CORRELATION BETWEEN CHARPY-V AND SUB-SIZE CHARPY TESTS RESULTS FOR AN UN-IRRADIATED LOW ALLOY RPV FERRITIC STEEL

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ABSTRACT

Conventional Charpy-V is largely used for the surveillance program of RPV (Reactor Pressure Vessel) embrittlement by neutron irradiation. Prolongation of service life of nuclear power plants and more stringent safety requirements are increasing the request for small test specimens such as sub-size Charpy. Furthermore, empirical correlation formulas between conventional Charpy-V and fracture toughness are largely used in practice. So, before using reduced specimen size, we have to look for possible relations between the two test geometries.

The present investigation is performed on a nuclear RPV typical low alloy ferritic steel 16MND5 (eq. A508 Cl3). The batch used here was extracted from a nozzle opening in the RPV. Instrumented impact tests were performed on conventional Charpy-V and sub-size Charpy for a large temperature range (-196°C up to 300°C). The famous hyperbolic tangent curve from W. Oldfield [1] is fitted to the absorbed impact energy results. This adjustment is then used in order to get some meaning values for this test, such as for example Upper Shelf Energy (USE), Ductile to Brittle Transition Temperature (DBTT) or temperature for a given level of energy (TK). The uncertainty on these parameters determination for a given confidence level will be also given.

Based on these results, different transferability correlation formulas such as normalisation factors, VTT correlation and ORNL [2] method are tried and commented. Furthermore, some discussion will be added on the fracture mode of the different specimens and in particular for the sub-size geometry.

INTRODUCTION

The possibility of using Sub-Size specimens to monitor the mechanical properties of RPV steels is receiving increasing attention. The potential results of using such small samples are as follows :

- the reduction of activated materials to use for a given result,
- the possibility of testing Sub-Size Charpy specimens manufactured from broken halves Charpy-V previously tested surveillance specimens,
- the increase of tested specimens for experimental irradiations.

If this size reduction is nearly without any problem for some specimens such as tensile tests, it is not the same for Charpy tests. The results obtained on reduced specimens must be comparable to those on standard size and compact tension (CT) specimens. In fracture mechanics, it is called a transferability problem and is always a matter of discussions and research even for more conventional geometry.
The Sub-Size Charpy geometry (3x4x27 mm) developed in the frame of ESIS TC 5 [3] is of high interest. But, of course, before using another test than the well know conventional Charpy-V test, it requires a large validation for the new test and it also need to establish strong connections with the usual ones (Charpy-V and CT 25). This article will present the material used for this validation, the test devices and the results in terms of absorbed transition curves. Then, correlations between Sub-Size Charpy and Charpy-V already proposed in the literature will be tested and commented.
This article is linked to another one [4] devoted to finite element simulations.

MATERIAL AND TEST DEVICES

Material

The material is a low alloy manganese ferritic steel with nickel and molybdenum additions. It is referenced 16MND5 in French designation and is very near from A508 Cl.3. It is a nozzle opening of a real nuclear pressure vessel manufactured by Creusot Loire Industry. It is perfectly representative of 1300 MW PWR. This block has already been largely used in preceding studies and in particular in [5]. The chemical composition is given in the following table :

Table 1 : *Chemical composition for PWR 16MND5 steel.*

		C	Mn	Si	Ni	Cr	Mo	Cu	S	P	Al	V
Mes. 3/ 4	Thickness	0.159	1.37	0.24	0.70	0.17	0.50	0.06	0.008	0.005	0.023	<0.01
Imposed RCC-M	Mini		1.15	0.10	0.50		0.43					
	Maxi	0.22	1.60	0.30	0.80	0.25	0.57	0.20	0.015	0.02	0.04	0.03

Thermal treatment of this steel included three different steps :

- Quenching : after austenitisation at 865/ 895°C during 4h40, a water quenching by product immersion was achieved. This step was repeated two times.
- Recovering : 630/ 645°C during 7h30 followed by a cooling in free air.
- Stress relief : was performed at 610°C for 8h00.

The resulting microstructure is bainitic. The sampling was performed at the 3/ 4 thickness and the direction is axial (T) for tensile tests and axial-radial (T-S) for Charpy and toughness tests.

Conventional Charpy-V

Span : 40 mm

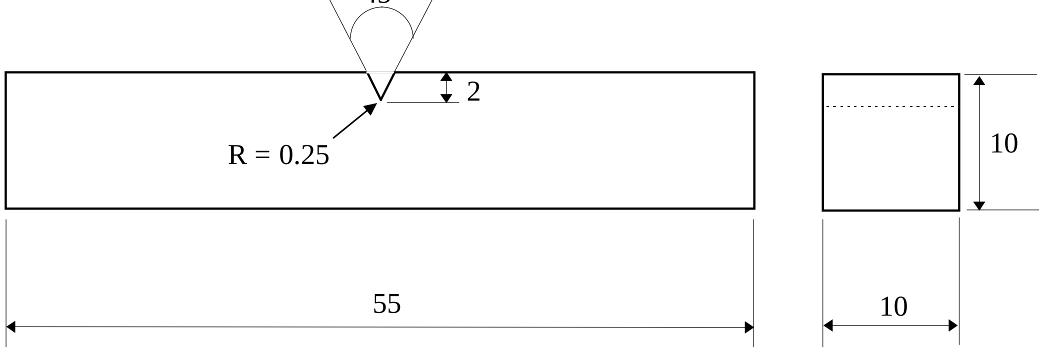

Figure 1 : *Main dimensions of Charpy-V specimen, from EN-10045.*

The test device used for conventional Charpy-V tests is an instrumented 350 J Tinius-Olsen Impact machine. It is in conformity with EN-10045 for the machine and also for specimen geometry.

Sub-Size Charpy

The test device used here is a 50 J Zwick Mini Charpy with an automatic positioning of the specimen. The striker is instrumented with stain gauges and an optical sensor is installed on the pendulum mass for displacement measurement. Specimens, striker and anvils geometries are in accordance with ESIS TC5 Draft [3].

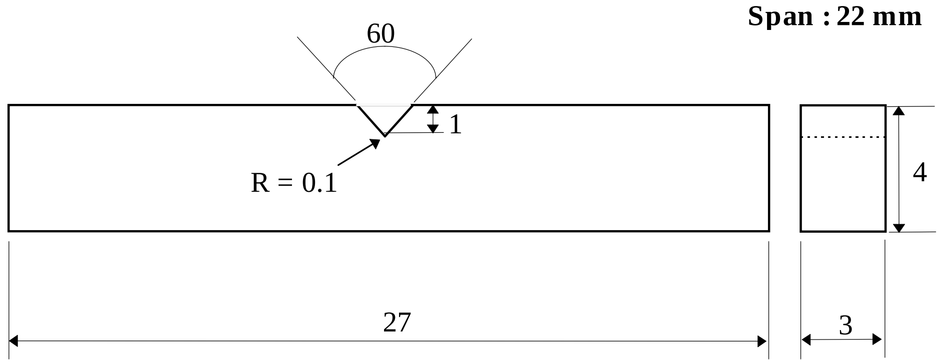

Figure 2 : *Main dimensions of Sub-Size Charpy specimen, from [3].*

Table 2 : *Main dimensions for Charpy and Sub-Size Charpy, from EN-10045 and [3].*

Dimensions (mm)	Charpy-V	Sub-Size Charpy
Specimen Length	55	27
Specimen Height	10	4
Specimen Width	10	3
Specimen Notch Depth	2	1
Specimen Notch Angle	45°	60°
Specimen Notch Tip Radius	0.25	0.1
Distance between Anvils (Span)	40	22
Anvil Radius	1	1
Angle of Taper of Anvils	11°	11°
Angle of Taper of Striker	30°	30°
Radius at tip of Striker	2	2
Maximum Width of Striker	-	18

Specimens and impact tools dimensions are compared in the following table 2. Load calibration has been performed under static condition with a reference piezo-electric sensor. For this, a special device was designed in order to press the two load cells one against the other one. The evaluation of temperature loss during the transfer from the furnace to the support until the impact has always been a major concern for experimentalists. Size reduction of specimens increases this problem. So, a careful calibration of this temperature loss has been performed with an instrumented Sub-Size Charpy specimen. A 0.5 mm K thermocouple was introduced in the specimen by one of its extremity and the top of the thermocouple is located just under the notch. The transfer time from the furnace until the impact has been measured and is equal to 1.85 s. Then, series of tests with the instrumented specimen has been performed at different temperatures and thus give temperature loss after 1.85 s. A temperature loss graph has been done from -150°C up to +300°C. The correction to apply varies respectively from +3°C down to -10°C. This curve is not perfectly linear in particular for positive temperatures.

TEST RESULTS

Absorbed Energy Transition Curve

For Charpy-V, more than 100 specimens were used for the transition curve. This gives a reliable shape and well identified characteristic points and it will also be useful for a scatter evaluation.

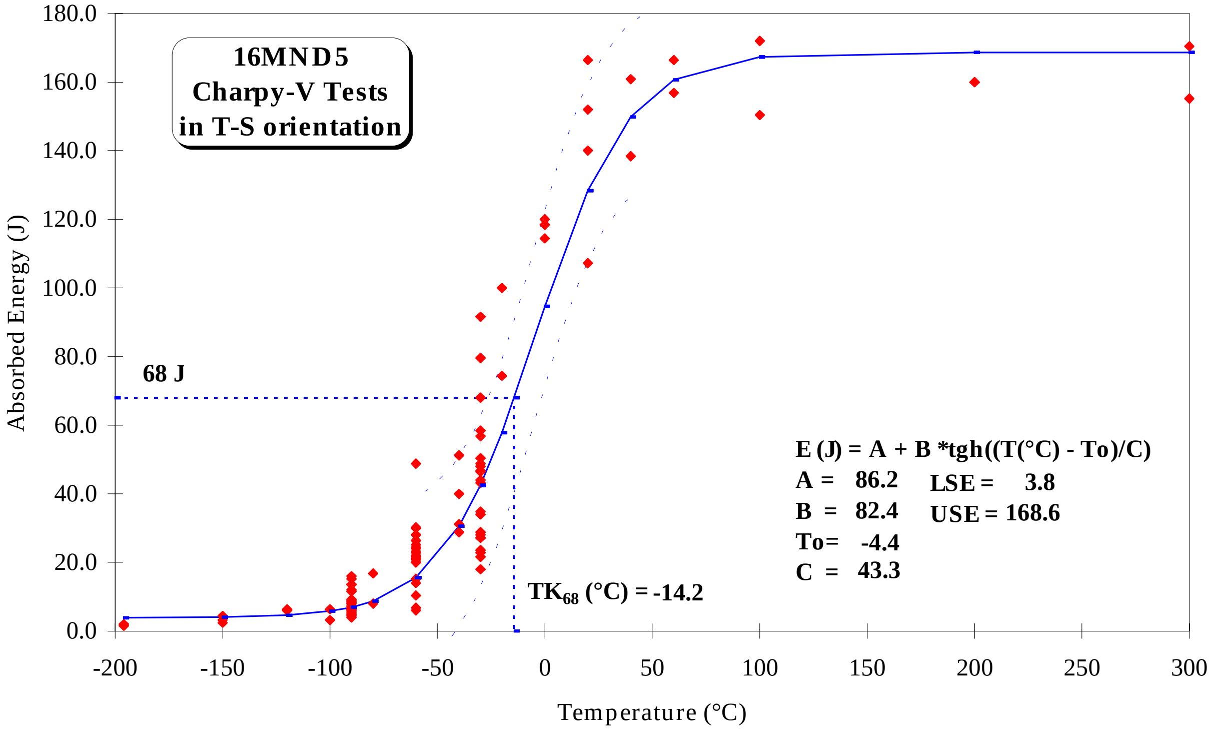

Figure 3 : *Absorbed energy transition curve of 16MND5 for Charpy-V specimen.*

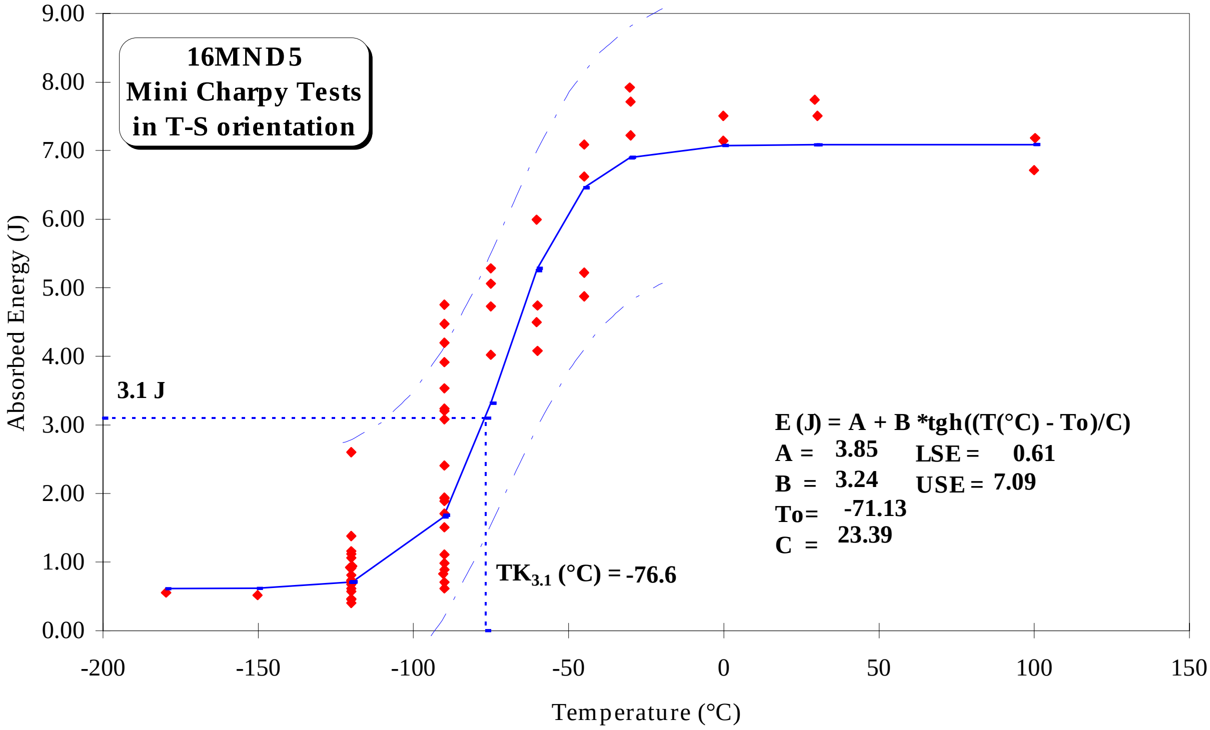

Figure 4 : *Absorbed energy transition curve of 16MND5 for Sub-Size Charpy specimen.*

For Sub-Size geometry, more than 60 specimens have been broken giving also a good definition of the transition curve. Then, characteristic values have been determined by the Oldfield [1] hyperbolic tangent adjustment which is given by the following equation :

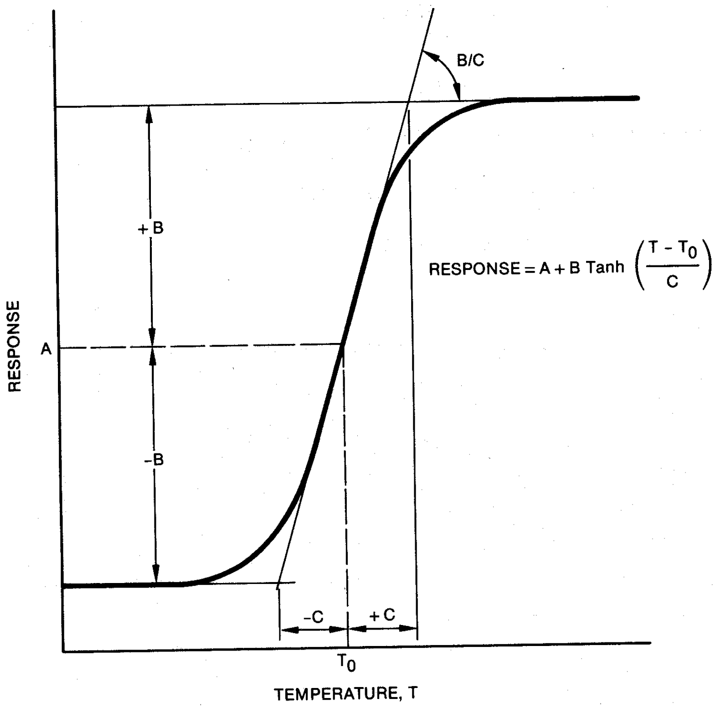

Figure 5 : *Hyperbolic tangent adjustment as defined by [1].*

$$E(J) = A + B \cdot \tanh\left[\frac{(T - T_0)}{C}\right] \quad (1)$$

where A, B, C and T_0 are parameters and are graphically defined in figure 5.
Relation with conventional characteristic points can be established, such as :

$$USE = A + B$$
$$LSE = A - B$$
$$DBTT = T_0$$
$$\text{Transition Onset} = T_0 - C$$
$$\text{Slope} = B / C$$

Where USE is the Upper Shelf Energy, LSE the Lower Shelf Energy and DBTT the Ductile Brittle Transition Temperature.
The next table gives these parameters values for the two specimen geometry.

Table 3 : *Characteristic parameters of the hyperbolic tangent adjustment for full and sub-size.*

E (J)	A (J)	B (J)	To (°C)	C (°C)	LSE (J)	USE (J)	TK (°C)
Charpy-V	86.2 ± 4.3	82.4 ± 5.0	-4.4 ± 4.0	43.3 ± 6.4	3.8 ± 9.3	168.6 ± 9.3	-14.2
Mini Charpy	3.8 ± 0.46	3.2 ± 0.63	-71.1 ± 7.4	23.4 ± 15.0	0.6 ± 1.1	7.1 ± 1.1	-76.6

In this table, we also indicate the temperature index corresponding to a particular energy level which is commonly equal to 68 J for Charpy-V and 3.1 J for Sub-Size Charpy. For each parameters, confidence intervals on the estimates of each parameter are given for a confidence level of 95% (± 2σ). These values were obtained via the use of a conjugated gradient for the fitting and a sensitivity analysis. The corresponding upper and lower confidence bounds for the predicted energy level are given on the graphs only for the transition range (due to statistical inference, the values given for lower and upper shelves are too high [1]). For temperature indexes, the predicted 95% confidence interval are not indicated in table 3 because they are non symmetric. For Charpy-V and Sub-Size Charpy, they are respectively equal to {-2.8°C,-26.5°C } and {-108.5°C,-58.5°C }. These results show that scatter associated to Sub-Size Charpy seems to be greeter than the one observed for Charpy-V, but this requires further confirmation.
From table 3, we also noticed that the DBTT shift (ΔDBTT) is equal to 66.7°C and the temperature index shift (ΔTK) is equal to 62.5°C. The ratio between upper shelves energies is 23.8 and only 6.3 between lower shelves energies. Instrumented curves giving load versus time or deflection are given and used in the companion article [4].

CORRELATION BETWEEN SUB-SIZE AND FULL SIZE CHARPY

Upper Shelf Energy (USE)

A lot of work has already been done in order to correlate USE between full size and sub-size (e.g. Corwin [6], Schubert [7], Louden [8] and so on). Lucon [9] gave a synthetic overview of these approaches. Proposed formulas are often based on a Normalisation Factor (NF) of energy for the USE. The definition of this NF is as follows :

$$NF = \left(\frac{USE_{Charpy-V}}{USE_{SubSize\,Charpy}} \right) \tag{2}$$

The value of NF can be established either directly from experiments, either through quite simple mechanical based relations. The most commonly used expressions give values included between 8.9 and 26.5. The lack of these approaches is that they are based only on elastic considerations and are not able to take into account the yielding, the ductile tearing nor constraint change. The experimental based approach gives values within 21.6 ± 2.6 [9] for more than 10 different materials (mainly pressure vessel steels).

For the steel considered in the present investigation, the experimental NF value is equal to 23.8 and so, is in accordance with the value reported by other investigators such as [9] and [2].

Another procedure proposed for the evaluation of NF is the VTT approach which is based on a power law fit of the corresponding J-integral versus ductile stable crack growth ($J = C \cdot \Delta a^m$) [9]. This formulation has been established on an experimental basis. The particularity of this equation is that it is transcendent as m is dependant on the $USE_{Charpy-V}$. Z and n were found to be respectively equal to 184 J and 0.34 [9].

$$NF = \frac{10}{B} \cdot \left(\frac{8}{b} \right)^{1+m} \qquad \text{with} \qquad m = \left(\frac{USE_{Charpy-V}}{Z} \right)^{n} \tag{3}$$

The next figure is giving a graphical representation of these results. The experimental reported NF value for the steel under consideration (23.8) is in very good agreement with the interval (21.6 ± 2.6) based on other experimental results or with the VTT correlation.

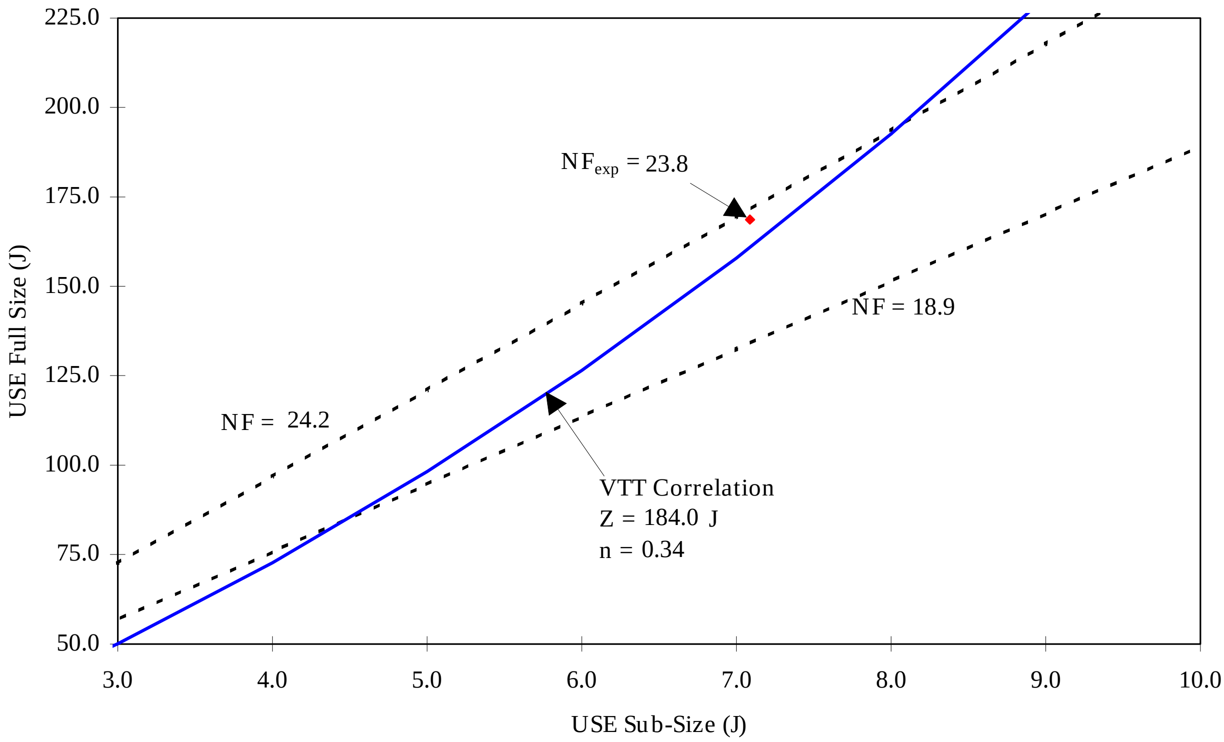

Figure 6 : *Experimental and empirical values for Normalisation Factor between USE.*

Ductile Brittle Transition Temperature (DBTT) Shift

The transition temperature shift (ΔDBTT) is defined by :

$$\Delta DBTT = DBTT_{Charpy-V} - DBTT_{Sub-Size} \tag{4}$$

Of course, this relation can be applied to DBTT but also to temperature indexes (TK). We experimentally find 66.7°C and 62.5°C respectively. This is in very good agreement with the value (65 ± 30°C) reported by E. Lucon et al. [9].

Lower Shelf Energy (LES)

For LSE, the NF ratio can also be applied. The value experimentally obtained on 16MND5 is equal to 6.3 which is lower than the value (8.9) reported by Solokov et al. [2]. Note that this value is not often reported and that the fitting procedure has a high influence on the precision of LSE determination.

ORNL Correlation

Solokov et al. [2] have proposed a normalisation procedure applicable to the whole transition curve. The Sub-Size Charpy absorbed energy is first re-scaled and then a temperature shift is applied. This gives a transition curve which is comparable to the Charpy-V curve. These two steps are detailed as follows :

1- Absorbed energy is re-scaled by the following relation :

$$NF = (1 - SFA(T)) \cdot NF_{LSE} + SFA(T) \cdot NF_{USE} \tag{5}$$

where SFA(T) is the Shear Fracture Appearance and can be measured either from fracture surface observation (i.e. surface ratio of ductile tearing and cleavage partsor via empirical formulas [3]). The obtained value varies from 0 (purely brittle) to 1 (only ductile) with increasing temperature.

2- Sub-Size temperatures are shifted with the following relation :

$$T_{Charpy-V} = T_{Sub-Size} + \Delta DBTT \tag{6}$$

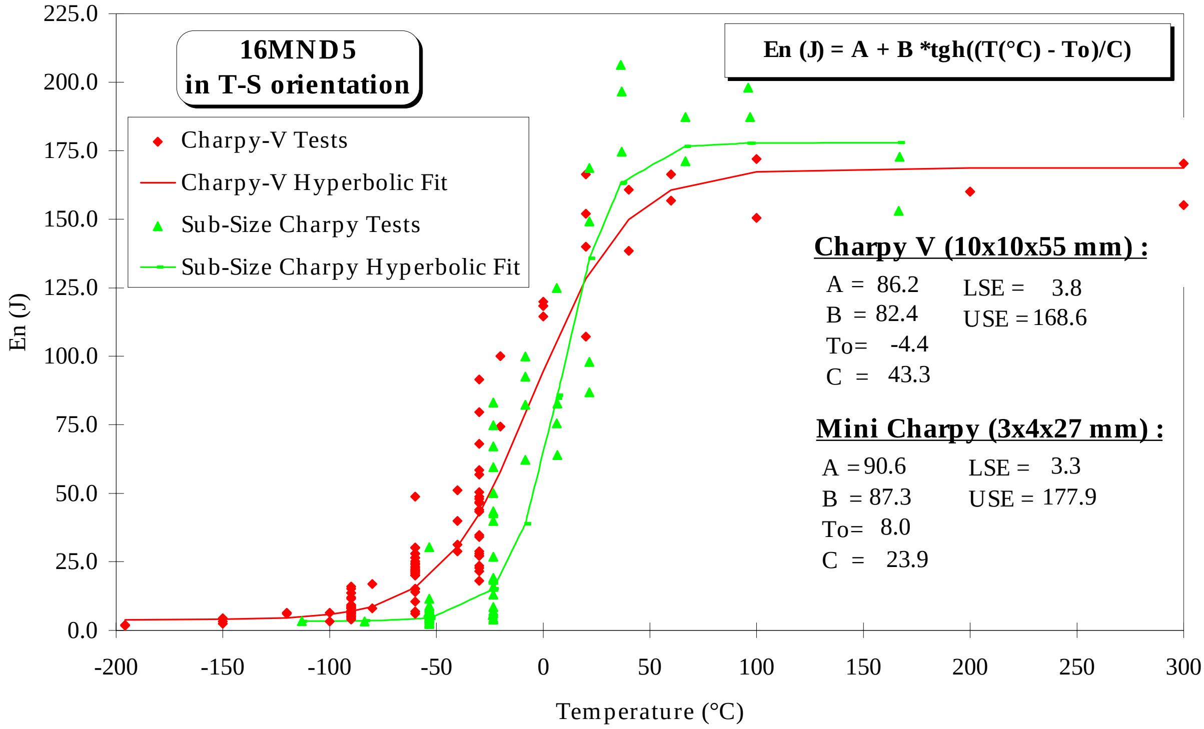

Figure 7 : *ORNL methodology applied to Sub-Size Charpy results and compared to Charpy-V.*

This method has been applied here with calibrated coefficients (i.e. NF factors and ΔDBTT are those measured on 16MND5) to Sub-Size experimental points in order to put them in the Charpy-V absorbed energy graph. Then, the hyperbolic tangent fit was performed by considering those transformed points. So, the correspondence between the two curves is quite good, in particular for the upper and lower shelves energies. DBTT shift is a little too big giving thus a difference of about 12°C between the two curves. But an interesting feature is observable on these curves : the slopes B/ C are not the same. C remains approximately constant during the transformation and B is increased in order to get the correct upper shelf energy. This means that the second step of the methodology is probably not so simple as a simple temperature shift. A slope correction must also be applied in Eqn. 6. This means that a coefficient equal to the ratio $C_{Charpy-V}/C_{Sub-Size}$ (1.9 in our case) should be applied to the temperature scale. With such a transformation, the two curves exhibit a very good agreement, but this modification needs further validation.

CONCLUSIONS

Zwick 50 J Sub-Size pendulum is able to test ESIS TC 5 [3] specimen types. Before the tests, a first phase was devoted to calibration of the load cell and the optical sensor. Attention was also paid to temperature loss during the specimen transfer from the furnace to the anvils until impact occurs.
Then, transition curves have been established with Charpy-V (10x10x55 mm) and Sub-Size Charpy (3x4x27 mm) specimens for un-irradiated 16MND5 RPV low alloy ferritic steel (eq. A508 Cl.3). Characteristic values have been determined by Oldfield hyperbolic tangent adjustment [1]. Confidence intervals on parameters and on predicted energy show that scatter associated to Sub-Size Charpy seems greater than for Charpy-V but this need further confirmation.
The ratio between upper shelves experimentally reported is equal to 23.8. This value is in accordance with the values reported in the literature for similar steels [9] and is well predicted by the VTT correlation. It is only 6.3 for lower shelves. The transition temperature shift (ΔDBTT) between the two specimen geometry is equal to 66.7°C which is also in good agreement with the values given by Lucon [9]. A methodology developed by Solokov [2] at ORNL was applied in order to transform the Sub-Size Charpy transition curve in the Charpy-V scales. This was done with adapted coefficients and we noticed that a simple temperature shift is probably insufficient. A slope correction should also be applied to the temperature relation.

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