower bound type fracture toughness estimates also for inhomogeneous materials. As shown in Table 4 the SINTAP MC evaluation gives reference temperatures T_0^{SINTAP} for the discs 1-1.1, 1-1.9 and 1-1.12 clearly higher than the standard T_0. The course of T_0^{SINTAP} through the welding seam SN0.1.4. in Fig. 5 also shows the lowest values in the root region and an increase from the inner surface to 22 mm distance within the filling layers. The filling layer (disc 1-1.12) beyond the root has a T_0^{SINTAP} value comparable with disc 1-1.3.

Table 4 also contains the Charpy-V parameters ductile-to-brittle transition temperature TT_{41J} and upper shelf energy of disc1-1.1. There are no Charpy-V data available from the weld metal SN0.1.4. in the initial condition. The evaluated TT_{41J} of 51°C is close to the so called "critical embrittlement temperature" for the initial condition, T_{K0}, of welding seam SN0.1.4. reported in the manufacturing protocol as 46°C. The evaluated upper shelf energy is on the level expected for WWER-440 weld metal. The estimated "critical embrittlement temperature" in the irradiated condition, T_K, before the annealing in 1988 is reported as 186°C [2,7]. To determine T_K after recovery annealing of the RPV 6 mm thick compact specimen samples were cut from the inner wall of the welding seam SN0.1.4. by means of an EDM machine in 1988. Sub size KLST (3 mm·3 mm·27 mm) impact specimens according to DIN EN 10045-1 (1991) were machined from those compact specimens. The orientation of the KLST specimens was TL (specimen axis axial and crack growth direction circumferential). Using the KLST specimens a ductile-to-brittle transition temperature at an impact energy of 1.9 J, $TT_{1.9J}$, of -35°C was determined for the inner surface of the welding seam SN0.1.4. [7]. That $TT_{1.9J}$ of -35°C can be converted into a Charpy V-notch transition temperature as follows: $TT_{41J} = TT_{1.9J} + 65K = -35°C + 65K = 30°C$. The scatter of this correlation ± 35K is rather high [8] and therefore the uncertainty of the applied conversion likewise. The TT_{41J} determined with standard Charpy V-notch specimens and reported in Table 4 is 51°C. Taking into account the difference in the orientation of the specimens and the re-irradiation of two cycles the TT_{41J} estimated with KLST specimens after the recovery annealing is realistic. In this case the re-irradiation causes an increase of TT_{41J} by 21K.

As shown in Table 4 and Fig. 5 the highest value of the MC T_0 was not determined at the surface layer. There is a difference of about 40K between the locations 8 mm and 22 mm distant from the inner surface of the welding seam SN0.1.4.. In this case the T_K values determined with samples from the inner surface do not represent the most conservative value.

The MC approach and the associated reference temperature, T_0, as defined in the test standard ASTM E1921, is rapidly moving from the research laboratories to application in integrity assessment of components and structures [9,10]. It is more naturally suited to probabilistic analyses because it defines both a mean transition toughness value and a distribution around that value. It is reasonable to expect that in the future the determination of nuclear power plant operating limits will be based on Master Curve methods. For WWER reactors the "Unified Procedure for Lifetime Assessment of Components and Piping in WWER NPPs - VERLIFE" [11] defines a reference temperature, RT_0, used in integrity assessment of WWER reactors as:

$$RT_0 = T_0 + \sigma \qquad (1)$$

where

T_0 reference temperature according to ASTM E1921-05

σ is a margin $\sigma = \sqrt{\sigma_1^{\,2} + \delta T_M^{\,2}}$

σ_1 standard deviation according to ASTM E1921-05

δT_M considers the scatter in the materials; if this value is not available the application of the following values is suggested
$\delta T_M = 10°C$ for the base material,
$\delta T_M = 16°C$ for weld metals.

The VERLIFE procedure suggests the following RT_0 indexed lower bound curve for WWER base and weld metal:

$$K_{JC}^{5\%}(T) = \min\left\{25.2 + 36.6 \cdot e^{[0.019\,(T-RT_0)]};\quad 200\right\} \quad in\, MPa\sqrt{m} \qquad (2)$$

Eq. (2) agrees with the standard MC for 5% fracture probability in ASTM E1921-05.

Table Figure 8 summarises the reference temperatures, RTT_0, evaluated according to the VERLIFE procedure for the investigated discs of trepan 1-1. The RTT_0 were evaluated using the T_0 and T_0^{SINTAP} according to ASTM E1921-05 and the SINTAP MC procedure, respectively. Fig. 7 shows the K_{Jc} values versus test temperature normalised to the individual RTT_0 of the different thickness locations. The K_{Jc} values adjusted to a specimen thickness of 1T are not completely enveloped by the VERLIFE WWER lower bound fracture toughness curve. The application of RTT_0^{SINTAP} as index temperature ensures that all measured K_{Jc} values are now enveloped by VERLIFE lower bound fracture toughness curve (Fig. 8).

Table 5 Location of the investigated discs within trepan 1-1, neutron fluences and reference temperatures evaluated according to the VERLIFE procedure

code disc	distance from inner surface (centre disc) mm	neutron fluence (E>1MeV)			VERLIFE	
		before* 10^{18} n/cm^2	after* 10^{18} n/cm^2	total 10^{18} n/cm^2	RTT_0 °C	RTT_0^{SINTAP} K
1-1.1	8.3	0.71	24.23	24.93	27.5	49.7
1-1.3	21.9	0.64	21.47	22.11	66.3	66.3
1-1.6	42.3	0.51	16.89	17.40	12.2	12.2
1-1.9	69.9	0.36	11.63	11.99	-23.4	3.6
1-1.12	93.8	0.26	8.21	8.47	37.0	62.3

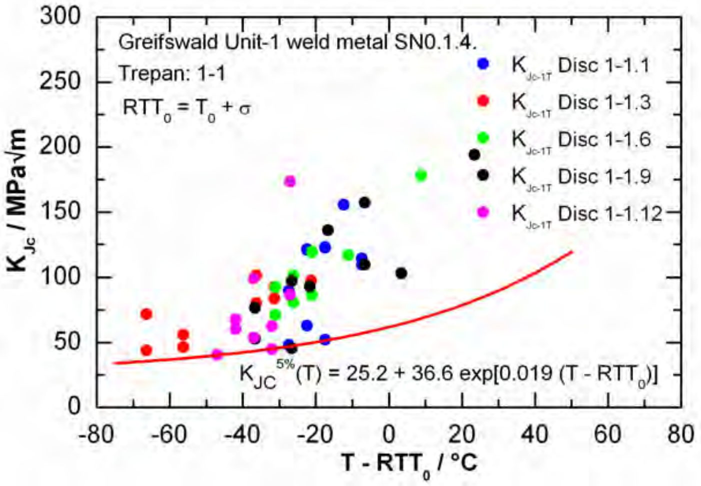


Fig. 7 K_{Jc} values measured on Charpy size SE(B) specimens, adjusted to 1T (25.4 mm) specimen size versus the test temperature normalised to RTT_0 of the different discs and SINTAP lower bound curve

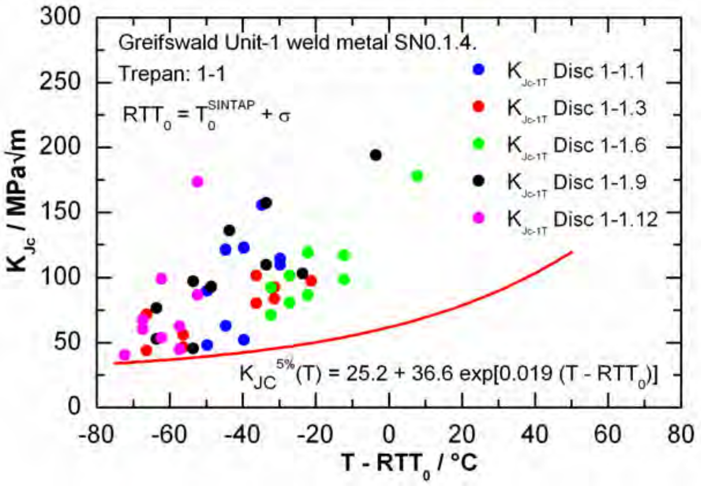


Fig. 8 K_{Jc} values measured on Charpy size SE(B) specimens, adjusted to 1T (25.4 mm) specimen size versus the test temperature normalised to RTT_0^{SINTAP} of the different discs and SINTAP lower bound curve

SUMMARY AND CONCLUSION

The paper presents first results of the post mortem investigations performed into the reactor pressure vessels (RPV) of the Russian WWER-440 type reactors. Trepans were taken from the core weld SN0.1.4 and base metal of the unit 1 RPV. This RPV was annealed after 15 years of operation and operated for two more years. At first the trepan of the core welding seam was investigated by Master Curve (MC) and Charpy V-notch testing. Specimens from 5 locations through the thickness of the welding seam were tested according to ASTM E1921-05. The reference temperature T_0 was calculated with the measured fracture toughness values, K_{Jc}, at brittle failure of the specime. Generally the K_{Jc} values measured on pre-cracked and side-grooved Charpy size SE(B) specimens of the investigated weld metal follows the course of the Master Curve. The K_{Jc} values show a remarkable scatter. More values than expected lie below the 5% fractile. In addition the MC SINTAP procedure was applied to determine T_0^{SINTAP} of the brittle fraction of the data set. There are remarkable differences between T_0 and T_0^{SINTAP} indicating macroscopic inhomogeneous weld metal. The highest T_0 was about 50°C at a distance of 22 mm from the inner surface of the weld. It is 40 K higher compared with T_0 at the inner surface. This is important for the assessment of ductile-to-brittle temperatures measured with sub size Charpy specimens made of weld metal from the inner RPV wall. This material does not represent the most conservative condition. Nevertheless, the Charpy transition temperature TT_{41J} estimated with results of sub size specimens after the recovery annealing was confirmed by the testing of standard Charpy V-notch specimens.

The VERLIFE procedure prepared for the integrity assessment of WWER RPV was applied on the measured results. It enables the determination of a reference temperature, RTT_0 to index a lower bound fracture toughness curve. This curve agrees with the MC 5% fractile as specified in ASTM E1921-05. The measured K_{Jc} values are not enveloped by this lower bound curve. However, the VERLIFE lower bound curve indexed with the SINTAP reference temperature RTT_0^{SINTAP} envelops the K_{Jc} values. Therefore for a conservative integrity assessment the fracture toughness curve indexed with a RT representing the brittle fraction of a dataset of measured K_{Jc} values has to be applied.

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