SCK•CEN

STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

SCK•CEN Contribution to the IAEA Round Robin Exercise on WWER-440 RPV Weld Metal Irradiation Embrittlement, Annealing and Re-Embrittlement 2nd Progress Report

presented and distributed in Vienna, July 7-9 1999

E. van Walle, R. Chaouadi, M. Scibetta, E. Lucon, M. Wéber
SCK•CEN, Boeretang 200, B-2400 Mol, Belgium

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RMR

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Tel. (+32-14) 33 30 00
Fax (+32-14) 32 12 16

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First Author:	**Eric van Walle**	15/9/99	
Co-Author:	**Rachid Chaouadi** **Marc Scibetta** **Enrico Lucon**	 1/9/99 6/9/99	
Project Manager:	**Eric van Walle**	15/9/99	
Departmental Manager:	**Eric van Walle**	15/9/99	

Studiecentrum voor Kernenergie, SCK•CEN , 2400 Mol, België
Centre d'Etude de l'Energie Nucléaire, SCK•CEN, 2400 Mol, Belgique

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1. Introduction

The objective of SCK•CEN to contribute to this RR on WWER-440 weld material is twofold:

1. to gain experience in the field of WWER-440 steels;
2. to analyse the RR-data according to the models used and developed at SCK•CEN in order to check their validity and applicability.

Last year, we reported information on the testing of the unirradiated material: chemical analysis, Charpy-V impact testing, tensile testing and fracture toughness determination. The only missing results were the reference tests on mini-Cv specimens. They are reported here. In Annex 1 an analysis is presented that overviews the correlations between the SCK•CEN mini results and the SCK•CEN standard Charpy-V data.

During the 1998 progress meeting, we outlined the possible irradiation strategies that could be followed to complete the program. It was stated then that two irradiation facilities, CHIVAS or MERLIN both making use of the Belgian MTR BR2, could be loaded with the samples to obtain the irradiated (I), irradiated-annealed (IA) and irradiated-annealed-reirradiated (IAR) conditions. We decided to use the CHIVAS facility and have performed the first irradiation CHIVAS-7.
Actually, we are annealing part of the CHIVAS-7 specimens in order to reinsert them in the CHIVAS-8 experiment that is scheduled in the last trimester of 1999.

We foresee that the testing of the I and IA conditions will be finalised by November 1999, while the IAR-testing will be done by January 2000. This will allow us to finalise the project before the summer of 2000.

2. Test matrix

SCK•CEN purchased part 2 of weld N° 502 representative for WWER-440 weld material and identified as block 502.2. The certification report on the weld manufacturing, heat treatment, chemical composition and mechanical test results can be found in reference [1]. The cutting scheme of the 502.2-block was made according to the procedure stipulated in the terms of reference, IAEA TC Project RER/9/035 WWER-SC-192 [2]. The extracted specimens are of

Charpy-V impact type (Cv), Pre-cracked Charpy (PCCv), Tensile specimens (T) and mini Cv (3x4x27mm). Table 1 gives the specimen identification.

Table 1. Samples extracted from block 502.2

WWER-440-block N° 502.2	Cv	PCCv	T	mini Cv
specimen orientation	T-L	T-L	T	T-L
# of specimens as fabricated	60	60	24	96
position	layer 1, 2	layer 3, 4	layer 5	layer 6,7,8,9
identification	5.01.1-2 through 5.30.1-2	5.01.3-4 through 5.30.3-4	5.01.5 through 5.24.5	5.01.6-7-8-9 L+R through 5.12.6-7-8-9 L+R

3. Reference Testing

The reference testing on the Cv impact, 3PB-PCCv static fracture toughness and tensile testing was reported in the first progress report [3]. Here we will show, without going into too many details, how our data fit into the existing database of this RR.

3.1 Cv-impact testing: comparison with other participants

Figure 1 shows the tanh fits of the energy data of all participants that reported data during the first progress meeting. As most participants only reported energy data, we limit ourselves to those results. The fit is a least square tanh fit where the lower shelf equals 0 and the upper shelf is taken to be the average energy of the 100% shear data.

Figure 1:Individual energy transition curves of WWER-440 weld material

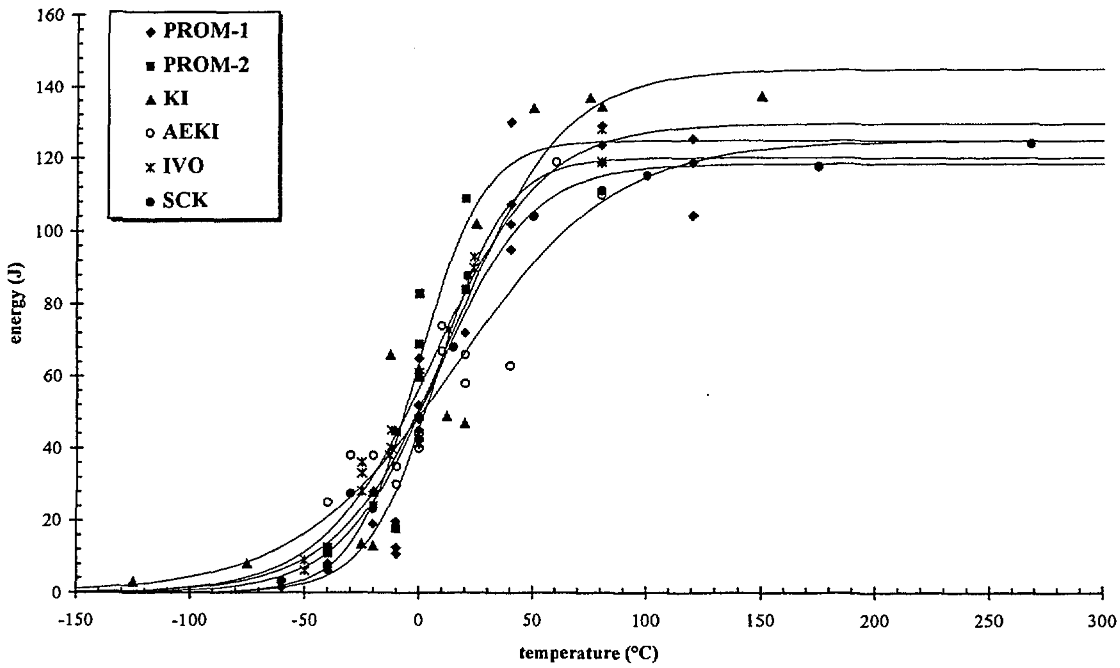


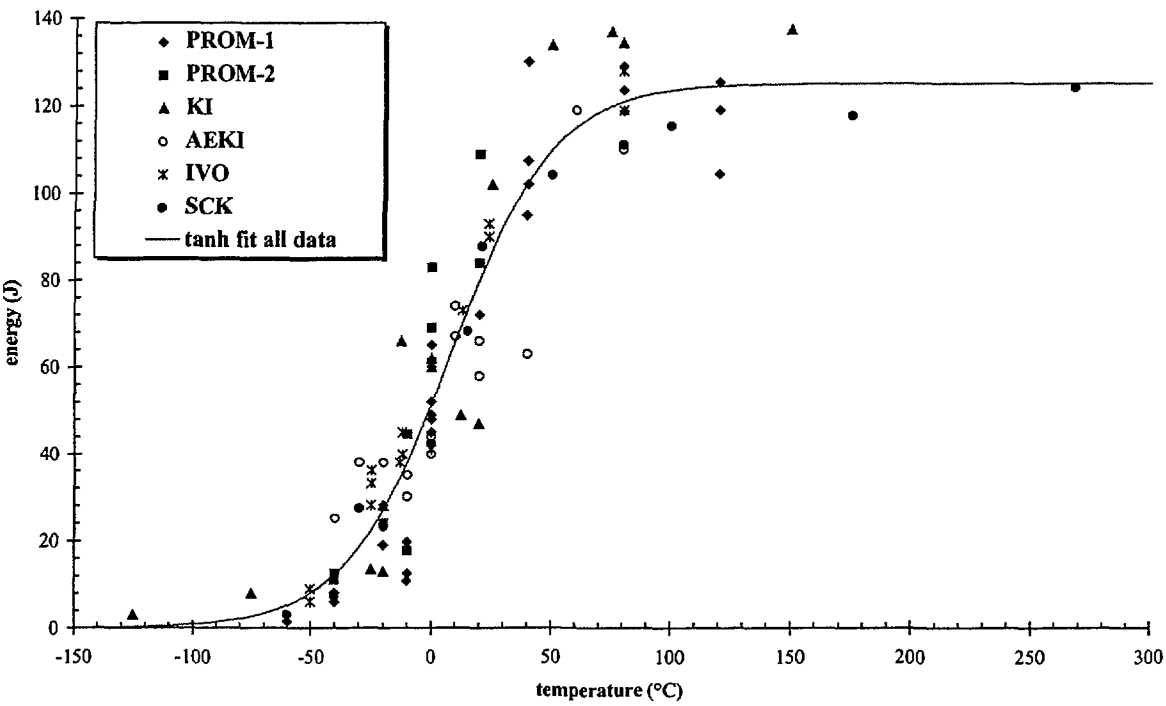
Table 2 Individual fitting results for Charpy-impact data

Lab	N	T_{min}	T_{max}	USE	T_{68J}	T_{41J}	T_{28J}
PROM-1	25	-60	120	120	11,5	-2,2	-10,2
PROM-2	9	-40	20	***125***	1,9	-10,6	-17,9
KI	15	-125	150	145	12,0	-7,6	-19,7
AEKI	14	-40	80	***125***	21,6	-9,4	-27,6
IVO	15	-50	80	130	8,4	-12,4	-24,7
SCK	12	-60	268	119	13,0	-6,2	-17,3
all	90	-125	268	125	11,5	-7,6	-18,9

note: *italic USE values were fixed due to lack of statistics*

The parameters used for these fits are given in Table 2. As can be seen, are the results rather consistent taken into account that some data sets did not have enough statistics on the upper shelf. The overall analysis is shown in Figure 2; the fitting results can be found in Table 2.

Figure 2: mean energy transition curve of WWER-440 weld material



3.2 Mini Cv-impact testing

The tests on mini Cv specimens of dimensions 3x4x27mm were performed on an instrumented Wolpert PW5 pendulum equipped with a 15J impact hammer. The temperature chamber is calibrated and very stable. The transfer time from the temperature chamber to the pendulum is less than 2 seconds. This is, due to the small thermal mass of the mini specimen, enough to have a substantial temperature change [4]. Therefore, all subsize test temperatures were adjusted for the temperature loss caused by specimen transfer from the conditioning bath to the impact position, using the relationship [4]:

$$T_{adjusted} = T_{nominal} - 0.1119 \cdot (T_{nominal} - 14.79)$$

The experimental results including the temperature correction are given in Table 3. The temperature corrected tanh fits are shown in Figures 3 to 5. The results are to be compared with those of other participants using the same geometry. Annex 1 gives an overview of the correlation methodologies between the SCK•CEN mini and standard impact data.

Table 3: Charpy-V impact on mini specimens

ID	T [° C] nominal	T [° C] adjusted	E [J]	SFA [%]	LE [mm]
5.03.9R	-125	-109,4	0,21	3	0,07
5.02.9L	-100	-87,2	0,47	5	0,072
5.10.9R	-75	-65,0	0,85	14	0,131
5.12.9L	-60	-51,6	2,64	24	0,391
5.11.9R	-50	-42,7	3,72	51	0,484
5.04.9L	-40	-33,9	4,44	75	0,599
5.10.9L	-25	-20,5	5,3	88	0,672
5.08.9L	0	1,7	5,6	92	0,702
5.01.9R	25	23,9	5,78	97	0,788
5.05.9R	50	46,1	6,24	100	0,835
5.06.9L	100	90,5	6,29	100	1,001
5.07.9R	260	232,6	5,53	100	0,885

Figure 3: Charpy impact on mini: energy

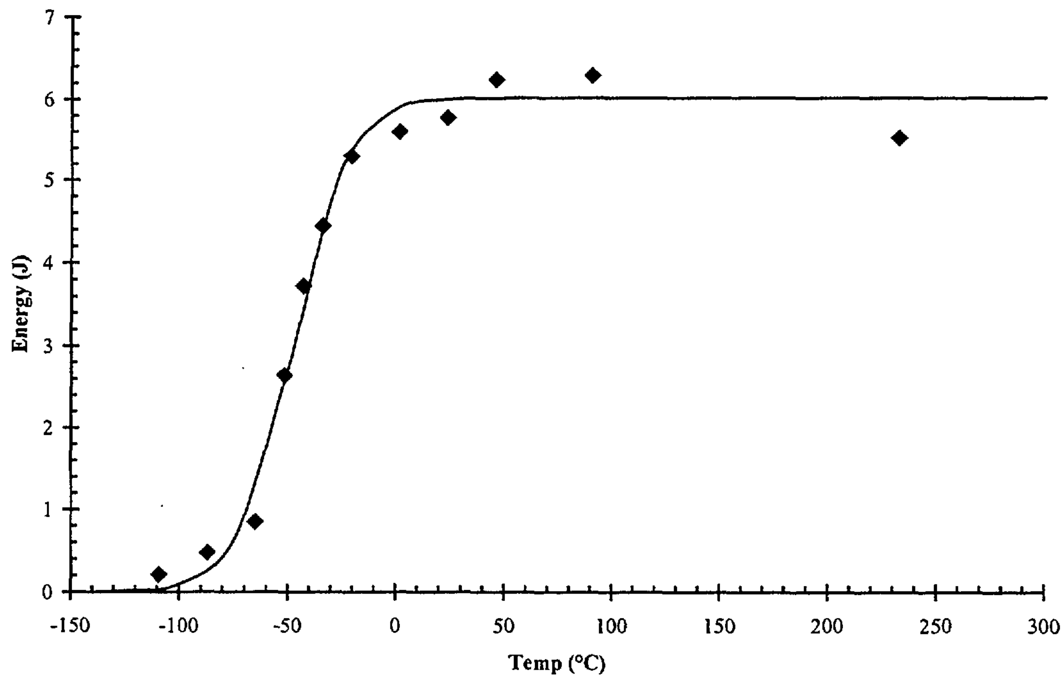


Figure 4: Charpy impact on mini: SFA

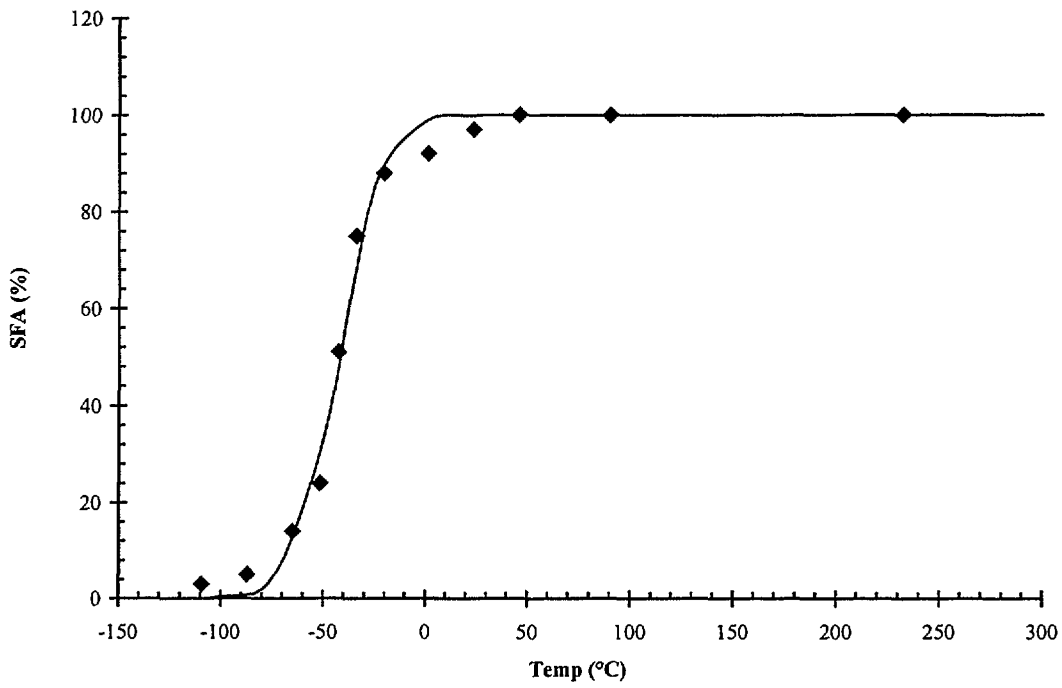
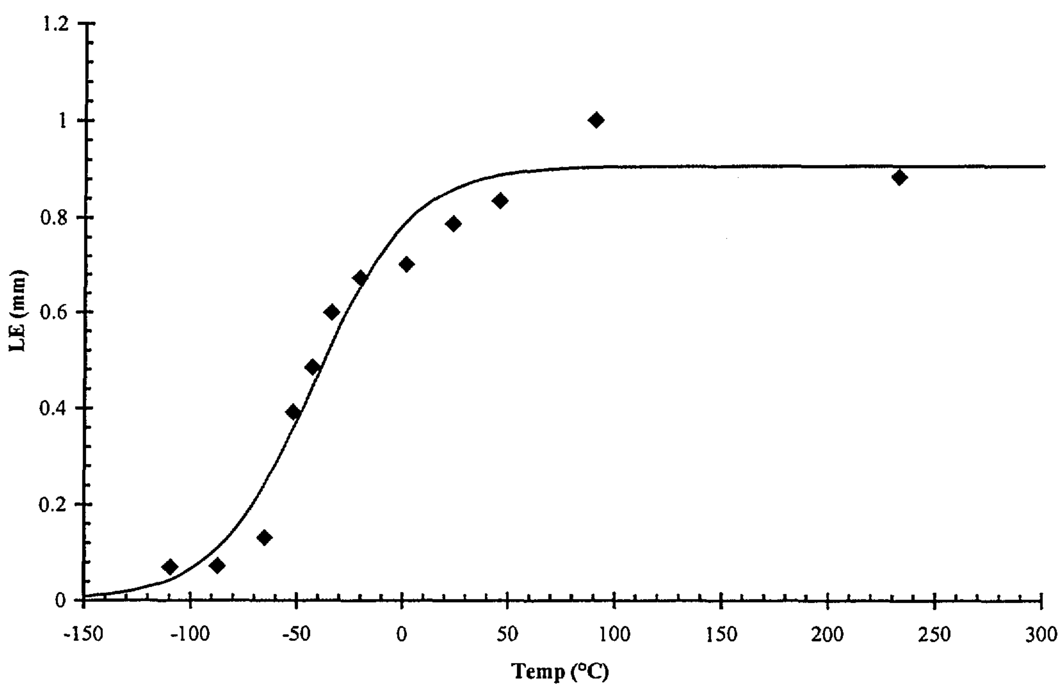


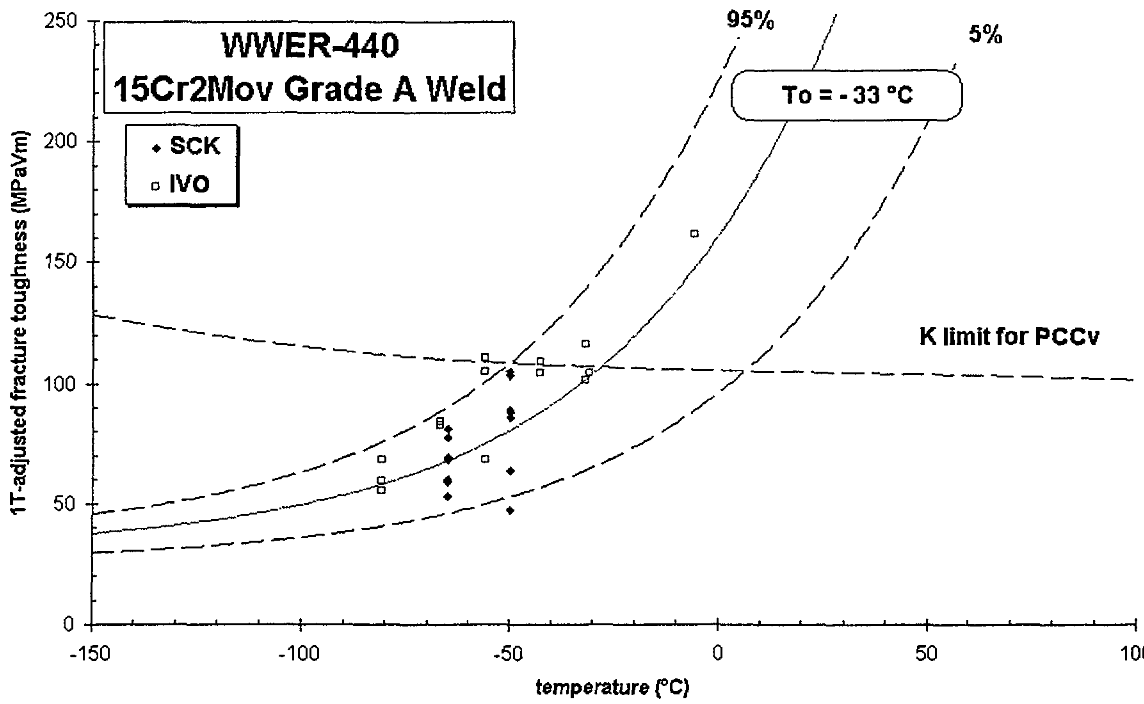
Figure 5: Charpy impact on mini: LE



3.3 PCCv static 3PB testing: comparison with other participants

Figure 6 compares the results of IVO and SCK•CEN, the only available data at the first progress meeting. The T_0 fit only considers the SCK•CEN data, but the data are clearly in accordance with the IVO results, that might reflect a slightly lower T_0 reference temperature.

Figure 6: initiation fracture toughness data of IVO and SCK•CEN



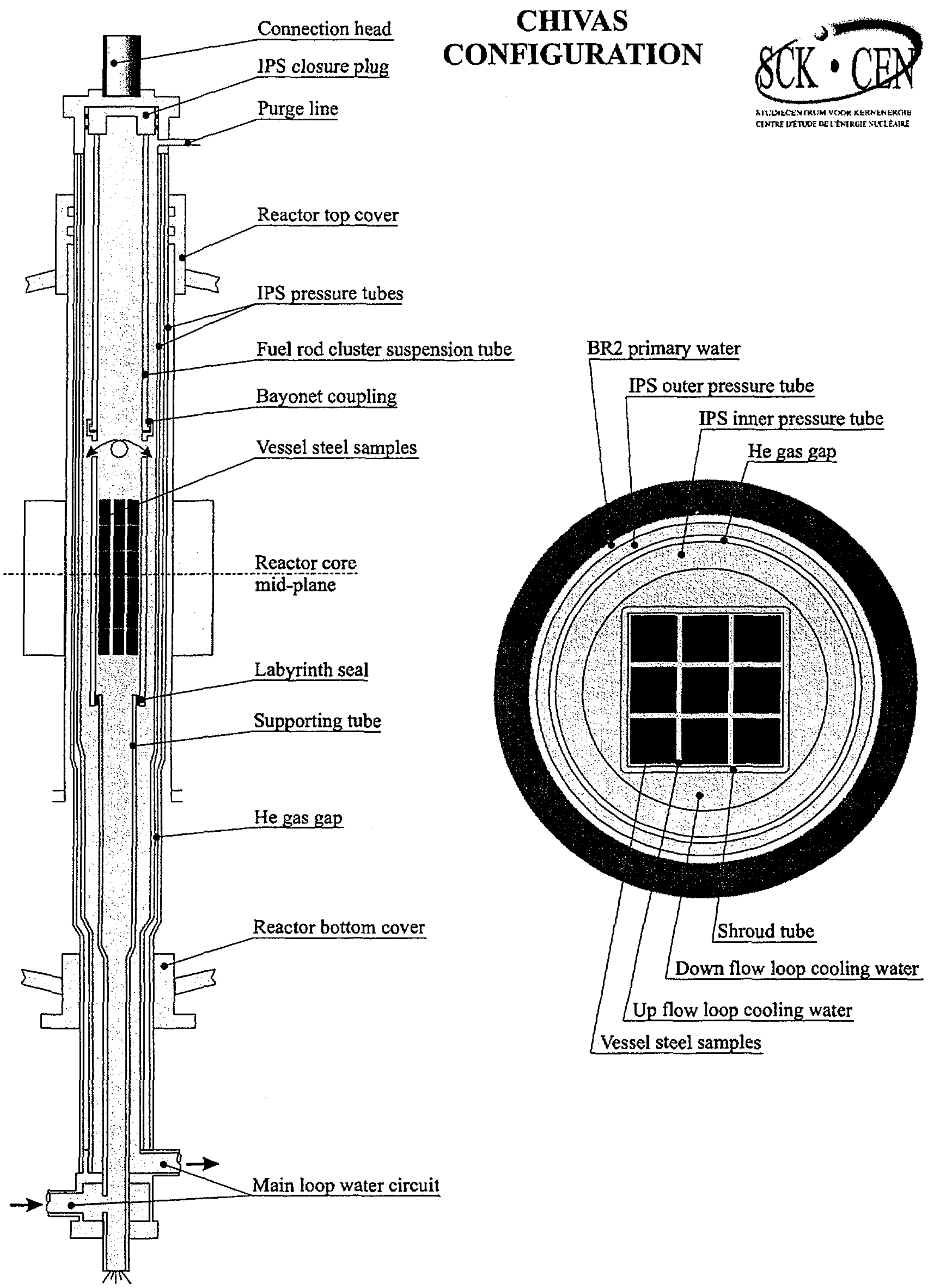
4. Irradiation

As reported in the first progress meeting, two possible irradiation possibilities existed. One was the MERLIN pool side facility, yet to be built at the time of the progress meeting. In the mean time the decision was taken to halt this development due to the high cost involved. We therefore took advantage of the second possibility: CHIVAS.

CHIVAS is an irradiation program that is carried out in the CALLISTO-loop of the BR2 Material Test Reactor, located at SCK•CEN. The acronym CALLISTO stands for CApabiLity for Light water Irradiation in Steady state and Transient Operation, and defines a pressurised water loop with three legs that allows to perform accelerated and selective irradiation under PWR-conditions. The temperature, pressure and water chemistry can be changed as desired. A schematic representation of one leg is given in Figure 7. Its principal application is the irradiation of PWR-fuels up to high burn-up in well determined environments. The last few years, the loop is more and more used for selective irradiation of reactor pressure vessel steels. The availability of three separate legs allows to irradiated up to 162 Charpy-type specimens at once. Every leg has 9 rods (identified A through I) each containing six irradiation positions corresponding to standard Charpy-V type specimens (55mm long).

The first irradiation was designated CHIVAS-7. Two legs, IPS1 and 3, of the Callisto loop were used to irradiate 183 specimens (equivalent to 108 Charpy-size positions available within the two legs) — at a temperature of 268°C and a pressure of some 140 bar. Charpy V, tensile and mini-specimens were loaded according to the schedule given in Tables 4 and 5. The 'levels' indicated in those tables refer to the position of the specimens relative to the BR2 mid-plane (+ above, - below). The BR2 irradiation was scheduled in such way that the baskets were rotated at mid-term in order to guarantee a uniform fluence of some 5 x 10^{19}n/cm² (E > 1 MeV). The temperature of the capsule was recorded and is 268°C –2/+4°C. The capsule was loaded with extended dosimetry at three levels in the legs. The dosimeters were uniquely

Figure 7: The CHIVAS facility



defined. Precise fluence determinations will be made after analysis of these dosimeters. All specimens were in direct contact with circulating water.

Table 4: CHIVAS 7 - IPS 1 loading

Level	Rod A	Rod B	Rod C	Rod D	Rod F	Rod G	Rod I
∇ +120	Dosimeter		Dosimeter			Dosimeter	Dosimeter
∇ +100	NFE711A		NFE711C			NFE711G	NFE711I
∇ +100	PCCV	PCCV	PCCV	PCCV	PCCV	PCCV	PCCV
∇ +45	5.06.3	5.07.3	5.08.3	5.09.3	5.10.3	5.30.4	5.17.3
∇ +45	PCCV	PCCV	PCCV	PCCV	PCCV	PCCV	PCCV
∇ -10	5.18.3	5.19.3	5.20.3	5.26.3	5.27.3	5.28.3	5.30.3
∇ -10	CV	CV	CV	CV	CV	CV	CV
∇ -65	5.06.1	5.07.1	5.08.1	5.09.1	5.10.1	5.13.1	5.16.1
∇ -65	Dosimeter		Dosimeter			Dosimeter	Dosimeter
∇ -95	NFE712A		NFE712C			NFE712G	NFE712I
∇ -95	CV	CV	CV	CV	CV	CV	CV
∇ -150	5.27.1	5.28.1	5.29.1	5.30.1	5.10.2	5.11.2	5.12.2
∇ -150	PCCV	PCCV	PCCV	PCCV	PCCV	PCCV	PCCV
∇ -205	5.08.4	5.09.4	5.10.4	5.11.4	5.12.4	5.13.4	5.15.4
∇ -205	PCCV	PCCV	PCCV	PCCV	PCCV	PCCV	PCCV
∇ -260	5.23.4	5.24.4	5.25.4	5.26.4	5.27.4	5.28.4	5.29.4
∇ -260	Dosimeter		Dosimeter			Dosimeter	Dosimeter
∇ -290	NFE713A		NFE713C			NFE713G	NFE713I

Level	Rod E	Level	Rod H					
∇ +120	Dosimeter	∇+120						
∇ +100	NFE711E	∇+100						
∇ +100	Tensile	∇+100						
∇ +71.5	5.03.5		PCCV					
∇ +71.5	Tensile		5.16.3					
∇ +44.5	5.04.5	∇ +45						
∇ +44.5	Tensile	∇ +45						
∇ +17.5	5.05.5		PCCV					
∇ +17.5	Tensile		5.29.3					
∇ -9.5	5.06.5	∇ -10						
∇ -9.5	Tensile	∇ -10	mini	mini	mini	mini	mini	mini
∇ -36.5	5.07.5	∇ -38	5.01.6R	5.03.6R	5.05.6R	5.07.6R	5.09.6R	5.11.6R
∇ -36.5	Tensile	∇ -38	mini	mini	mini	mini	mini	mini
∇ -65	5.08.5	∇ -66	5.02.6R	5.04.6R	5.06.6R	5.08.6R	5.10.6R	5.12.6R
∇ -65	Dosimeter	∇ -66						
∇ -95	NFE712E	∇ -93						

Table 4 continued

Level	Rod E	Level	Rod H					
∇ -95 ∇ -123 ∇ -123 ∇ -150	Tensile 5.09.5 Tensile 5.10.5	∇-93 ∇-121 ∇-121 ∇-149	mini 5.01.7R mini 5.02.7R	mini 5.03.7R mini 5.04.7R	mini 5.05.7R mini 5.06.7R	mini 5.07.7R mini 5.08.7R	mini 5.09.7R mini 5.10.7R	mini 5.11.7R mini 5.12.7R
∇ -150 ∇ -177 ∇ -177 ∇ -205	Tensile 5.13.5 Tensile 5.14.5	∇-149 ∇-204	PCCV 5.14.4					
∇ -205 ∇ -260	CV 5.21.2	∇-204 ∇-232 ∇-232 ∇-260	mini 5.01.8R mini 5.02.8R	mini 5.03.8R mini 5.04.8R	mini 5.05.8R mini 5.06.8R	mini 5.07.8R mini 5.08.8R	mini 5.09.8R mini 5.10.8R	mini 5.11.8R mini 5.12.8R
∇ -260 ∇ -290	Dosimeter NFE713E	∇-260 ∇-290						

Table 5: CHIVAS 7 - IPS 3 loading

Level	Rod A*	Rod B*	Rod C*	Rod D*	Rod F*	Rod G*	Rod I*
∇ +120 ∇ +100	Dosimeter NFE731A		Dosimeter NFE731C			Dosimeter NFE731G	Dosimeter NFE731I
∇ +100 ∇ +45	CV 5.03.1	CV 5.01.2	CV 5.02.2	CV 5.03.2	CV 5.05.2	CV 5.07.2	CV 5.08.2
∇ +45 ∇ -10	PCCV 5.01.4	PCCV 5.02.4	PCCV 5.03.4	PCCV 5.04.4	PCCV 5.05.4	PCCV 5.06.4	PCCV 5.07.4
∇ -10 ∇ -65	CV 5.17.1	CV 5.18.1	CV 5.19.1	CV 5.20.1	CV 5.24.1	CV 5.27.2	CV 5.26.1
∇ -65 ∇ -95	Dosimeter NFE732A		Dosimeter NFE732C			Dosimeter NFE732G	Dosimeter NFE732I
∇ -95 ∇ -150	CV 5.13.2	CV 5.14.2	CV 5.15.2	CV 5.16.2	CV 5.17.2	CV 5.18.2	CV 5.19.2
∇ -150 ∇ -205	PCCV 5.16.4	PCCV 5.17.4	PCCV 5.18.4	PCCV 5.19.4	PCCV 5.20.4	PCCV 5.21.4	PCCV 5.22.4
∇ -205 ∇ -260	CV 5.22.2	CV 5.23.2	CV 5.24.2	CV 5.25.2	CV 5.28.2	CV 5.29.2	CV 5.30.2
∇ -260 ∇ -290	Dosimeter NFE733A		Dosimeter NFE733C			Dosimeter NFE733G	Dosimeter NFE713I

Level	Rod E*	Level	Rod H*					
∇ +120 ∇ +100	Dosimeter NFE731E	∇ +120 ∇ +100						
∇ +100 ∇ +45	CV 5.04.2	∇ +100 ∇ +45	CV 5.06.2					
∇ +45 ∇ +17 ∇ +17 ∇ -10	Tensile 5.15.5 Tensile 5.16.5	∇ +45 ∇ -10	CV 5.09.2					
∇ -10 ∇ -37 ∇ -37 ∇ -65	Tensile 5.17.5 Tensile 5.18.5	∇ -10 ∇ -38 ∇ -38 ∇ -66	mini 5.01.6L mini 5.02.6L	mini 5.03.6L mini 5.04.6L	mini 5.05.6L mini 5.06.6L	mini 5.07.6L mini 5.08.6L	mini 5.09.6L mini 5.10.6L	mini 5.11.6L mini 5.12.6L
∇ -65 ∇ -95	Dosimeter NFE732E	∇ -66 ∇ -93						
∇ -95 ∇ -123 ∇ -123 ∇ -150	Tensile 5.24.5 Tensile 5.23.5	∇ -93 ∇ -121 ∇ -121 ∇ -149	mini 5.01.7L mini 5.02.7L	mini 5.03.7L mini 5.04.7L	mini 5.05.7L mini 5.06.7L	mini 5.07.7L mini 5.08.7L	mini 5.09.7L mini 5.10.7L	mini 5.11.7L mini 5.12.7L
∇ -150 ∇ -177 ∇ -177 ∇ -205	Tensile 5.20.5 Tensile 5.19.5	∇ -149 ∇ -204	CV 5.20.2					
∇ -205 ∇ -260	CV 5.26.2	∇ -204 ∇ -232 ∇ -232 ∇ -260	mini 5.01.8L mini 5.02.8L	mini 5.03.8L mini 5.04.8L	mini 5.05.8L mini 5.06.8L	mini 5.07.8L mini 5.08.8L	mini 5.09.8L mini 5.10.8L	mini 5.11.8L mini 5.12.8L
∇ -260 ∇ -290	Dosimeter NFE733E	∇ -260 ∇ -290						

The specimen selection for the different conditions I, IA and IAR was done. The specimens selected for IAR will be loaded in CHIVAS-8, that will be irradiated in the fall of 1999. Only one leg is needed. The irradiation conditions will be the same as for CHIVAS-7.

5. Annealing and testing

The annealing of the IA and IAR specimens is actually been done. The annealing conditions are those specified in the terms of reference, namely 475°C+- 10°C.

The testing of the I and IA condition will be done by November 1999.

6. Conclusions

This report contains the actual status of the SCK•CEN contribution to the IAEA Round Robin Exercise on WWER-440 RPV Weld Material Irradiation, Annealing and Re-Embrittlement. The reference testing of the unirradiated material was finalised. The CALLISTO irradiation facility that make use of the Belgian MTR reactor BR2, was used for the CHIVAS-7 experiment. The experiment was dismantled. Annealing is actually performed and the CHIVAS-8 irradiation will be carried out in the fall. Testing of all specimens will be finalised by the end of January 2000

7. Acknowledgements

The authors are indebted to the technical staff of the LHMA, the TCH and the BR2 department, more particular to W. Claes and his team for dismantling, to R. Mertens and R. Vosch for the specimen machining and testing.

8. References

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[2] IAEA Round Robin Exercise on WWER-440 RPV Weld Material Irradiation, Annealing and Re-Embrittlement: Terms of Reference, IAEA TC Project RER/9/035 WWER-SC-192, November 1996

[3] van Walle E., et al., 'SCK•CEN Contribution to the IAEA Round Robin Exercise on WWER-440 RPV Weld Material Irradiation, Annealing and Re-Embrittlement', BLG 768, 1998.

[4] E. Lucon, E. van Walle, A. Fabry, J.-L. Puzzolante, A. Verstrepen, R. Vosch and J. Van de Velde, "Correlations between Standard and Miniaturised Charpy-V Specimens", SCK•CEN Report BLG-797, 1998.

Annex 1: APPLICATION OF CORRELATION METHODS TO MINI-Cv INSTRUMENTED IMPACT ROUND ROBIN DATA ON WWER-440 WELD MATERIAL

The results of instrumented impact tests on subsize Charpy V-notch specimens, performed by SCK•CEN in the frame of the IAEA Round Robin on WWER-440 RPV Weld (15Cr2MoV Grade A), have been analysed in relation to full-size impact results; the correlation methodologies relevant to USE values and index temperatures, outlined in the SCK•CEN BLG-797 Report [1], have been used.

Temperature adjustment

As a first step, all subsize test temperatures have to be adjusted for the temperature loss caused by specimen transfer from the conditioning bath to the impact position, using the relationship [1]:

$$T_{adjusted} = T_{nominal} - 0.1119 \cdot (T_{nominal} - 14.79)$$

Upper Shelf Energy (USE)

Considering the tests where Shear Fracture Appearance (SFA) is greater than 95%, a subsize USE value of 5.96 J is obtained; the predicted values of USE for full-size specimens ($USE_{fs/pred}$) are given in Table 1, along with percent differences with respect to the experimental value calculated from SCK•CEN full-size tests ($USE_{fs/exp}$ =117.5 J).

Table 1 - Predictions of full-size USE value.

Correlation method	Ref.	$USE_{fs/pred}$ (J)	ΔUSE (%)
Normalization [B·b]	[2,3]	53.0	-55
Normalization [$(B\cdot b)^{3/2}$]	[2,3]	141.3	+20
Normalization [$B\cdot b^2$]	[4,5]	157.9	+34
Normalization [Bb^2/LK_t]	[6]	77.5	-34
Empirical, ORNL	[7]	127.0	+8
Empirical, SCK•CEN	[1]	128.5	+9
Exponential fit, SCK•CEN	[1]	121.5	+3
J-integral method, VTT	[8]	125.1	+7

The methods delivering the best predictions (ΔUSE ≤ 10%) are highlighted in the table.

If the full-size USE value obtained from the analysis of all the participants' data sets is considered ($USE_{fs/exp(ALL)}$ = 125 J), the VTT J-integral method delivers the most accurate prediction (ΔUSE = +0.08%).

Index (transition) temperatures

From the hyperbolic tangent fit of dial energy, lateral expansion and SFA data obtained on subsize specimens, the following index temperatures are obtained:

$$T_{1.9J} = -57.1\ °C$$
$$T_{3.1J} = -46.7\ °C$$
$$T_{0.3mm} = -57.3\ °C$$
$$FATT_{50} = -42.9\ °C$$

The temperatures listed above have been analysed with respect to the corresponding index temperatures calculated from SCK•CEN full-size specimen data:

$$T_{40.7J} = -6.5\ °C$$
$$T_{67.8J} = 12.7\ °C$$
$$T_{0.89mm} = -3.4\ °C$$
$$FATT_{50} = 12.8\ °C$$

The predicted values of full-size index temperatures (**$T_{XX,pred}$**) are given in Tables 2 to 5, along with temperature differences with respect to the experimental values given above. In each table, the method delivering the closest prediction is highlighted.

Table 2 - Predictions of full-size $T_{40.7J}$ index temperature values.

Correlation method	Ref.	$T_{40.7J,pred}$ (°C)	$\Delta T_{40.7J}$ (°C)
Empirical shift, Siemens	[9,10]	7.9	+14.4
Empirical shift, SCK•CEN	[1]	2.5	+9.0
Linear fit, SCK•CEN	[1]	-9.0	-2.5

Table 3 - Predictions of full-size $T_{67.8J}$ index temperature values.

Correlation method	Ref.	$T_{67.8J,pred}$ (°C)	$\Delta T_{67.8J}$ (°C)
Empirical shift, Siemens	[9,10]	18.3	+5.6
Empirical shift, SCK•CEN	[1]	12.9	+0.2
Linear fit, SCK•CEN	[1]	3.2	-2.5

Table 4 - Predictions of full-size $T_{0.89mm}$ index temperature values.

Correlation method	Ref.	$T_{0.89mm,pred}$ (°C)	$\Delta T_{0.89mm}$ (°C)
Empirical shift, Siemens	[9,10]	7.7	+11.1
Empirical shift, SCK•CEN	[1]	2.3	+5.7
Linear fit, SCK•CEN	[1]	-9.2	+5.8

Table 5 - Predictions of full-size $FATT_{50}$ index temperature values.

Correlation method	Ref.	$FATT_{50,pred}$ (°C)	$\Delta FATT_{50}$ (°C)
Empirical shift, Siemens	[9,10]	22.1	+9.3
Empirical shift, SCK•CEN	[1]	16.7	+3.9
Linear fit, SCK•CEN	[1]	7.6	-5.2

Overall, for the WWER-440 Weld material the shift determined empirically from SCK•CEN database (59.6 °C) delivers the most accurate predictions.

The same ranking of the different approaches remains valid if we consider index temperatures calculated from fitting full-size dial energy values reported by all the Round Robin participants ($T_{40.7J(ALL)}$ = -7.6 °C and $T_{67.8J(ALL)}$ = 11.5 °C).

Scaling of energy versus temperature curve

Dial energy values measured from subsize tests can be scaled and shifted in order to simulate the corresponding full-size transition curve, following an approach originally proposed by ORNL [7]. The scaled curve is obtained through the following steps: energies are normalized using a factor varying from the ratio of fracture areas in the lower shelf ($NF_{brittle}$) to the empirical USE ratio in the upper shelf ($NF_{ductile}$), proportionally to the value of SFA:

$$E_{fs} = E_{ss} \times \left[NF_{brittle} \frac{100 - SFA\%}{100} + NF_{ductile} \frac{SFA\%}{100} \right]$$

the curve fitting the normalized energies is then shifted forward by an amount corresponding to the average empirical shift of index temperatures.

Figure 1 shows the comparison between scaled and measured full-size energy data using the original ORNL approach ($NF_{ductile}$ = 21.3, temperature shift = 38 °C).

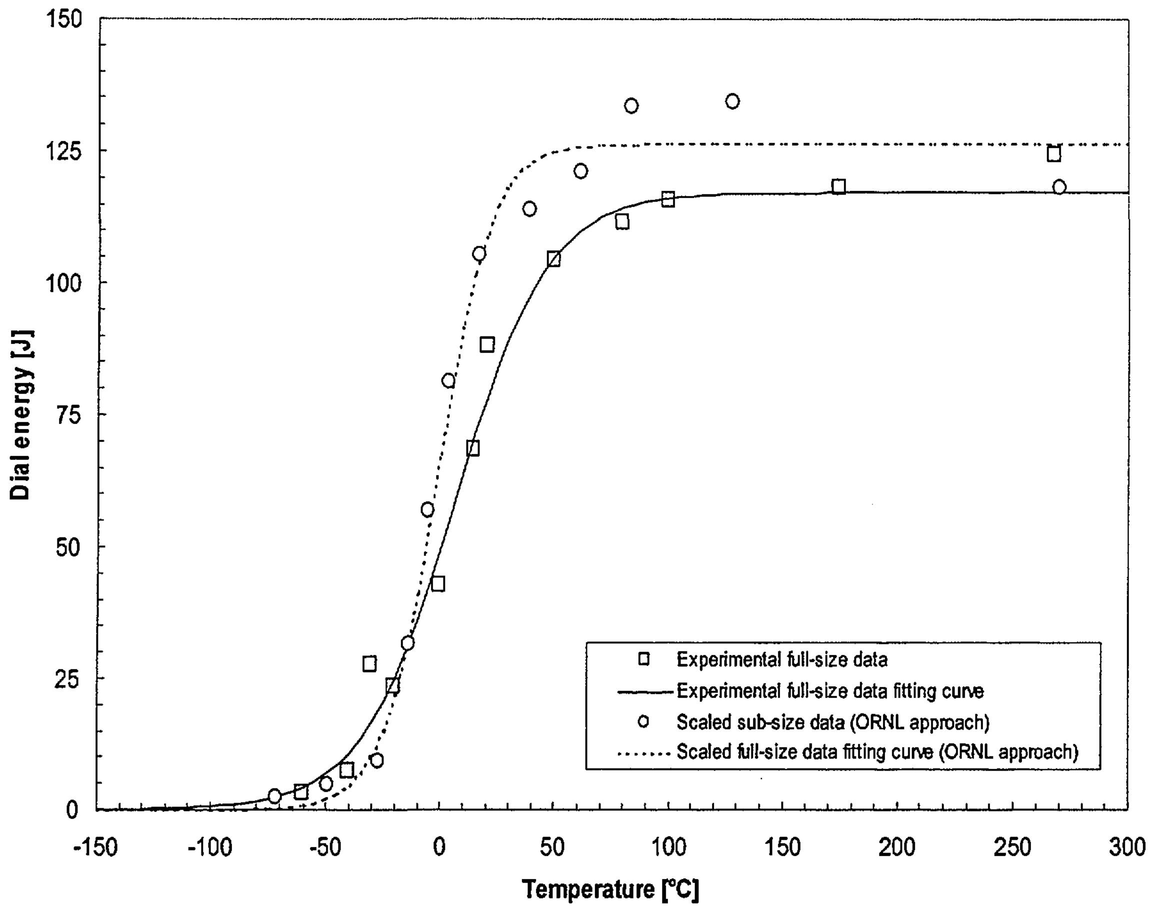

Figure 1 - Comparison between measured and scaled full-size dial energies (ORNL approach).

Figure 2 shows the same comparison, but using factors obtained from the analysis of SCK•CEN database [1] (ORNL modified approach: $NF_{ductile} = 21.56$, temperature shift = 61.8 °C).

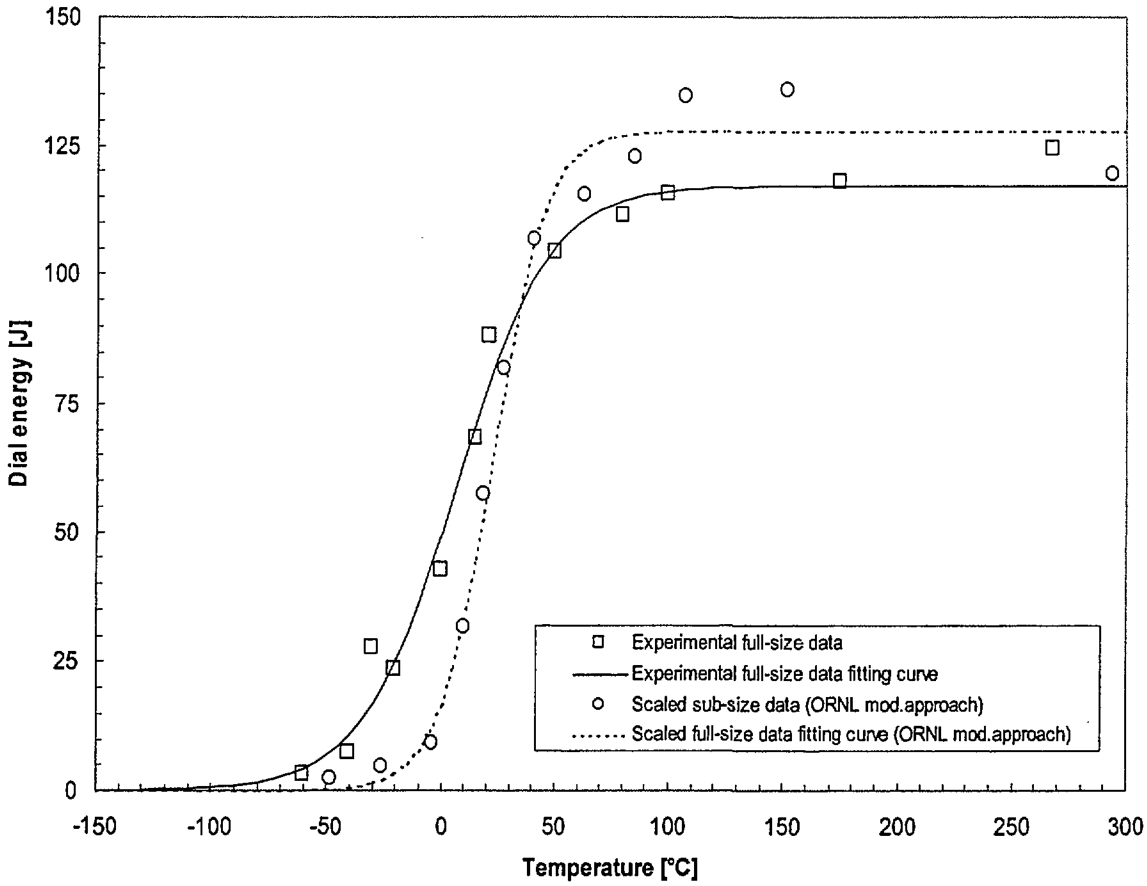

Figure 2 - Comparison between measured and scaled full-size dial energies (ORNL modified approach).

For the WWER-440 weld material, the accuracy of prediction seems substatially equivalent in the two cases.

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