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EFDA Technology Workprogramme 2002
Tritium Breeding and Materials
Materials Development – TTMS-001

E. Lucon

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## Abstract

EUROFER (formerly referred to as EUROFER97) is presently the main candidate as structural material for the Breeding Blankets Modules of DEMO and will be used for the Test Blankets Modules developed in the EU. Its specification results from a 20 year R&D effort and collaborative work performed under the auspices of the International Energy Agency.

Tensile, Charpy impact and precracked Charpy specimens extracted from a forged bar (heat n° E83699) have been irradiated during 4 cycles in the BR2 reactor at 300 °C up to a fluence of $3.69 \times 10^{20}$ n/cm² (E > 1 MeV), in the frame of the IRFUMA-II experiment. Mechanical test results have been obtained from the irradiated samples, allowing to assess the consequences of neutron exposure on the mechanical strength (hardening) and toughness properties (embrittlement) of the material, after comparison with data obtained in the unirradiated condition.

In spite of the limited amount of relevant data available in the open literature, the effects of irradiation on the mechanical properties of EUROFER at doses between 0.3 and 0.8 dpa have been compared with those observed on other RAFM steels (F82H in particular), under comparable irradiation conditions (temperature and doses).

## Keywords

RAFM steels, EUROFER, irradiation, IRFUMA-I, IRFUMA-II, hardening, embrittlement, F82H.

# Table of contents

# 1 Introduction

High Chromium ferritic/martensitic steels, with Cr content between 9% and 12%, were developed more than fifty years ago and have been used for a long time in the power-generation industry as boiler and turbine materials, as well as for other applications. In the early 1970's, they were considered for fast breeder fission reactors and later for fusion applications, mainly on account of their better resistance to swelling as compared to austenitic stainless steels [1].

In the last 15 years of the past century and up to present, fusion material programs in Europe, Japan and US have been focused on developing Reduced Activation Ferritic/Martensitic (RAFM) steels, which would reduce the environmental impact of the irradiated steel after the service lifetime of a fusion reactor. This was achieved by selectively replacing chemical elements which, in a fusion neutron spectrum, would transmute into high-energy radiation emitters with long half-life.

In the European Union, within the Long Term Programme of EFDA, remarkable efforts are being spent by several Scientific Institutions for the characterization and optimization of a reference RAFM steel, which was given the name of EUROFER97 (or more simply EUROFER). This was modelled after the conventional T91 alloy and exhibits a tempered martensitic microstructure which allows operation at relatively high temperatures (up to 500 – 550 °C); presently, attempts at extending the temperature operational range to 650 – 700 °C are being investigated through the application of alternative manufacturing routes, such as ODS (Oxide Dispersion Strengthening).

SCK•CEN has been actively contributing in the last 3 years to the international characterisation effort by investigating the properties of EUROFER both in the unirradiated and irradiated conditions. Three irradiation campaigns have been carried out in the BR2 material test reactor located in Mol:

- IRFUMA-I, conducted in 2000 at 300 °C up to an average accumulated dose of 0.32 dpa [2,3];
- IRFUMA-II, conducted in 2001 at 300 °C up to an average accumulated dose of 0.55 dpa [4];
- IRFUMA-III, conducted in 2001-2002 at 300 °C up to an estimated accumulated dose of 1.1 dpa [5].

Such investigations are considered to be fundamental steps in the characterisation of the material's irradiation sensitivity; furthermore, it is well known that the lower is the irradiation temperature, the higher is the irradiation damage.

This report contains detailed results of the mechanical characterisation of the EUROFER specimens irradiated in IRFUMA-II (300 °C, 0.55 dpa), as well as in-depth information about the properties of the steel in the unirradiated condition.

# 2 Material and irradiation conditions

The EUROFER steel was modelled after the T91 alloy by selectively replacing several elements which would transmute in a fusion reactor spectrum into high-energy emitters with long half-life: namely, W and Ta replaced Mo and Nb, respectively. Such replacements are expected to have a negligible effect on mechanical properties but are beneficial from a radiological point of view.

EUROFER has a martensitic microstructure which allows operation at relatively high temperatures, up to 500 – 550 °C, and offers good dimensional stability under high neutron dose level conditions. Moreover, it exhibits higher swelling resistance as compared to austenitic steels (about 1% volume per 100 dpa with respect to 1% volume per 10 dpa, [6]).

The EUROFER steel was produced by Böhler AG (Germany) under various product forms (plates of different thicknesses and forged bars) in order to demonstrate the feasibility of the industrial production route. Plates were produced with thicknesses of 8, 14 and 25 mm; six bars with 100 mm diameter were also produced.

FZK Karlsruhe, responsible of the production and distribution of the material, delivered to SCK•CEN a 168 cm-long portion of one of the forged bars, corresponding to heat n°E83699. The relevant inspection certificate, which contains information about the chemical composition, the heat treatment and the mechanical properties of the bars, has been reproduced in [3]. Chemical composition and heat treatment, as reported by the manufacturer, are given in Table **1**.

Table 1 - *Chemical composition (wt%) and heat treatment of EUROFER.*

| C | Si | Mn | P | S | Cr | Mo | Ni | V | W | Cu | Co |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.12 | 0.07 | 0.44 | <0.005 | 0.004 | 8.99 | <0.001 | 0.007 | 0.19 | 1.10 | 0.022 | 0.004 |
| **Ti** | **Al** | **Nb** | **B** | **N** | **Pb** | **Ta** | **O** | **As** | **Sn** | **Zr** | **Sb** |
| 0.009 | 0.008 | <0.001 | <0.001 | 0.017 | <0.0003 | 0.14 | 0.0013 | <0.005 | <0.005 | <0.005 | <0.005 |
| Heat treatment: hardening 979 °C – 1h51min – Air; Tempering: 739 °C – 3h42min – Air. | | | | | | | | | | | |

All mechanical specimens (tensile, Charpy-V and precracked Charpy-V) used at SCK•CEN for the characterisation of EUROFER in the unirradiated and irradiated state have been extracted in the longitudinal direction (with the exception of two transversal Charpy specimens), according to the cutting scheme reproduced in Annex 1 and with respect to a reference plan which was arbitrarily chosen.

## *2.1 Irradiation conditions*

The irradiation campaign denominated IRFUMA-II was carried out from the second to the fifth and last irradiation cycle of 2001, at a nominal temperature of 300 ± 5 °C. Detailed information on the irradiation conditions have been given in a separate report [4].

Detailed dosimetry measurements have been performed and reported elsewhere [7]; on the basis of such measurements, the fluence and corresponding dose accumulated by each individual specimen has been calculated using a simplified, yet accurate model recently developed at SCK•CEN [8].

Due to the fact that the central portion of the irradiation rig (midplane region) was occupied by another experiment, the IRFUMA-II specimens had to be loaded into the peripheral portions of the rig, where the fluence gradient is elevated. As a consequence, significantly different fluences/doses were calculated for the individual specimens, with factors up to 5 and more between different samples (0.18 dpa versus 1.1 dpa).

The scatter in accumulated fluences/doses is clearly visible in the overview presented in Table 2.

Table 2 - *Fluences and doses accumulated by the specimens irradiated in IRFUMA-II.*

| Specimen type | Fluence ($\times 10^{20}$ n/cm², E > 1 MeV) | Dose (dpa) |
|---|---|---|
| Tensile | 3.46 ± 1.664 | 0.52 ± 0.250 |
| Cv | 3.05 ± 1.792 | 0.46 ± 0.269 |
| PCCv | 4.63 ± 1.974 | 0.69 ± 0.296 |

The overall average fast neutron fluence is **3.69 × 10^20 n/cm²** (E > 1 MeV), corresponding to **0.55 dpa**; standard deviations are respectively 1.855 × $10^{20}$ n/cm² and 0.278 dpa.

# 3 Matrix of tests performed

In the initial programme, only mechanical tests on the irradiated material were foreseen. However, very odd results were obtained from a first series of Charpy impact tests (details will be given afterwards); this cast serious doubts on the homogeneity of the material, and it was therefore deemed necessary to carry out a thorough characterisation of the mechanical properties of the forged bar in the unirradiated condition, rather than simply relying on results provided by partner institutions.

An overview of the tests performed and reported in this document is given in Table 3.

Table 3 - *Matrix of tests performed.*

| Condition | Type of test | No. of tests performed | Test T range (°C) |
|---|---|---|---|
| Unirradiated | Tensile | 8 | -150 to 300 |
| | Impact | 21+2[1] | -110 to 300 |
| | Toughness | 9 | -150 to -100 |
| Irradiated | Tensile | 12 | -150 to 300 |
| | Impact | 19[2] | -130 to 300 |
| | Toughness | 9 | -70 to -25 |

# 4 Tensile test results

## *4.1 Unirradiated condition*

Eight tensile specimens of cylindrical cross section (diameter D = 2.4 mm, reduced section length $L_o$ = 12 mm) were tested from -150 to 300 °C, according to the E8M and E21 standards. No extensometer was used to measure specimen elongation.

Test results are given in Table 4, in terms of yield strength ($\sigma_{p02}$), ultimate tensile strength ($\sigma_{UTS}$), uniform elongation ($\varepsilon_u$), total elongation ($\varepsilon_t$) and reduction of area ($Z$).

[1] Sampled in a different orientation.
[2] After a first series of 9 tests, 10 additional specimens were reconstituted and tested.

Table 4 - *Results of the tensile tests on the unirradiated specimens.*

| Spec. code | T (°C) | $\sigma_{p02}$ (MPa) | $\sigma_{UTS}$ (MPa) | $\varepsilon_u$ (%) | $\varepsilon_t$ (%) | Z (%) |
|---|---|---|---|---|---|---|
| 74H | -150 | 869 | 945 | 9 | 24 | 67 |
| 74G | -75 | 606 | 760 | 8 | 25 | 75 |
| 74E | 25 | 557 | 670 | 5 | 20 | 80 |
| 89 | 80 | 528 | 629 | 4 | 18 | 80 |
| 78E | 150 | 507 | 598 | 4 | 19 | 82 |
| 90 | 225 | 495 | 549 | 4 | 18 | 81 |
| 78F | 300 | 478 | 547 | 3 | 16 | 80 |
| 74F | 300 | 516 | 560 | 2 | 16 | 80 |

Yield and ultimate tensile strength data were fitted as a function of test temperature, obtaining the following expressions:

$$\sigma_{p02} = 503.89 + 38.98 \cdot e^{-0.0149}$$

for the yield strength, and

$$\sigma_{UTS} = 531.04 + 149.6 \cdot e^{-0.0067}$$

for the ultimate tensile strength. These fitting functions are relevant only to the test temperature range (-150 to 300 °C), and should not be extrapolated to higher temperatures.

Figure 1 and Figure 2 show yield and ultimate tensile strengths as a function of temperature; in the same Figures, test data obtained by partner institutions (NRG Petten, CEA Saclay and FZK Karlsruhe) on the bars and 14-mm thick plates are also shown. Values reported by Böhler in the inspection certificate are included as well.

Good agreement can be observed in the common temperature range (RT to 300 °C) between SCK•CEN results and data provided by other institutions.

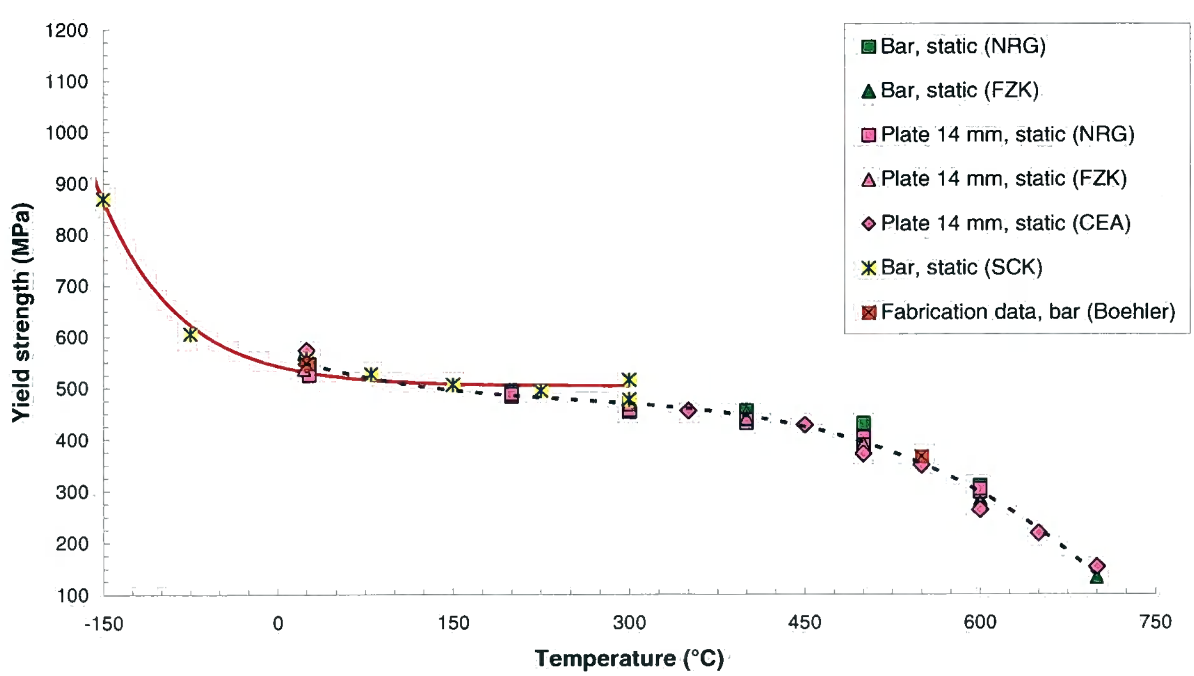


Figure 1 - *Yield strength results on EUROFER in the unirradiated condition.*

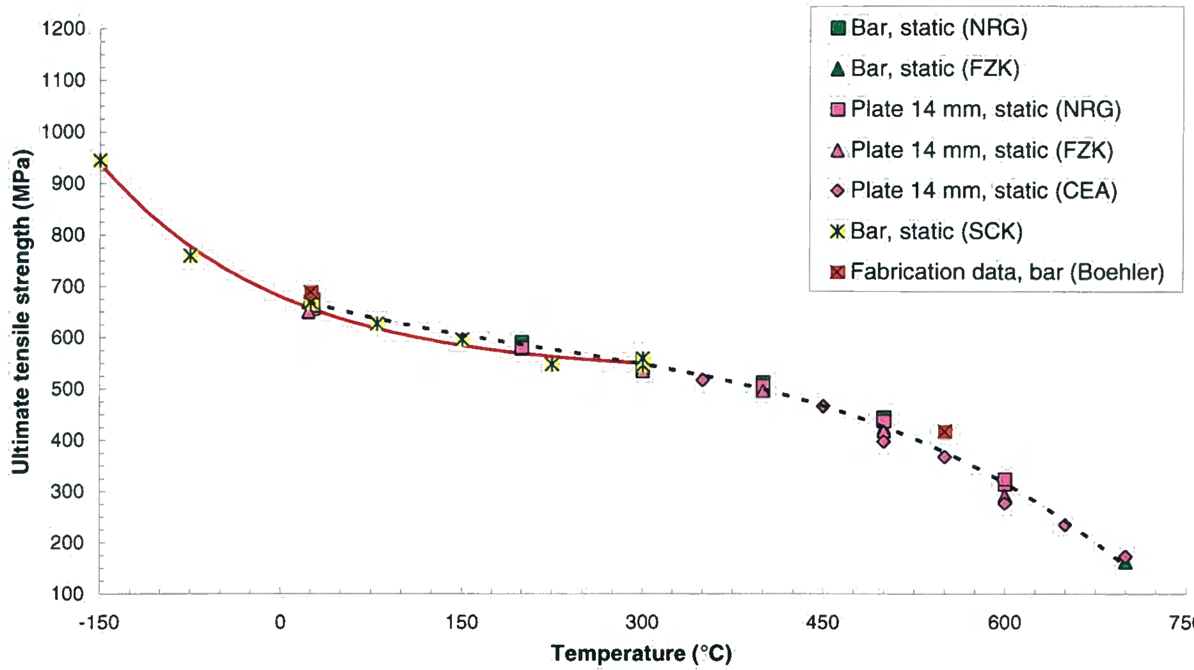


Figure 2 – *Ultimate tensile strength results on EUROFER in the unirradiated condition.*

### *4.2 Irradiated condition (IRFUMA-II, 0.52 dpa)*

Twelve tensile specimens of cylindrical cross section (diameter D = 3 mm, reduced section length $L_o$ = 15 mm) were tested from -150 to 300 °C, according to the E8M and E21 standards. No extensometer was used to measure specimen elongation.

Test results are given in Table 5.

Table 5 - *Results of the tensile tests on the irradiated specimens (IRFUMA-II).*

| Spec. code | T (°C) | $\sigma_{p02}$ (MPa) | $\sigma_{UTS}$ (MPa) | $\varepsilon_u$ (%) | $\varepsilon_t$ (%) | Z (%) | Dose (dpa) |
|---|---|---|---|---|---|---|---|
| 3R | -150 | 972 | 993 | 7 | 24 | 67 | 0.15 |
| 3S | -150 | 1000 | 1017 | 4 | 19 | 72 | 0.31 |
| 3T | -75 | 781 | 829 | 6 | 19 | 73 | 0.44 |
| 3U | -75 | 816 | 848 | 5 | 19 | 75 | 0.57 |
| 3V | 31 | 751 | 751 | 0 | 12 | 79 | 0.71 |
| 3W | 30 | 775 | 775 | 0 | 13 | 78 | 0.83 |
| 3X | 150 | 600 | 655 | 5 | 16 | 80 | 0.16 |
| 3Y | 150 | 642 | 668 | 3 | 14 | 78 | 0.33 |
| 3B | 225 | 681 | 681 | 0 | 11 | 79 | 0.75 |
| 3C | 225 | 691 | 691 | 0 | 10 | 75 | 0.89 |
| 3Z | 300 | 617 | 627 | 2 | 11 | 76 | 0.47 |
| 3A | 300 | 642 | 643 | 1 | 11 | 76 | 0.61 |

Due to the significant scatter in accumulated doses, we decided to regroup and analyse tensile specimens irradiated in IRFUMA-I and IRFUMA-II, according to the following doses:

a) from 0.15 to 0.5 dpa: 18 tests (12 from IRFUMA-I and 6 from IRFUMA-II), average 0.33 $\pm$ 0.089 dpa;
b) from 0.57 to 0.89 dpa: 6 tests (all from IRFUMA-II), average 0.71 $\pm$ 0.123 dpa.

Figure 3 and Figure 4 show respectively yield and ultimate tensile strengths for the two sub-groups of irradiated specimens, compared with SCK•CEN baseline data.

The hardening produced by irradiation is 84 MPa for $\sigma_{p02}$ and 66 MPa for $\sigma_{UTS}$, in terms of athermal stress component[3], for sub-group (a); for sub-group (b), we calculate a further increase of 86 MPa for the yield and 67 MPa for the UTS.

At room temperature, strengths increase with respect to the unirradiated state by 121 MPa and 55 MPa, respectively, for sub-group (a); a further increase of 85 MPa and 37 MPa is measured for sub-group (b). In terms of ductility parameters, we observe a general decrease in the elongation values, whereas reduction of area remains substantially unaffected.

The influence of dose values on the tensile properties of the individual samples has been verified by executing Vickers hardness measurements on two broken Charpy specimens, characterized by significantly different accumulated doses; the following has been measured, averaging 12 measurements per sample:

- on specimen E97-53 (dose = 0.92 dpa): HV5 = 249.7 $\pm$ 3.26
- on specimen E97-49 (dose = 0.29 dpa): HV5 = 233.6 $\pm$ 4.54

The difference in hardness (16.1) corresponds to a difference of approximately 45-50 MPa in terms of ultimate tensile strength according to a relevant ISO Technical Report [9].

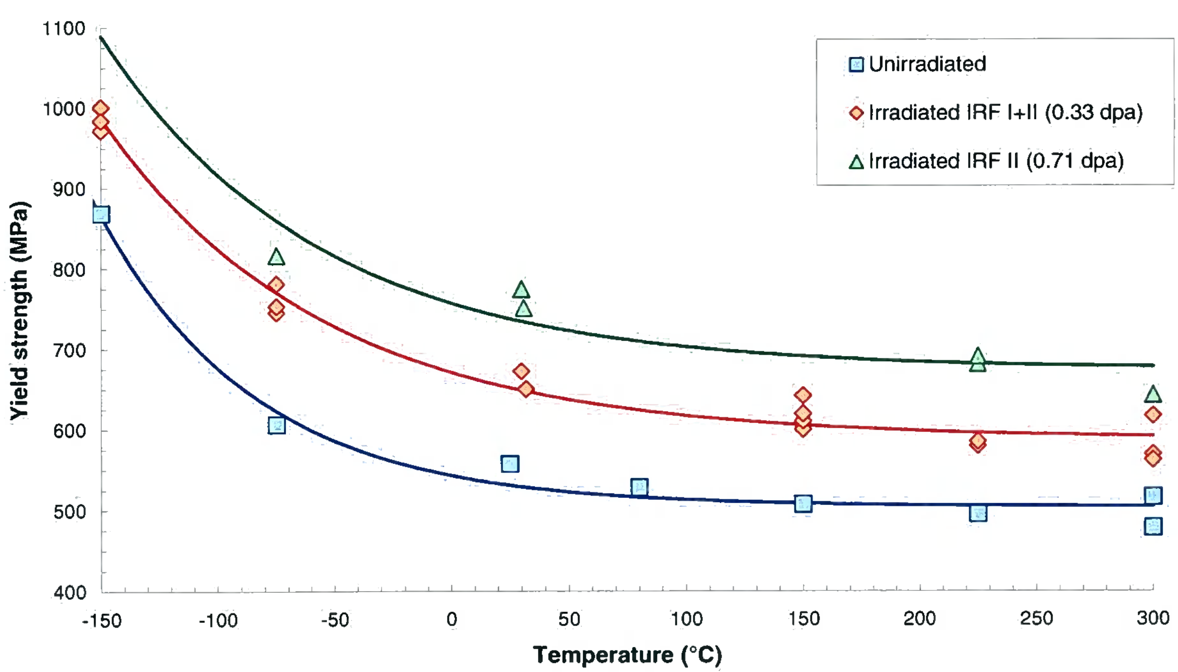


Figure 3 - *Yield strength results on EUROFER irradiated and comparison with data from the baseline condition.*

[3] If the regression curve for tensile strengths has the form $\sigma = \sigma_{ath} + \sigma_o \cdot e^{-\alpha \cdot T}$, $\sigma_{ath}$ is the athermal component.

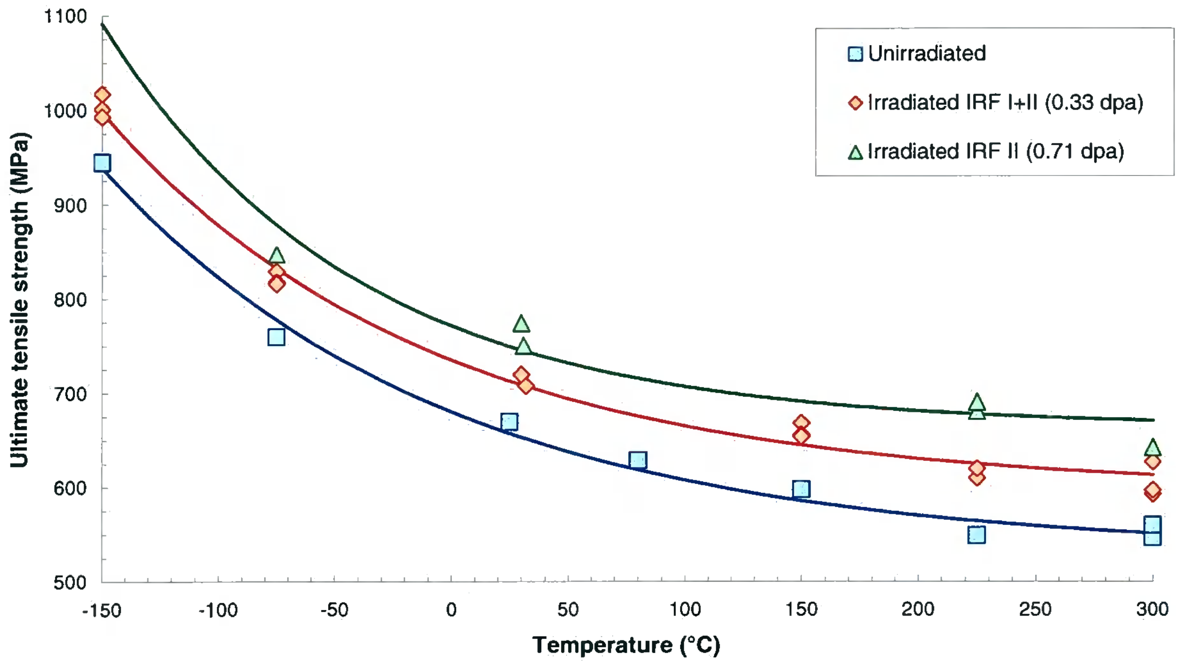


Figure 4 – *Ultimate tensile strength results on EUROFER irradiated and comparison with data from the baseline condition.*

In terms of total elongation at fracture, irradiation produces a decrease with respect to the baseline condition (Figure 5). Throughout the temperature range investigated, however, even for the highest doses $\varepsilon_t$ remains always greater than 10%.

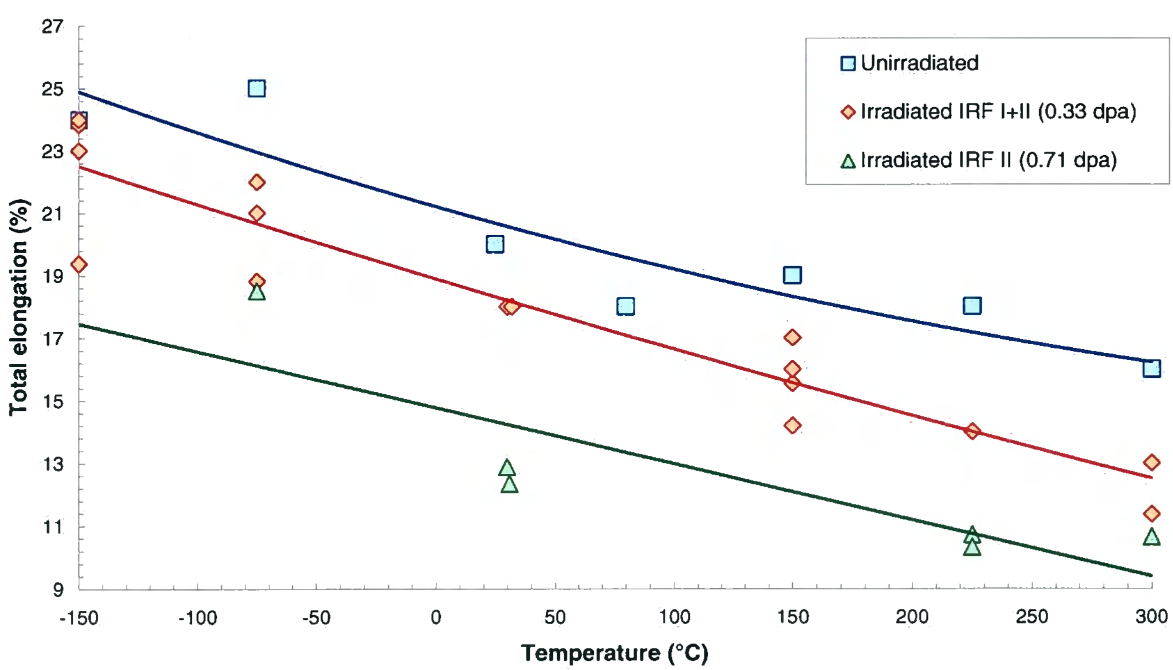


Figure 5 – *Total elongation values measured on EUROFER irradiated and comparison with data from the baseline condition.*

### *4.3 Comparisons with other RAFM steels*

In terms of tensile properties (i.e. mechanical strength), the consequence of neutron irradiation strongly depends on the irradiation temperature. Below 400 - 500 °C, irradiation-induced microstructural changes lead to lattice hardening, causing an increase in yield stress and ultimate tensile strength and a decrease in uniform and total elongation. The magnitude of the hardening decreases with increasing temperature until it disappears between 400 to 500 °C [10,11]. For RAFM steels, relatively limited data exist for neutron irradiations below 400 °C and doses below 5 dpa [12].

As an example, tensile tests on the MANET I steel (a type 11Cr-MoVNb alloy) irradiated in HFR at 250 and 350 °C to about 0.5 to 10 dpa, indicated that rapid hardening occurred up to ≈1.5 dpa, after which it leveled off; saturation was concluded to occur at ≤ 5 dpa [13,14]. Further tensile tests on the same steel showed that, for irradiation at 300 °C, an increase of 37% for the yield stress and and 31% for the UTS were observed at accumulated doses of about 0.3 dpa [14]; such figures are larger than what reported in [3] for the first irradiation of EUROFER up to 0.32 dpa (20% for $\sigma_{p02}$ and 10% for $\sigma_{UTS}$).

More recently, a collection was published of mechanical test results obtained from several martensitic steels, irradiated at 300 °C to different doses in the HFR reactor in Petten [15]. The steels characterized were F82H mod. (plates, EB-welds and TIG welds) and BS-9Cr2WVTa. Data corresponding to baseline conditions, 2.5 dpa, 5 dpa and in the range 8-12 dpa were reported.

Typical chemical compositions of the MANET I, F82H and BS-9Cr2WVTa steels are given in Table 6 [10].

Table 6 - *Typical chemical compositions (wt%) for the MANET-I, F82H and 9Cr2WVTa steels.*

| Steel | C | Si | Mn | Cr | Ni | Mo | V | Nb | W | N | B | Cu | Al | Ta |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MANET-I | 0.13 | 0.37 | 0.82 | 10.6 | 0.80 | 0.77 | 0.22 | 0.16 | | 0.020 | 0.0085 | 0.015 | 0.05 | |
| F82H | 0.092 | 0.20 | 0.083 | 7.73 | 0.032 | 0.0053 | 0.189 | 0.0057 | 2.06 | <0.01 | 0.003 | 0.0059 | 0.01 | 0.018 |
| 9Cr2WVTa | 0.11 | 0.21 | 0.44 | 8.9 | <0.01 | 0.01 | 0.23 | | 2.01 | 0.0215 | <0.001 | 0.03 | 0.017 | 0.06 |

In Figure 6 and Figure 7, EUROFER baseline and irradiated tensile data at 300 °C from the two sub-groups (0.33 dpa and 0.71 dpa) have been superimposed to the original figures in [15]; for the sake of comparison, "eyeball" trend curves have been drawn for the tensile properties of F82H plates in Figure 6. It appears that, with respect to the steels tested and in particular F82H plate materials, EUROFER undergoes a larger increase of mechanical strength, whereas ductility is affected to a negligible degree. Data at higher irradiation doses are however necessary, in order to establish at what dose tensile properties become saturated; the saturation level for F82H in its different product forms seems to be reached around 5 dpa according to the data in Figure 6.

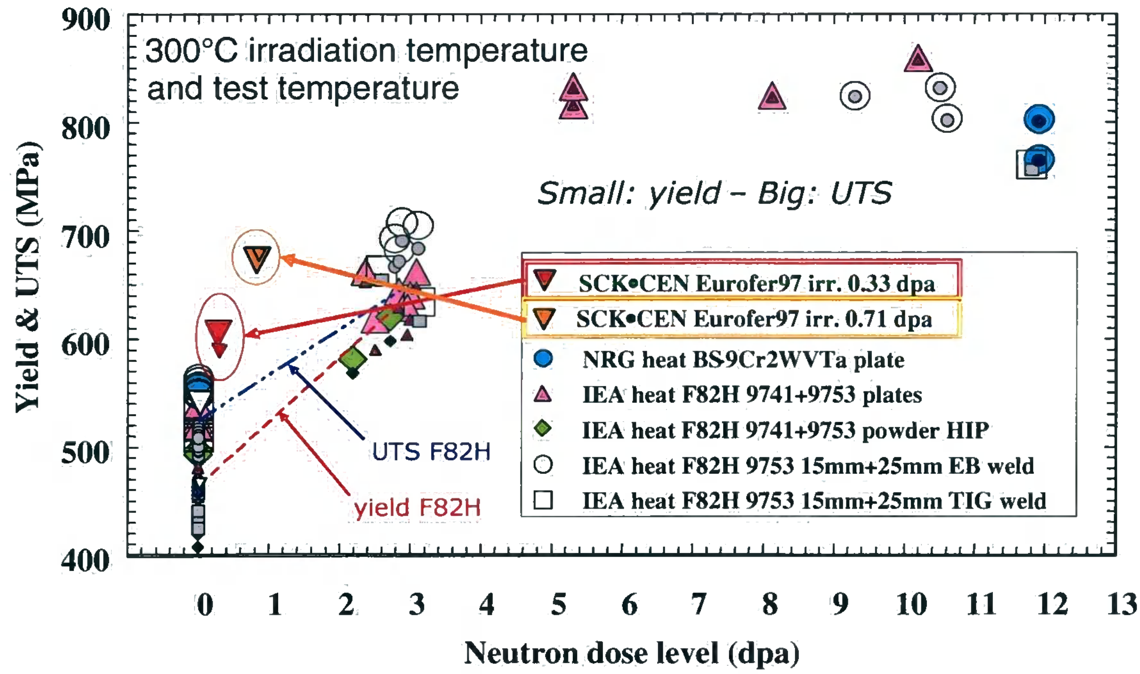


Figure 6 - *Comparison between EUROFER and F82H in terms of tensile strengths as a function of accumulated dose.*

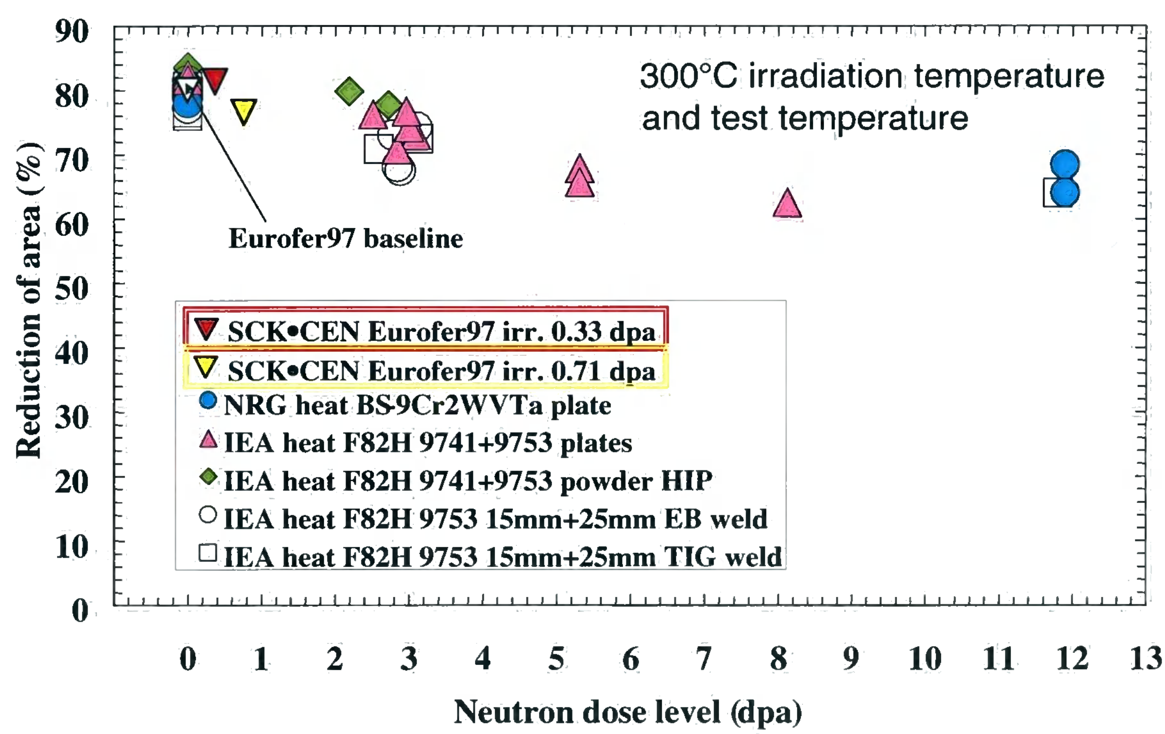


Figure 7 - *Comparison between EUROFER and F82H in terms of reduction of area as a function of accumulated dose.*

# 5 Impact test results

## *5.1 Unirradiated condition*

Twenty-seven Charpy V-notch specimens of standard type (cross section 10 × 10 mm², length 55 mm) have been tested from -110 to 300 °C, using two different impact testers, one situated in the non-controlled zone (Toni-MFL pendulum) and one inside a hot cell (Wolpert pendulum, normally used for testing irradiated materials). Both machines have a capacity of 300 J and were equipped with ISO-type instrumented strikers (tup radius = 2 mm). Tests were aimed at obtaining full transition curves for absorbed energy (KV), shear fracture appearance (SFA) and lateral expansion (LE); from these, DBTT (ductile-to-brittle transition temperatures) and USE (upper shelf energy) have been calculated. Two specimens had been sampled with a transversal orientation, to verify whether any orientiation effect was present.

The reason for using the Wolpert machine for testing unirradiated samples derived from the fact that anomalous results had been obtained using this pendulum on a first series of tests on IRFUMA-II irradiated samples (more details will be given in the next chapter). Such anomalies, which were observed below room temperature, were found to arise from the incorrect positioning of the specimen inside the environmental chamber, which below ambient temperature caused the actual temperature to be higher than the expected value. Of the seven low-temperature tests carried out on the Wolpert machine, four were performed before and three after the positioning problem was solved; the different behaviour can be clearly appreciated from the comparision with the remaining 18 test results obtained on the Toni-MFL machine.

Test results are summarized in Table 7.

Table 7 - *Results of the impact tests on EUROFER unirradiated. All specimens longitudinal orientation except where indicated.*

| Impact tester | Spec. code | T (°C) | KV (J) | SFA (%) | LE (mm) | Remarks |
|---|---|---|---|---|---|---|
| TONI-MFL | E97-86 | -110 | 5.12 | 0 | 0.089 | |
| TONI-MFL | E97-74 | -90 | 16.35 | 2 | 0.334 | |
| TONI-MFL | E97-78 | -80 | 26.07 | 5 | 0.462 | |
| TONI-MFL | E97-82 | -70 | 52.12 | 6 | 0.724 | |
| TONI-MFL | E97-81 | -65 | 30.278 | 6 | 0.432 | |
| TONI-MFL | E97-80 | -65 | 83.275 | 14 | 1.171 | |
| TONI-MFL | E97-76 | -60 | 71.46 | 16 | 0.934 | |
| TONI-MFL | E97E36 | -60 | 161.84 | 54 | 2.183 | |
| TONI-MFL | E97-101 | -60 | 99.04 | 28 | 1.374 | Transversal orientation |
| TONI-MFL | E97-77 | -50 | 184.60 | 71 | 2.249 | |
| TONI-MFL | E97E34 | -40 | 198.34 | 74 | 2.299 | |
| TONI-MFL | E97E35 | -20 | 243.90 | 100 | 2.215 | |
| TONI-MFL | E97-79 | 0 | 250.32 | 100 | 2.443 | |
| TONI-MFL | E97-58 | 24 | 240.27 | 100 | - | |
| TONI-MFL | E97-57 | 24 | 245.46 | 100 | - | |
| TONI-MFL | E97-75 | 24 | 247.30 | 100 | 2.476 | |
| TONI-MFL | E97-100 | 25 | 234.83 | 100 | 2.176 | Transversal orientation |
| TONI-MFL | E97-87 | 100 | 242.63 | 100 | 2.518 | |
| TONI-MFL | E97-88 | 200 | 250.04 | 100 | 2.508 | |
| TONI-MFL | E97-89 | 300 | 289.62 | 100 | 1.831 | Specimen jammed – test discarded |
| WOLPERT | E97-95 | -70 | 40.34 | 10 | 1.586 | |
| WOLPERT | E97-93 | -60 | 225.04 | 100 | 2.281 | Position/Temperature incorrect |
| WOLPERT | E97-94 | -60 | 98.10 | 32 | 1.238 | |

| Impact tester | Spec. code | T (°C) | KV (J) | SFA (%) | LE (mm) | Remarks |
|---|---|---|---|---|---|---|
| WOLPERT | E97-92 | -55 | 243.94 | 100 | 2.389 | Position/Temperature incorrect |
| WOLPERT | E97-91 | -50 | 240.46 | 100 | 2.392 | Position/Temperature incorrect |
| WOLPERT | E97-90 | -45 | 234.62 | 100 | 2.399 | Position/Temperature incorrect |
| WOLPERT | E97-96 | -45 | 194.99 | 72 | 2.256 | |

Test results were fitted using the hyperbolic tangent model:

$$P(T) = A + B\tanh\left(\frac{T - DBTT}{C}\right)$$

where: $P(T)$ is the fitted variable; $A$, $B$ and $C$ are fitting coefficients and $DBTT$ is the ductile-to-brittle transition temperature. Experimental points and transition curves are shown in Figure 8 (absorbed energy), Figure 9 (SFA) and Figure 10 (lateral expansion).

No influence of sampling orientation is visible on the data obtained. The two specimens machined in the T direction and tested one in the transition region and one in upper shelf, have therefore been included in the analyses.

The values of $DBTT$ and $USE$ obtained from the regressions are as follows:

- $DBTT_{KV}$ = -57.1 °C (from energy data)
- $USE$ = 244.3 J
- $DBTT_{LE}$ = -64.2 °C (from LE data)
- $FATT_{50}$ = -53.5 °C (from SFA data).

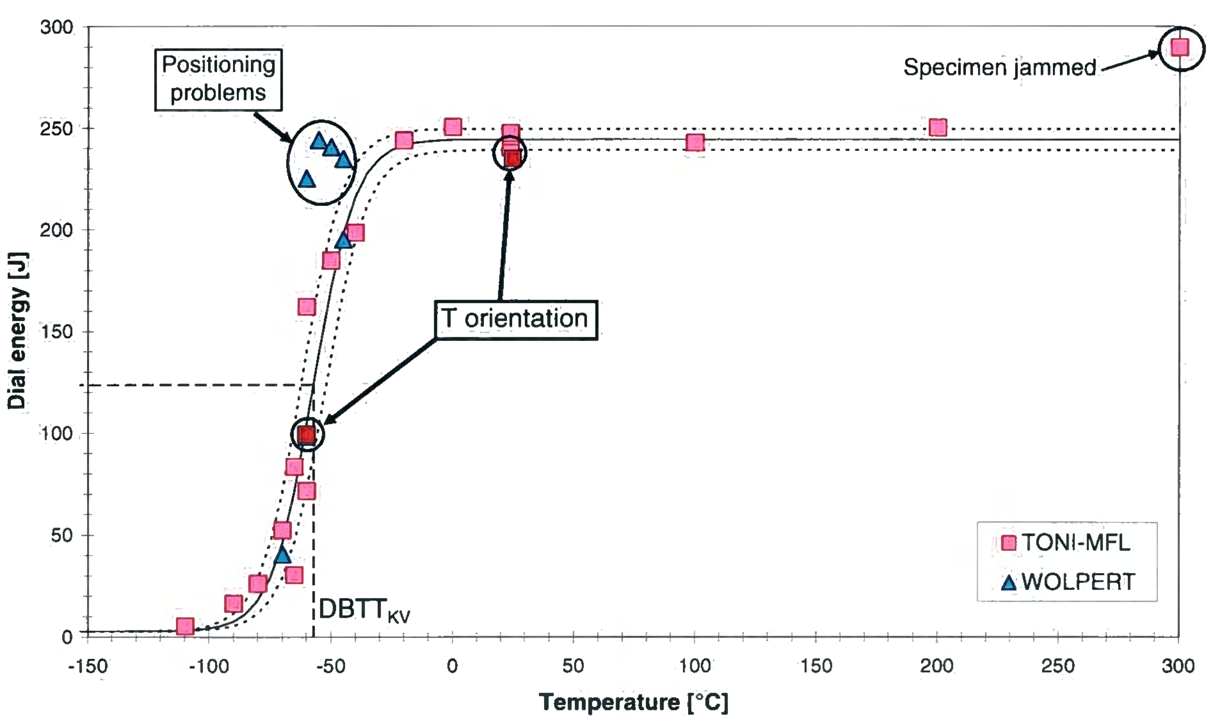


Figure 8 - *Absorbed energy data obtained on EUROFER unirradiated. Test results biased by positioning problems are clearly indicated, and were not included in the fit; the specimen tested at 300 °C was discarded from the analyses because it jammed between anvil and striker.*

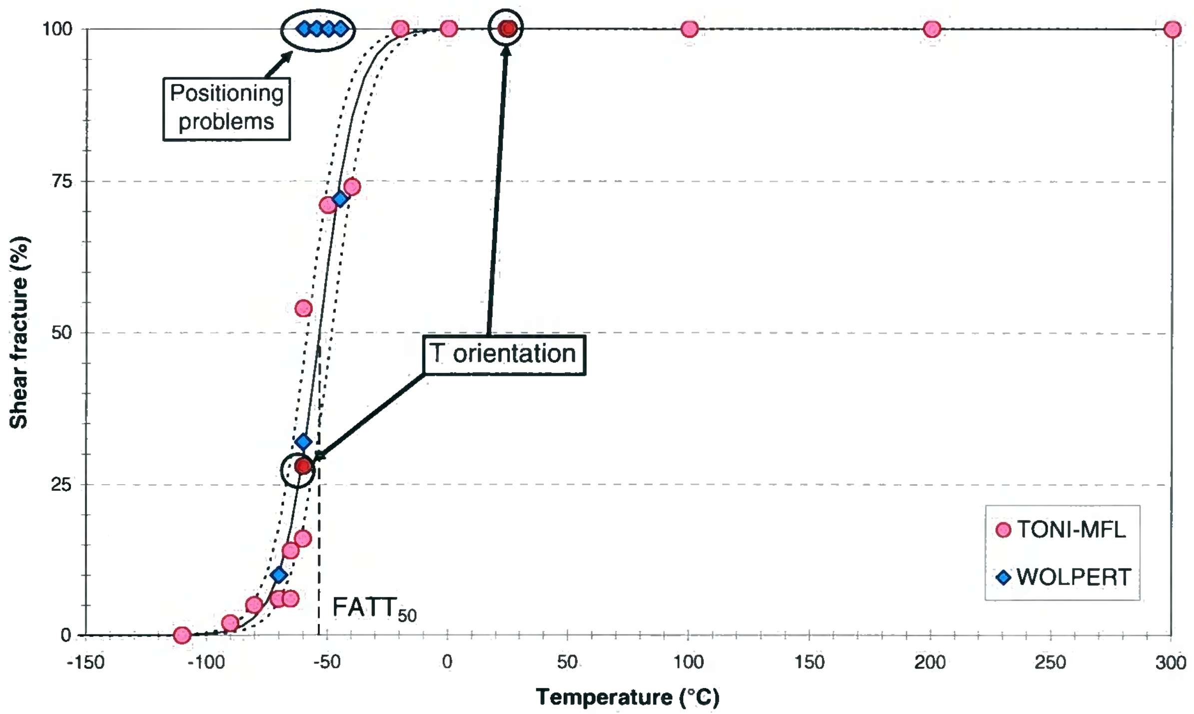


Figure 9 – *Shear Fracture Appearance obtained on EUROFER unirradiated.*

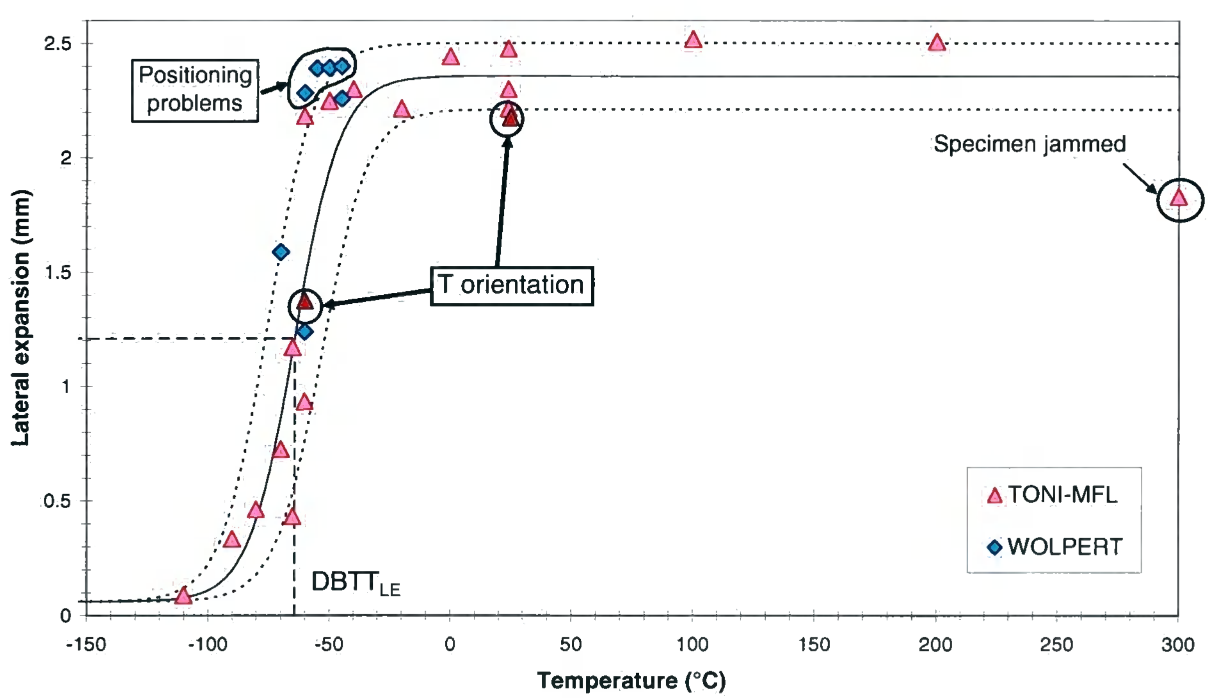


Figure 10 – *Lateral expansion data obtained on EUROFER unirradiated.*

Results obtained are in good agreement with data reported for the baseline condition by FZK on one of the bars and FZK and CEA on the 14 mm-thick plate, as can be seen in Figure 11 (KV) and Figure 12 (SFA). The discrepancy between the fitting curves in the lower transition region is caused by the limited number of tests available for FZK and CEA in that temperature range. For the sake of consistency, comparisons with irradiated data will be performed only with SCK results as given in Table 7.

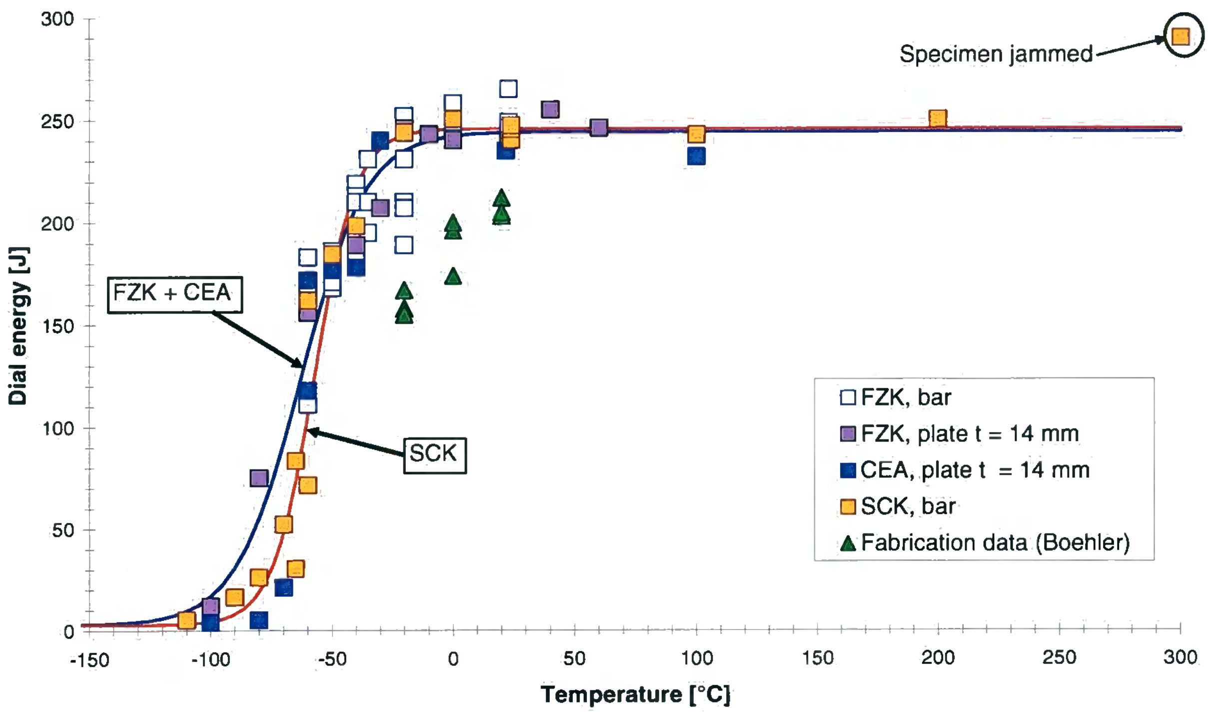


Figure 11 - *Comparison between absorbed energy data obtained by different labs on EUROFER unirradiated.*

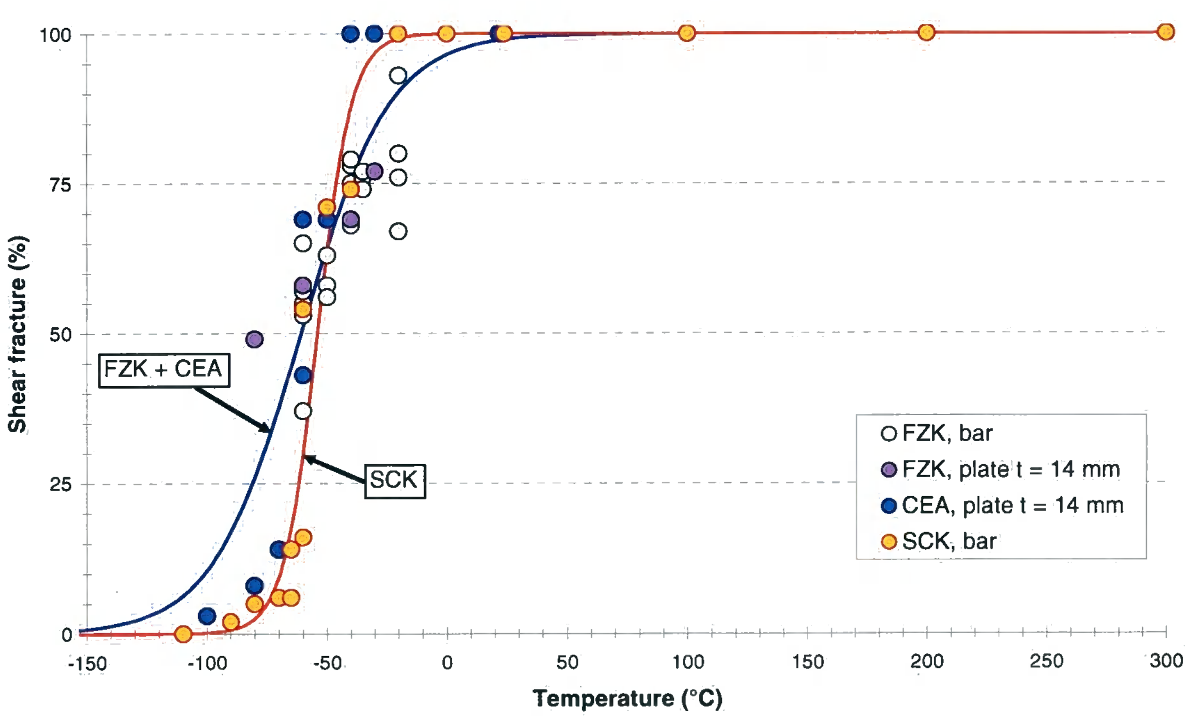


Figure 12 - *Comparison between Shear Fracture Appearance data obtained by different labs on EUROFER unirradiated.*

It should be also noted that, in Figure 11, absorbed energy data reported by the manufacturer (Böhler) are significantly lower; this might indicate that the values reported in the inspection certificate are actually obtained from the 25 mm-thick plate, which has been found to have worse toughness properties then the bars or the 14 mm plate [15].

### *5.2 Irradiated condition (IRFUMA-II, 0.46 dpa)*

A first series of impact tests was performed on the standard Charpy samples irradiated during IRFUMA-II, using the Wolpert machine located in hot cell. These specimens were tested previous to the unirradiated samples mentioned in §5.1; due to the incorrect automatic positioning of the samples, the low temperature tests gave unreliable results (negative *DBTT* shifts with respect to the baseline condition).

To prove that temperature data were seriously biased, two samples of the original IRFUMA-II batch were tested at low temperatures (-100 and -95 °C) using another machine located in a different hot cell: a 358 J Tinius-Olsen machine equipped with an instrumented striker conforming to the ASTM geometry (tup radius = 8 mm)[4]. The results of these tests fully confirmed the assumption based on temperature problems.

A second series of ten Charpy specimens were reconstituted using broken halves from the first series of samples; long inserts (22 mm) were used, in order to avoid any influence of the reconstitution process.

Out of the ten reconstituted specimens:

- three were tested on the Tinius-Olsen machine (all yielding absorbed energies well below 100 J, thus excluding any effect of the tup configuration);
- seven were tested on the Wolpert pendulum; among these, two samples were tested below RT before the temperature problems had been solved and should therefore be discarded from the analysis.

We are therefore left with ten reliable test results, which are summarized in Table 8 and graphically presented in Figure 13 (KV), Figure 14 (SFA) and Figure 15 (LE). The average dose for these specimens is 0.51 dpa.

Table 8 - *Results of the impact tests on EUROFER irradiated (IRFUMA-II, 0.51 dpa).*

| Impact tester | Spec. code | T (°C) | KV (J) | SFA (%) | LE (mm) | Dose (dpa) |
|---|---|---|---|---|---|---|
| TINIUS-OLSEN | E97-55 | -130 | 2.6 | 0 | 0.050 | 0.29 |
| WOLPERT | E97-51 | -100 | 12.51 | 8 | 0.228 | 0.64 |
| TINIUS-OLSEN | E97-56 | -95 | 4.1 | 0 | 0.119 | 0.41 |
| TINIUS-OLSEN | E97-56/R | -60 | 8.00 | 3 | 0.174 | 0.41 |
| TINIUS-OLSEN | E97-52/R | -50 | 6.00 | 2 | 0.068 | 0.80 |
| TINIUS-OLSEN | E97-55/R | -37.5 | 20.00 | 7 | 0.370 | 0.29 |
| WOLPERT | E97-52/L | -25 | 188.97 | 79 | 2.029 | 0.80 |
| WOLPERT | E97-50/L | 25 | 242.89 | 100 | 1.949 | 0.41 |
| WOLPERT | E97-50/R | 150 | 240.23 | 100 | 2.353 | 0.41 |
| WOLPERT | E97-51/L | 300 | 233.83 | 100 | 2.192 | 0.64 |

The following parameters have been calculated from the different transition curves:

[4] Below KV ≈ 200 J, the configuration of the impact striker is considered to have negligible influence on the absorbed energy [16].

- $DBTT_{KV}$ = -29.3 °C (from energy data)
- *USE* = 239.0 J
- $DBTT_{LE}$ = -32.5 °C (from LE data)
- $FATT_{50}$ = -29.2 °C (from SFA data).

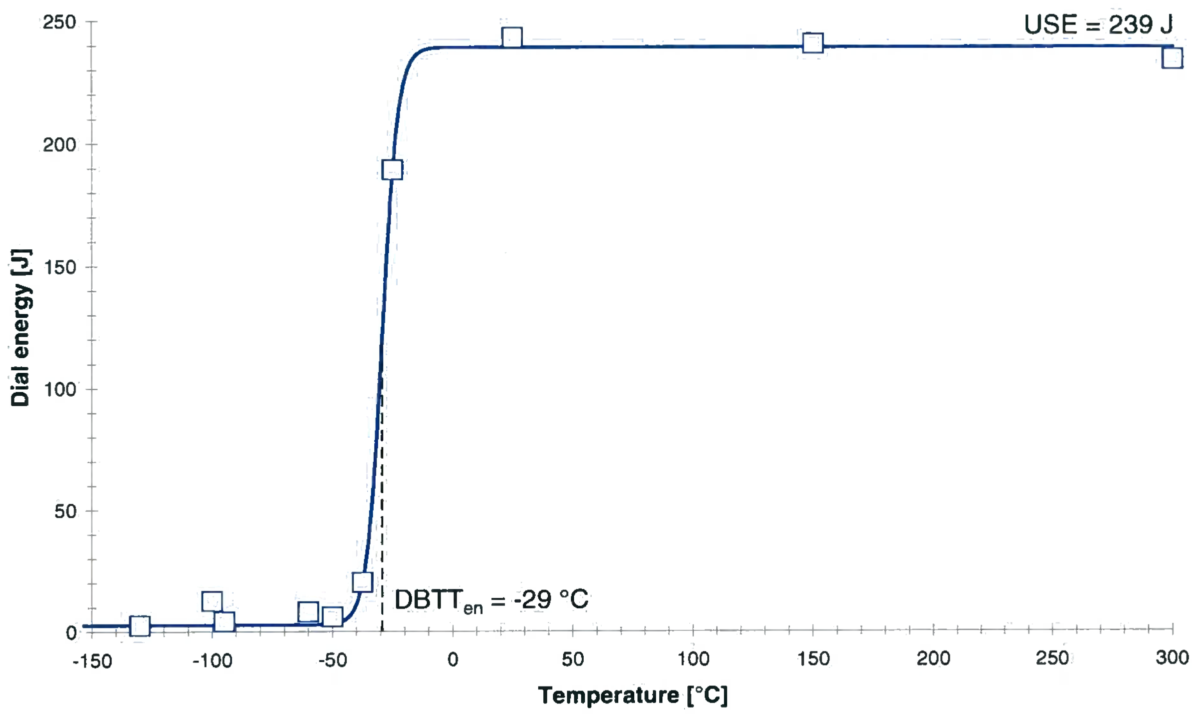


Figure 13 - *Absorbed energy data obtained from EUROFER irradiated (IRFUMA-II, 0.51 dpa).*

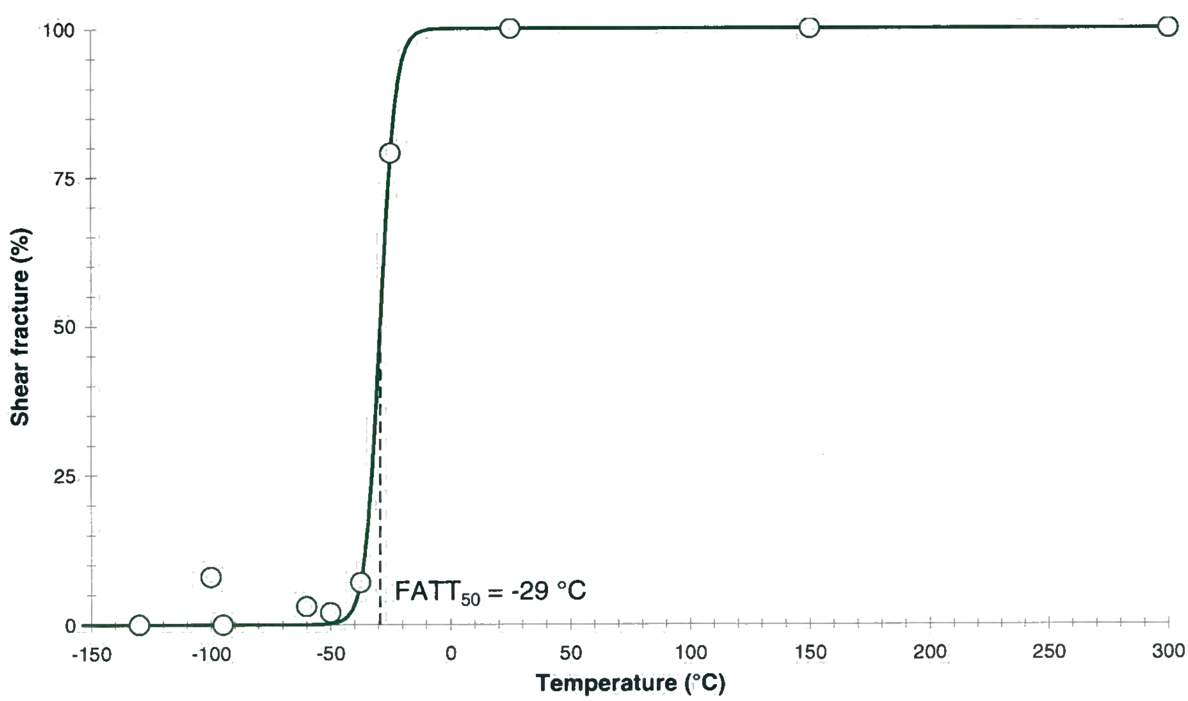


Figure 14 – *Shear Fracture Appearance data obtained from EUROFER irradiated (IRFUMA-II, 0.51 dpa).*

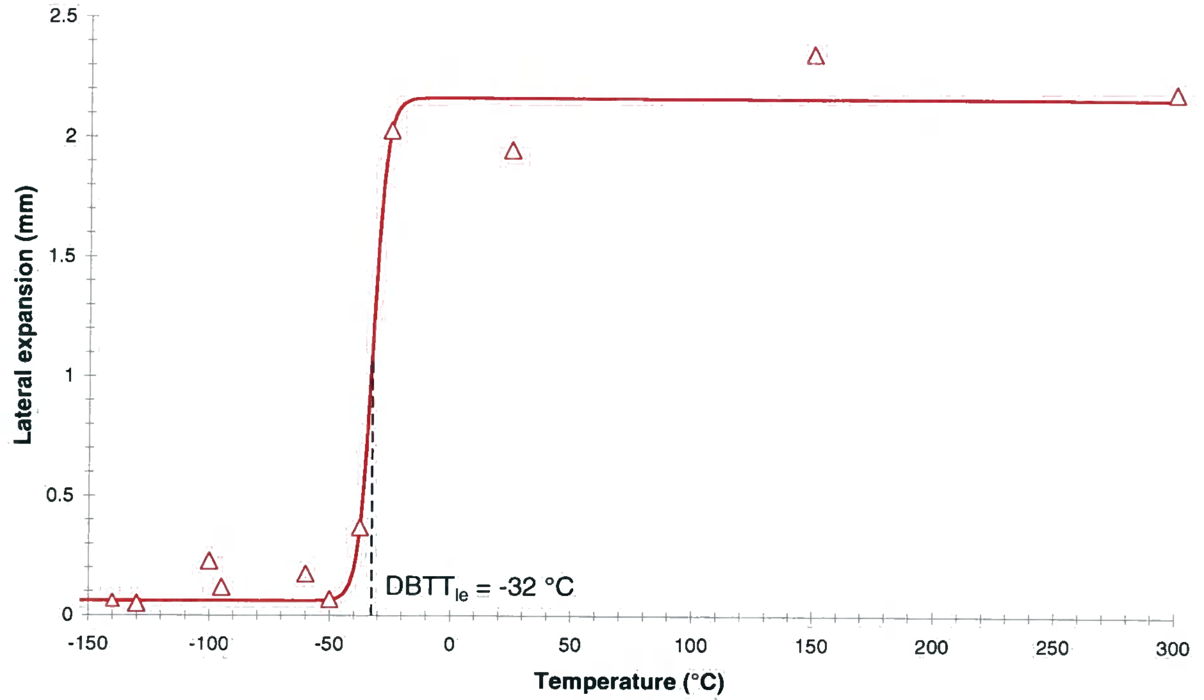


Figure 15 – *Lateral expansion data obtained from EUROFER irradiated (IRFUMA-II, 0.51 dpa).*

An extremely steep ductile-to-brittle transition can be observed, as already remarked in the case of the baseline condition and IRFUMA-I [3].

The effects of irradiation on the impact transition curves are illustrated in Figure 16 (KV), Figure 17 (SFA) and Figure 18 (LE). With respect to the results obtained from IRFUMA-I (0.27 dpa), irradiation to 0.51 dpa in IRFUMA-II produces an additional *DBTT* shift of about 15 °C. The total *DBTT* shift from the unirradiated condition is around 25-30 °C.

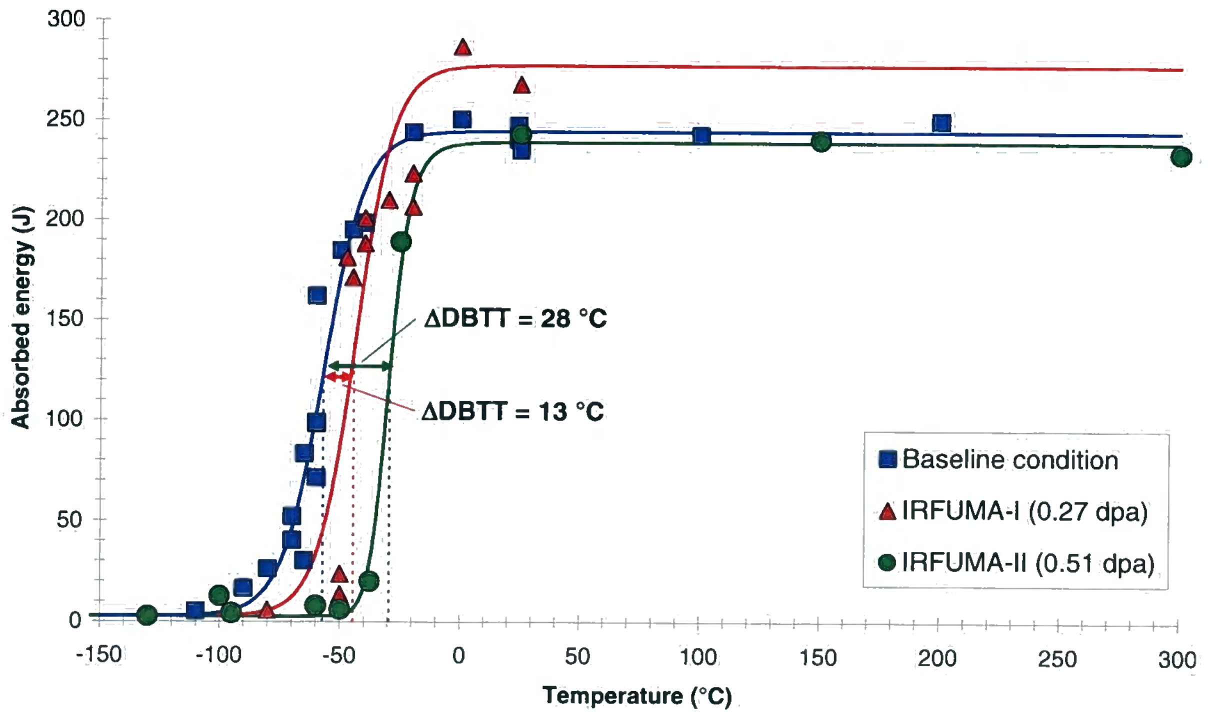


Figure 16 - *Comparison between unirradiated and irradiated EUROFER in terms of absorbed energy.*

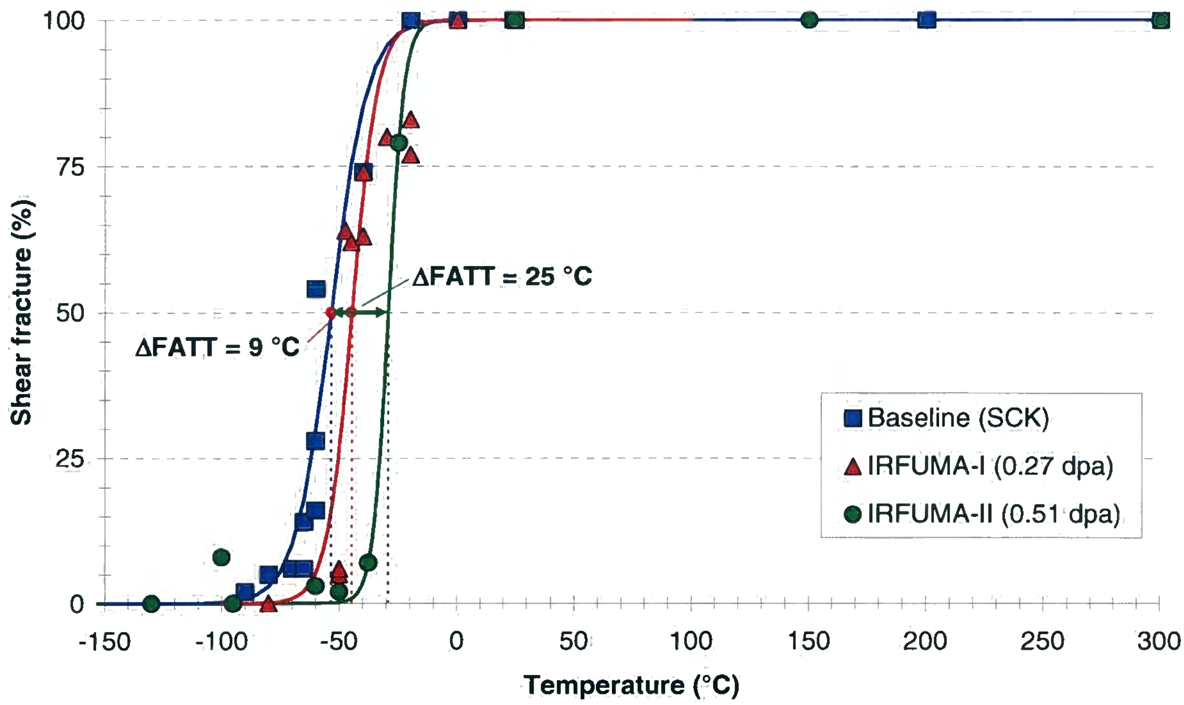


Figure 17 - *Comparison between unirradiated and irradiated EUROFER in terms of Shear Fracture Appearance.*

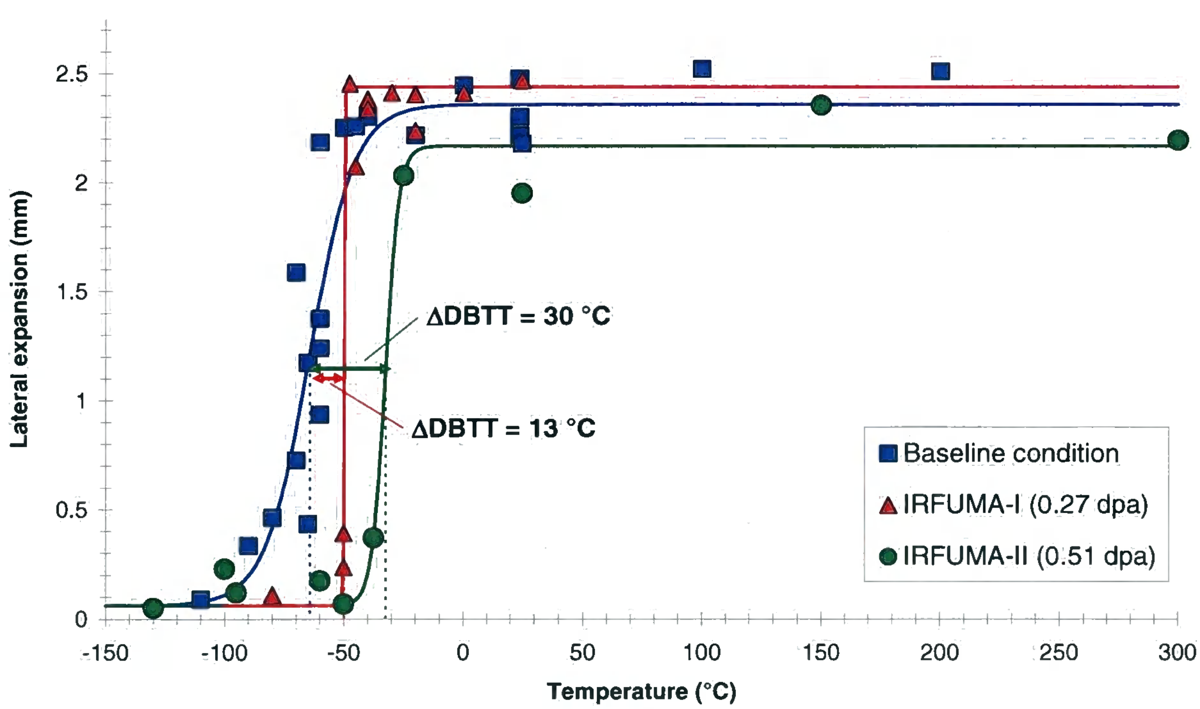


Figure 18 - *Comparison between unirradiated and irradiated EUROFER in terms of lateral expansion.*

### 5.3 *Comparisons with other RAFM steels*

Irradiation embrittlement of ferritic-martensitic steels is related to the hardening caused by the production of dislocation loops, dislocation lines and precipitates during irradiation below 600 °C [17,18]. Hardening is characterized by an increase in flow stress, and, under the assumption that the fracture stress is unaffected by irradiation and that the intersection of the fracture stress curve and the flow-stress curve defines the ductile-to-brittle transition temperature, the increase in flow stress causes a shift in the DBTT [17].

Furthermore, in a fusion reactor, large amounts of transmutation helium will form in the first wall of the structure; the presence of He in the irradiated steel can exacerbate the shift in DBTT [10]. DBTT shift is normally accompanied by a degradation of Upper Shelf Energy.

As in the case of tensile properties, evidence has been found that for most ferritic-martensitic steels the increase in DBTT and the decrease in USE are particularly pronounced below approximately 5 dpa, after which an effect of saturation starts to ensue [19].

The effect of Chromium content on the irradiation-induced DBTT shift has been extensively studied [20]. It was concluded that 8-9Cr steels showed the most promising behaviour, and they were recommended for consideration for "first wall and blanket of fusion reactors". The improved impact behaviour of 9Cr-WV relative to those with greater or lesser Cr contents has been demonstrated in several studies; a minimum of ΔDBTT was observed in the vicinity of 9% Cr [21].

Another extensive study [22] allows comparing DBTT shifts measured on EUROFER irradiated in IRFUMA-I and IRFUMA-II with measurements performed on several other RAFM steels irradiated in HFR under similar conditions (300 °C, 0.2 and 0.8 dpa); the results of such comparison are given in Table 9 and shown in Figure 19. Typical chemical compositions of OPTIFER-Ia, OPTIFER-II and MANET-II are given in Table 10.

Table 9 - *DBTT shifts measured on EUROFER and other RAFM steels irradiated at 300 °C.*

| Steel | Dose (dpa) | ΔDBTT (°C) | Reference |
|---|---|---|---|
| EUROFER | 0.31 | 13 | [3] |
| | 0.51 | 28 | (*This report*) |
| F82H | 0.2 | 15 | [22] |
| | 0.8 | 45 | |
| OPTIFER-Ia | 0.2 | 35 | |
| | 0.8 | 85 | |
| OPTIFER-II | 0.2 | 25 | |
| | 0.8 | 105 | |
| MANET-I | 0.2 | 70 | |
| | 0.8 | 130 | |
| MANET-II | 0.2 | 50 | |
| | 0.8 | 115 | |
| 9Cr2WVTa | 0.2 | 20 | |
| | 0.8 | 35 | |

Table 10 - *Typical chemical compositions (wt%) of OPTIFER-Ia, OPTIFER-II and MANET-II, steels.*

| Steel | C | Si | Mn | Cr | Ni | Mo | V | Nb | W | N | B | Zr | Ta |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OPTIFER-Ia | 0.11 | | 0.5 | 9.3 | | | 0.26 | | 0.96 | 0.016 | 0.006 | | 0.07 |
| OPTIFER-II | 0.13 | | 0.49 | 9.5 | | | 0.28 | | 0.01 | 0.016 | | | 0.018 |
| MANET-II | 0.10 | 0.20 | 1.0 | 10.5 | 0.6 | 0.58 | 0.2 | 0.15 | | 0.004 | | 0.02 | |

We observe that the performance of EUROFER at these low doses is better than all other RAFM steels shown in Figure 19, with a slight improvement with respect to F82H. It is also evident that radiation embrittlement is enhanced for Cr contents above 9%.

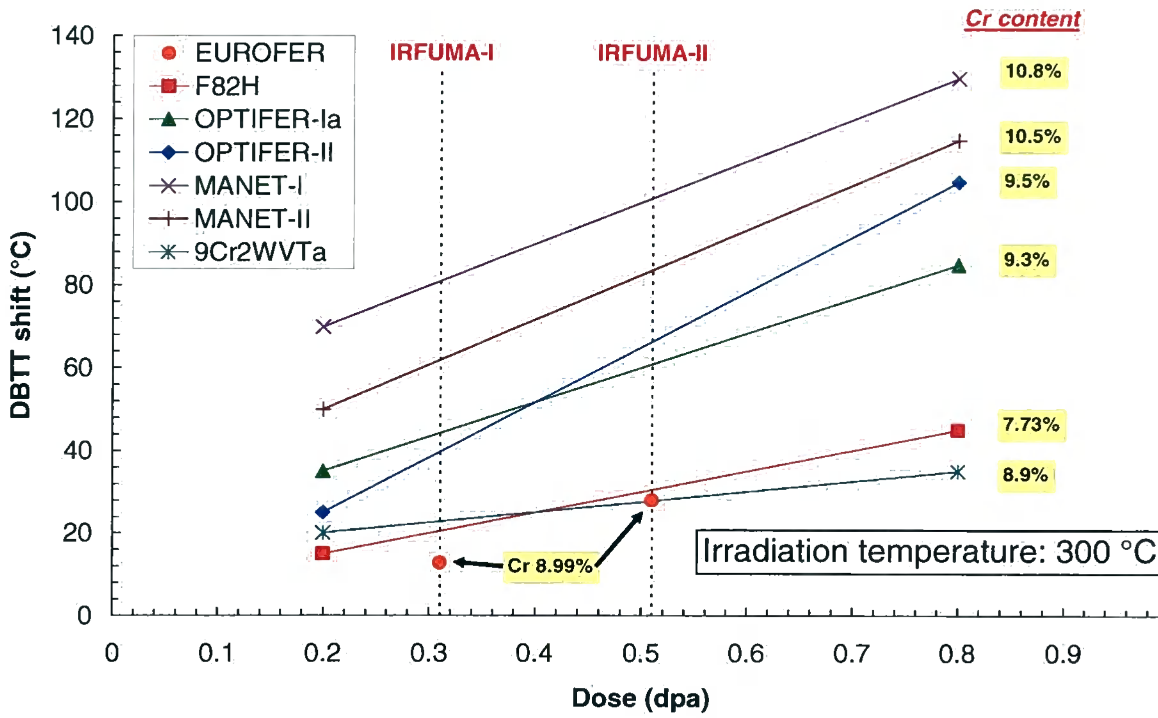


Figure 19 - *Comparison between various RAFM steels irradiated at 300 °C, in terms of DBTT shift [22]. Straight lines are just a guide for the eye, and SHOULD NOT be extrapolated to higher doses.*

# 6 Fracture toughness test results

## *6.1 Unirradiated condition*

### 6.1.1 Ductile-to-brittle transition region

For the baseline condition, fracture toughness tests on precracked Charpy-V specimens had already been performed in the ductile-to-brittle transition region and reported in conjunction with the IRFUMA-I campaign [3], since no unirradiated toughness data were available for the forged bars and for bend-type specimens.

Nine PCCv samples, several of which reconstituted, had been tested for Master Curve analysis between -150 and -100 °C; data from one of the specimens (E97-92) had to be discarded since the fatigue precrack was totally asymmetric (normal on one side, almost non-existant on the opposite). The calculated value of the reference temperature ($T_o$ = -123 °C) was invalid according to the ASTM E1921 standard, although the difference from the validity limit was relatively small.

In conjunction with the IRFUMA-II post-irradiation tests, three additional PCCv specimens have been tested; two of them, however, revealed the same extremely irregular fatigue precracking behaviour (Figure 20) and have been broken open, but not actually tested (the results would have been unusable anyway).

However, with the additional valid test (specimen E97-84), the calculated value of $T_0$ = -121 °C becomes fully valid according to E1921.

An overview of the tests performed and of the results of the Master Curve analysis is presented in Table 11 and Table 12, respectively. Master Curve and experimental data points are shown in Figure 21.

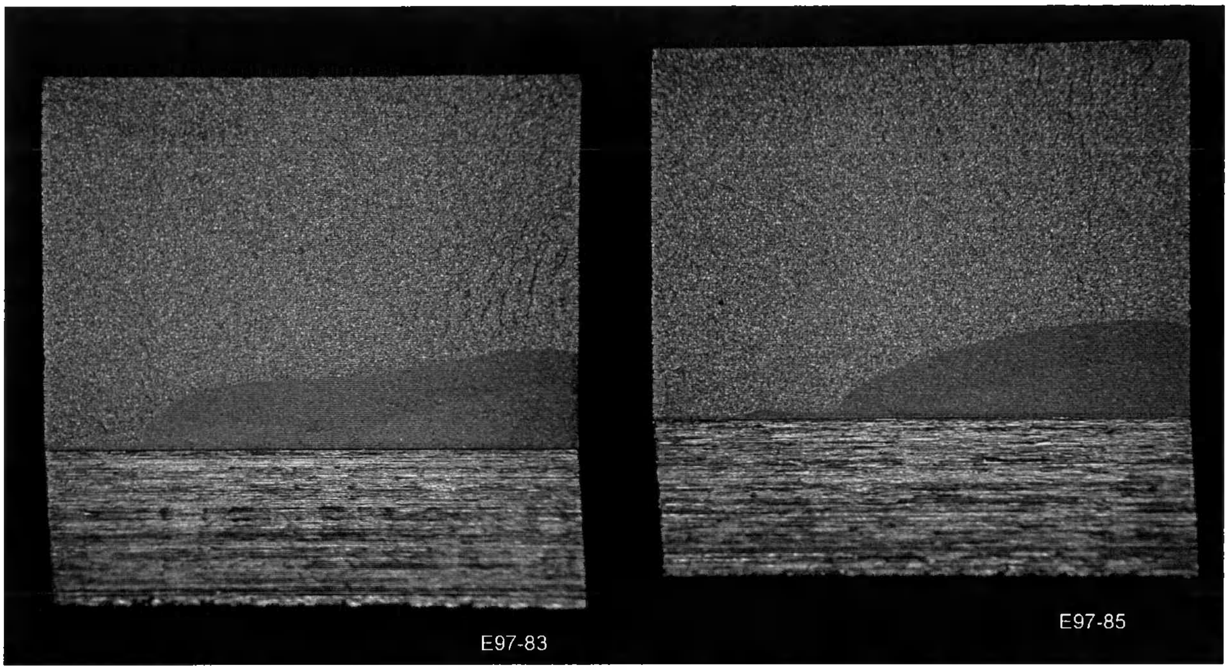


Figure 20 - *Fracture surfaces of specimens E97-83 and E97-85, showing the invalid fatigue crack propagation.*

Table 11 - *Individual results for fracture toughness tests on EUROFER in the baseline condition.*

| Spec. code | T (°C) | W (mm) | B (mm) | $a_o$ (mm) | Δa (mm) | $K_{Jc}$ (MPa√m) | DATA VALID |
|---|---|---|---|---|---|---|---|
| E97-71R | -150 | 10.005 | 10.005 | 5.131 | 0.00 | 60.0 | YES |
| E97-71 | -140 | 9.972 | 9.972 | 5.221 | 0.00 | 60.0 | YES |
| E97-84 | -130 | 9.930 | 9.999 | 3.622 | 0.00 | 46.8 | Precrack invalid |
| E97-73 | -130 | 9.972 | 9.972 | 4.891 | 0.00 | 168.7 | YES |
| E97-71L | -130 | 10.002 | 9.927 | 4.556 | 0.00 | 94.0 | YES |
| E97-72R | -100 | 10.022 | 10.022 | 5.276 | 0.00 | 89.9 | YES |
| E97-73L | -100 | 10.190 | 10.190 | 5.158 | 0.00 | 108.1 | NO ($K_{Jc} > K_{lim}$) |
| E97-73R | -100 | 10.012 | 10.012 | 5.091 | 0.00 | 108.0 | YES |
| E97-72L | -100 | 10.033 | 10.033 | 5.098 | 0.00 | 103.0 | YES |
| E97-71R | -100 | 10.017 | 10.017 | 5.101 | 0.00 | 229.7 | NO ($K_{Jc} > K_{lim}$) |

*W, B* = specimen width and thickness; $a_o$ = initial crack length; $\Delta a$ = ductile crack extension; $K_{Jc}$ = fracture toughness measured at cleavage.

Table 12 - *Results of the Master Curve analyses for EUROFER in the baseline condition.*

| Option | N | r | $K_{o,1TCT}$ (MPa√m) | $K_{med,1TCT}$ (MPa√m) | $T_o$ (°C) | σ (°C) |
|---|---|---|---|---|---|---|
| Multi-T | 10 | 7 | 119.8 | 111.1 | -121 | 6.8 |

$N$ = number of specimens tested, $r$ = number of valid data; $K_{o,1TCT}$ = scale parameter of the distribution (normalised); $K_{med,1TCT}$ = median value of the population (normalised); $T_o$ = reference temperature; $\sigma_{To}$ = associated standard deviation.

The calculated value of $T_o$ is in agreement with the results obtained by CIEMAT on 1/2TCT specimens extracted from the 14 mm-thick plate (which is known to have similar properties as the bars), after adjusting by 10 °C the calculated value to account for the higher level of constraint in the C(T) specimens ($T_o$ = -132 °C and $T_{o,adj}$ = -122 °C). Background and full details about this constraint adjustment have been given in [3]. Results reported by CIEMAT in [25] are reproduced in Figure 22.

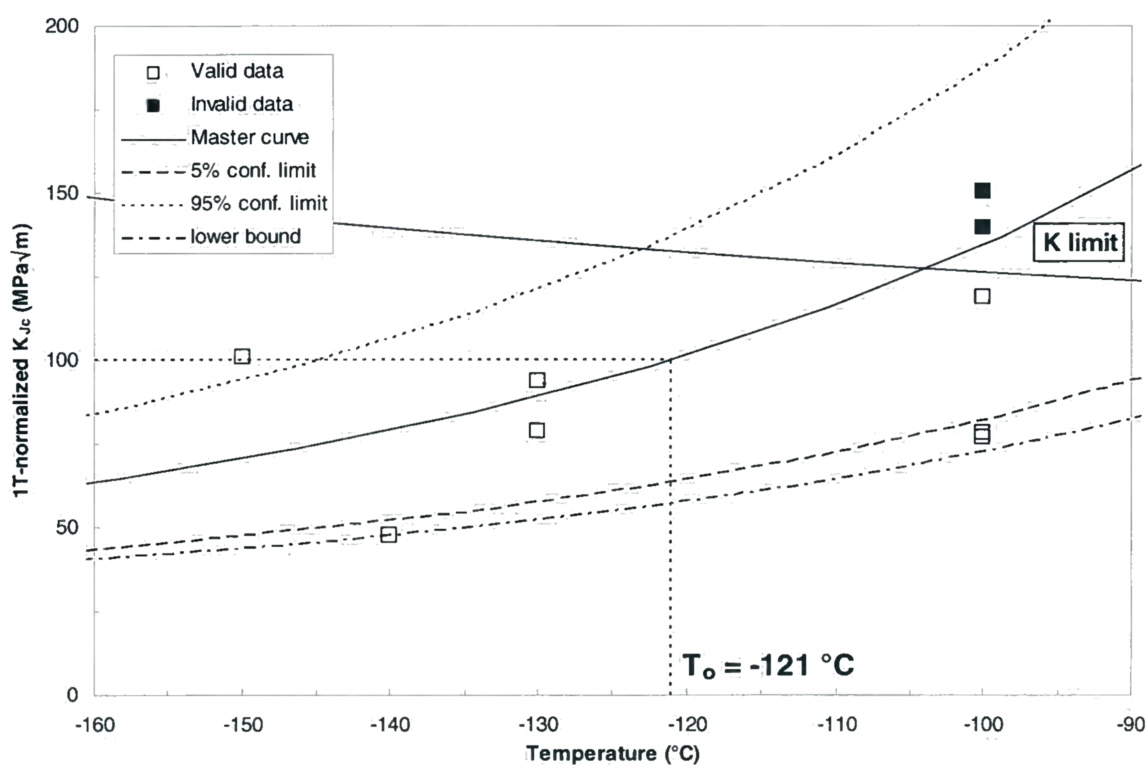


Figure 21 - *Fracture toughness results obtained on EUROFER in the baseline condition.*

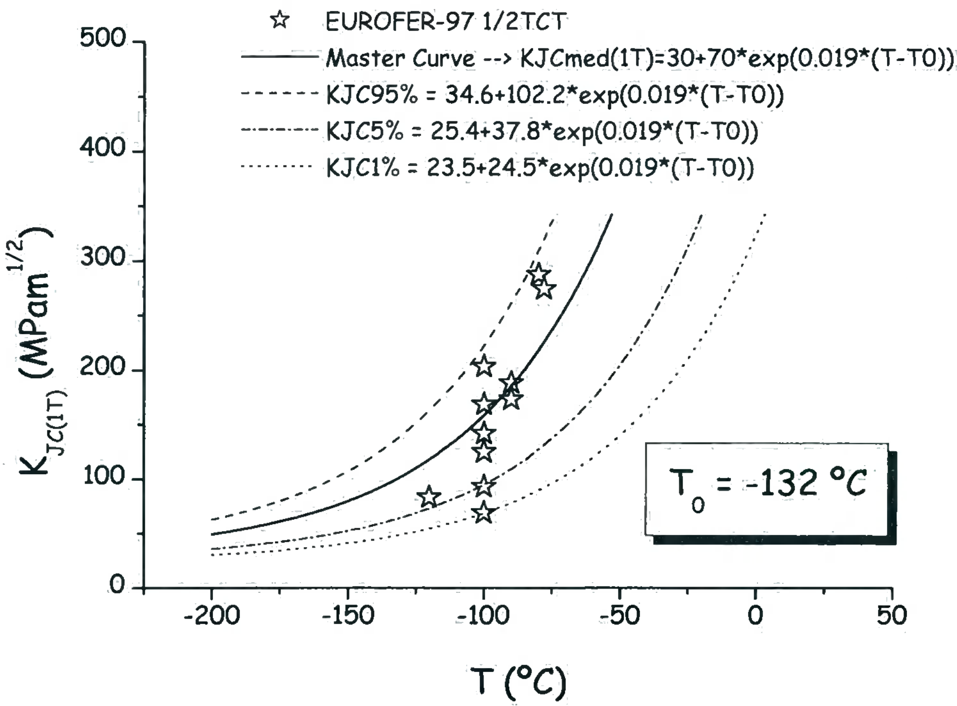


Figure 22 - *Results reported by CIEMAT on 1/2TCT specimens [25].*

### 6.1.2 Upper shelf region

One test has been performed at room temperature, where the material is fully ductile in the unirradiated condition. Therefore, this test allowed measuring the critical value of J-integral ($J_Q$[5]) and the crack-resistance curve (*J-R curve*) under elastic-plastic conditions. The test has been performed and analysed in accordance with the ASTM E1820-01 standard.

The single-specimen methodology used for measuring crack propagation during the test was the Unloading Compliance. Results are given in Table 13 and Figure 23.

Table 13 - *Results of the toughness test performed at RT.*

| Spec. code | $W$ (mm) | $B$ (mm) | $B_n$ (mm) | $a_o$ (mm) | $\Delta a_p$ (mm) | $J_Q$ (kJ/m²) | $K_{JQ}$ (MPa√m) | $TM$ (MPa) |
|---|---|---|---|---|---|---|---|---|
| E97-99 | 9.992 | 10.034 | 8.024 | 5.374 | 1.201 | 482.7 | 333.6 | 601.1 |

$B_n$ = specimen net thickness; $\Delta a_p$ = final crack extension; $J_{Ic}$ = critical value of J-integral; $K_{JIc}$ = correspondent fracture toughness; $TM$ = tearing modulus (slope of the crack resistance curve at the point of initiation).

[5] The limited size of the PCCv specimen does not allow measuring a valid critical $J_{Ic}$ value in accordance with the requirements of the E1820-01 standard.

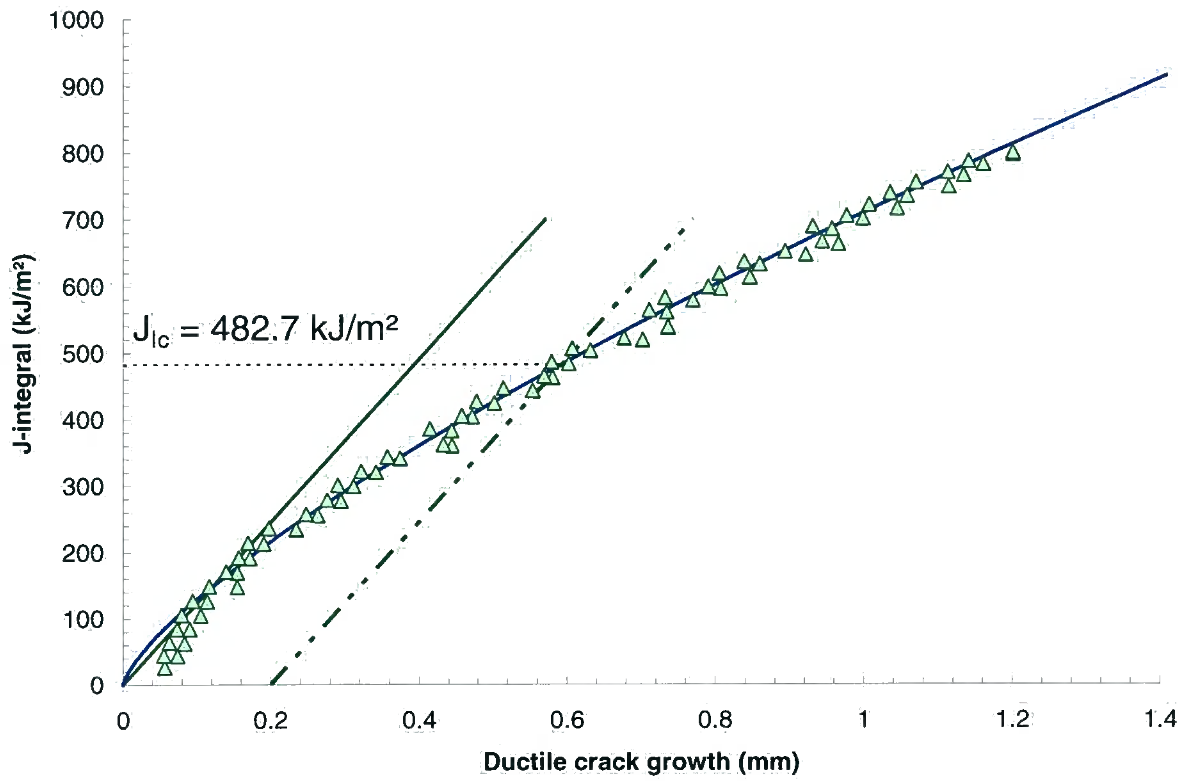


Figure 23 - *Result of the fracture toughness test carried out at RT.*

### *6.2 Irradiated condition (IRFUMA-II, 0.82 dpa)*

Nine fatigue precracked Charpy specimens of standard type have been tested from -70 to -25 °C, in order to establish the Master Curve and the reference temperature $T_o$ for the irradiated condition, in accordance with the ASTM E1921-02 standard. It should be emphasized that, strictly speaking, E1921 is applicable to ferritic steels only; however, evidence exists that the methodology is also amenable to ferritic-martensitic steels, which have a BCC cristalline structure and exhibit a clear ductile-to-brittle transitional behaviour.

All specimens were plain-sided (i.e. without side-grooves) and were tested in displacement control at a speed of 0.2 mm/min using an servohydraulic testbank.

Three of the specimens tested did not exhibit any cleavage, and were unloaded after a certain amount of ductile crack propagation; these tests cannot be used within the Master Curve analysis for the calculation of $T_o$. Furthermore, one of the specimens tested at -50 °C provided a $K_{Jc}$ value above the validity limit set by the standard ($K_{Jc,lim}$).

As a consequence, the number of valid data for the analysis (five) was lower than the minimum (six) required by the standard, and a valid reference temperature could not be obtained. Individual test results are given in Table 14, while Table 15 shows the results of the Master Curve analysis; individual data points and Master Curve with confidence bounds are presented in Figure 24. It should also be noted that the average dose accumulated by the specimens considered in the Master Curve analysis is 0.82 ± 0.22 dpa.

Table 14 - *Individual results for fracture toughness tests on irradiated EUROFER.*

| Specimen code | $T$ (°C) | $W$ (mm) | $B$ (mm) | $a_o$ (mm) | $\Delta a$ (mm) | $K_{Jc}$ (MPa√m) | DATA VALID | Dose (dpa) |
|---|---|---|---|---|---|---|---|---|
| E97-69 | -70 | 9.982 | 9.980 | 5.003 | 0.00 | 78.1 | YES | 0.96 |
| E97-70 | -70 | 9.995 | 9.986 | 5.053 | 0.00 | 87.4 | YES | 1.10 |
| E97-67 | -50 | 9.993 | 9.986 | 5.121 | 0.00 | 123.2 | YES | 0.49 |
| E97-68 | -50 | 9.989 | 9.979 | 5.233 | 0.18 | 239.2 | NO | 0.77 |
| E97-66 | -40 | 9.983 | 9.972 | 4.895 | 0.34 | **NO CLEAVAGE** | | 0.35 |
| E97-62 | -30 | 9.988 | 9.970 | 5.064 | 0.00 | 102.5 | YES | 0.65 |
| E97-64 | -30 | 9.999 | 9.982 | 4.926 | 0.00 | 149.4 | YES | 0.92 |
| E97-65 | -30 | 9.994 | 9.994 | 5.078 | 0.34 | **NO CLEAVAGE** | | 0.22 |
| E97-63 | -25 | 9.985 | 9.942 | 5.000 | 0.47 | **NO CLEAVAGE** | | 0.80 |

Table 15 - *Results of the Master Curve analysis for the irradiated EUROFER.*

| $N$ | $r$ | $K_{o,1TCT}$ (MPa√m) | $K_{med,1TCT}$ (MPa√m) | $T_o$ (°C) | $\sigma_{To}$ (°C) |
|---|---|---|---|---|---|
| 6 | 5 | 110.3 | 102.4 | -49 | 8 |

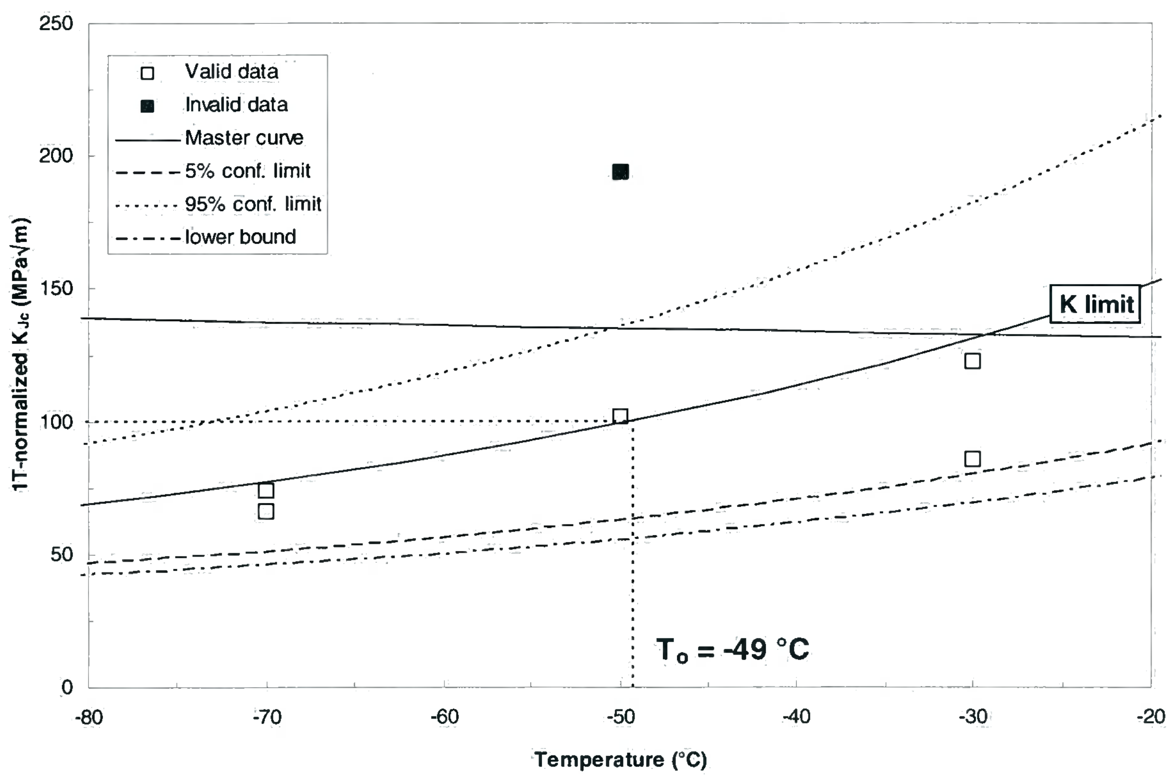


Figure 24 - *Fracture toughness results obtained on EUROFER irradiated.*

The effects of irradiation on the Master Curve and the reference temperature of EUROFER are illustrated in Figure 25, where data for the baseline condition, IRFUMA-I and IRFUMA-II are shown.

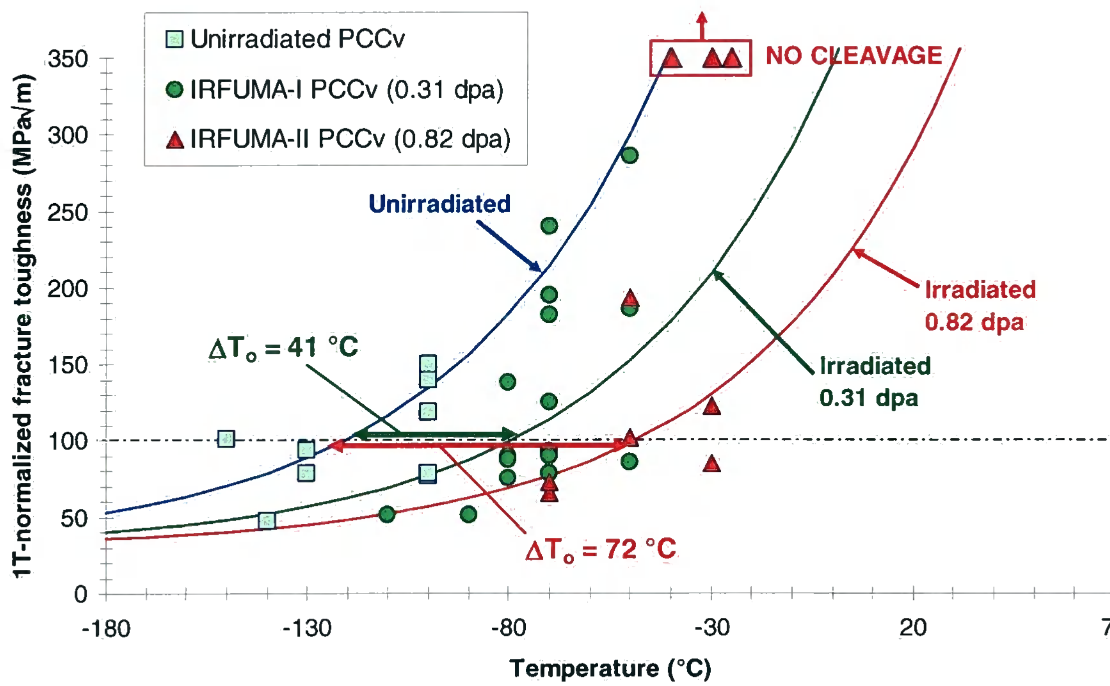


Figure 25 - *Normalised data points and Master Curves for the baseline condition and the two irradiated conditions.*

If we compare transition temperatures shifts calculated from Charpy tests in terms of $DBTT_{KV}$ and from toughness tests in terms of $T_o$, we obtain:

- for the first irradiation (IRFUMA-I):

$\Delta DBTT_{KV}$ = 13 °C for an accumulated dose of 0.27 dpa

$\Delta T_o$ = 41 °C for an accumulated dose of 0.31 dpa;

- for the second irradiation (IRFUMA-II):

$\Delta DBTT_{KV}$ = 28 °C for an accumulated dose of 0.51 dpa

$\Delta T_o$ = 72 °C for an accumulated dose of 0.82 dpa.

Therefore, even accounting for the higher fluence absorbed by PCCv specimens (especially in the case of IRFUMA-II) and without overlooking the uncertainties associated to the calculated transition temperatures, it appears that shifts measured in terms of toughness are larger than those obtained from impact tests. This is an issue which remains to be explained and requires further investigations.

However, the fact that only 9 specimens were available from the irradiation campaign and 3 of those did not fail by cleavage, thus being unusable from the analysis point of view, caused the calculated reference temperature to be invalid according to E1921-02 and associated to a rather large uncertainty (95% confidence interval: ±16 °C). Furthermore, the Master Curve methodology has been developed for (and validated on) ferritic steels, and its full applicability to ferritic/martensitic steels still has to be demonstrated. From the scatter which we observed in our tests, it appears that a reliable determination of $T_o$ for EUROFER ought to be based on a much larger number of experimental data, both for the unirradiated and irradiated conditions. All this has to be taken into account before drawing any conclusion on the difference between Charpy and toughness transition temperature shifts.

### *6.3 Comparisons with other RAFM steels*

Toughness data for RAFM steels in the unirradiated and irradiated condition are limited to a few studies on F82H and JLF-1 steels [26-32]. In the unirradiated condition, toughness properties are generally similar to those of the conventional Cr-Mo steels [26].

Results from experiments on F82H irradiated to 1.5 to 3 dpa in HFIR [31] and HFR [32] were used to make a comparison of the effect of irradiation on the toughness of HT9 and F82H [31].

In the baseline condition, minor differences were found in the range RT to 300 °C, where failure occurs by ductile tearing and toughness (calculated from J-integral at initiation) lies for both steels between 200 and 300 MPa√m [31].

The 100 MPa√m reference temperature for the unirradiated F82H steel was calculated to be –100 °C [15], about 20 °C higher than for the unirradiated EUROFER as reported in this work (-121 °C). Although data for F82H are still limited, irradiation to 1.6 to 2.5 dpa at 250 °C had a much smaller effect than for HT9, in that F82H retained considerable toughness. In the test temperature range investigated (RT – 300 °C), where low uniform elongation was observed in tensile tests, failure in toughness tests occurred by ductile tearing, indicating that tensile strengthening is not accompanied by embrittlement in fracture toughness tests [31].

Unfortunately, fracture toughness data on ferritic-martensitic steels irradiated under conditions (temperature and fluence) comparable to those of either the IRFUMA-I or the IRFUMA-II experiments are presently not available in the open literature.

## CONCLUSIONS

Tensile, impact and fracture toughness tests have been performed on the EUROFER steel, irradiated in the BR2 reactor at 300 °C up to an average accumulated dose of 0.55 dpa, in the frame of the IRFUMA-II campaign.

By comparing test results with data obtained from the unirradiated material, the following has been observed:

- The scatter in accumulated doses led us to subdivide irradiated specimen in two groups, associated respectively to average doses of 0.33 and 0.71 dpa; hardening with respect to the baseline condition for the first sub-group can be quantified as an increase of 17% or 84 MPa for the yield strength and 12% or 66 MPa for the ultimate tensile strength, with reference to the athermal stress component. The corresponding figures for the second sub-group are 34% or 170 MPa for the yield strength and 25% or 133 MPa for the ultimate tensile strength.
- Total elongation is further reduced by 4-6%, but remains greater than 10% throughout the temperature range investigated (-150 to 300 °C); reduction of area slightly decreases but remains higher than 65%.
- The ductile-to-brittle transition temperature measured from Charpy tests shifts by 28 °C for an accumulated dose of 0.51 dpa, which represents a further increase of 15 °C with respect to the first irradiation (0.27 dpa); the level of Upper Shelf Energy decreases only slightly with respect to the unirradiated state.

- Fracture toughness tests performed on PCCv specimens irradiated to 0.82 dpa yield a shift of the reference temperature of 72 °C, significantly higher than the shift of Charpy-based index temperatures (even accounting for the higher fluence); the increase of $T_o$ from the previous irradiation (0.31 dpa) is 31 °C. Three samples tested between -40 and -25 °C did not show any cleavage failure. The reliability of the reference temperatures is however put in question due to the lack of statistics, which produce a large uncertainty on the calculated values.

Test results from IRFUMA-II specimens were compared with data reported in the literature for other RAFM steels, such as F82H; the following was observed.

- Significantly higher hardening (in terms of $\sigma_{p02}$ and $\sigma_{UTS}$ increase) was measured for EUROFER as compared to F82H, irradiated and tested under similar conditions by NRG Petten.
- The Charpy-based DBTT shift is lower or equivalent to that of several other RAFM steels irradiated at 300 °C up to doses lower than 1 dpa. When compared to F82H, the behaviour of EUROFER appears slightly better.
- No meaningful statement can be formulated for fracture toughness, due to the lack of equivalent data in the open literature.

An overview of the effects of irradiation on the mechanical properties of EUROFER, as emerged from the study presented here, is given in Table 16, which also includes the results of the IRFUMA-I campaign.

Table 16 - *Overview of the effects of neutron irradiation on EUROFER.*

| Type of test | Experiment | Dose (dpa) | Effect measured *(from the unirradiated state)* | |
|---|---|---|---|---|
| Tensile | IRFUMA-I & II | 0.15-0.5 | $\Delta\sigma_{p02}$ = 84 MPa (17%)<br>$\Delta\sigma_{UTS}$ = 66 MPa (12%) | (athermal component) |
| | IRFUMA-II | 0.57-0.89 | $\Delta\sigma_{p02}$ = 170 MPa (34%)<br>$\Delta\sigma_{UTS}$ = 133 MPa (25%) | |
| | IRFUMA-I & II | 0.15-0.5 | $\Delta\sigma_{p02}$ = 121 MPa (23%)<br>$\Delta\sigma_{UTS}$ = 206 MPa (39%) | (R.T.) |
| | IRFUMA-II | 0.59 | $\Delta\sigma_{p02}$ = 55 MPa (8%)<br>$\Delta\sigma_{UTS}$ = 92 MPa (14%) | |
| Charpy | IRFUMA-I | 0.27 | $\Delta DBTT_{KV}$ = 13 °C - $\Delta DBTT_{LE}$ = 14 °C<br>$\Delta FATT_{50}$ = 9 °C | |
| | IRFUMA-II | 0.51 | $\Delta DBTT_{KV}$ = 28 °C - $\Delta DBTT_{LE}$ = 31 °C<br>$\Delta FATT_{50}$ = 24 °C | |
| Fracture toughness | IRFUMA-I | 0.31 | $\Delta T_o$ = 41 °C | |
| | IRFUMA-II | 0.82 | $\Delta T_o$ = 72 °C | |

## RECOMMENDATIONS FOR FUTURE WORK

The investigations following the different IRFUMA campaigns allowed us studying irradiation-induced hardening and embrittlement effects on EUROFER. However, due to the axial cosine flux distribution of the BR2 reactor, the neutron fluence has been found to be not uniform for all samples, especially in the case of IRFUMA-II; the same is expected to be the case for the specimens of IRFUMA-III as well.

Therefore, it is recommended to couple the on-going mechanical characterisation activities with the following actions:

- evaluation of irradiation damage hardening accumulation as a function of neutron exposure;
- microstructure examinations as a function of neutron exposure, using TEM (transmission electron microscopy) and PAS (positron annihilation spectroscopy);
- where needed, supplementary mechanical tests (Charpy impact and fracture toughness), in case the characteristic parameters (DBTT, $T_o$) are poorly defined due to lack of statistics or scatter in accumulated doses;
- investigation of loading rate effects, in order to find an explanation for the significant difference between temperature shifts measured from Charpy and toughness tests.

From the already broken Charpy and PCCv specimens, sub-size specimens for tensile testing and microstructure examination (TEM, PAS) could be machined; new Charpy samples for impact and fracture toughness testing could also be obtained by reconstitution. Specimen selection should be done so as to more accurately investigate specimens of uniform fluence within a large range of accumulate dose.

It is expected that, through a better characterization including both microscopic and macroscopic properties, a better understanding be achieved of the underlying damage accumulation kinetics for an improved assessment of the EUROFER steel for fusion application.

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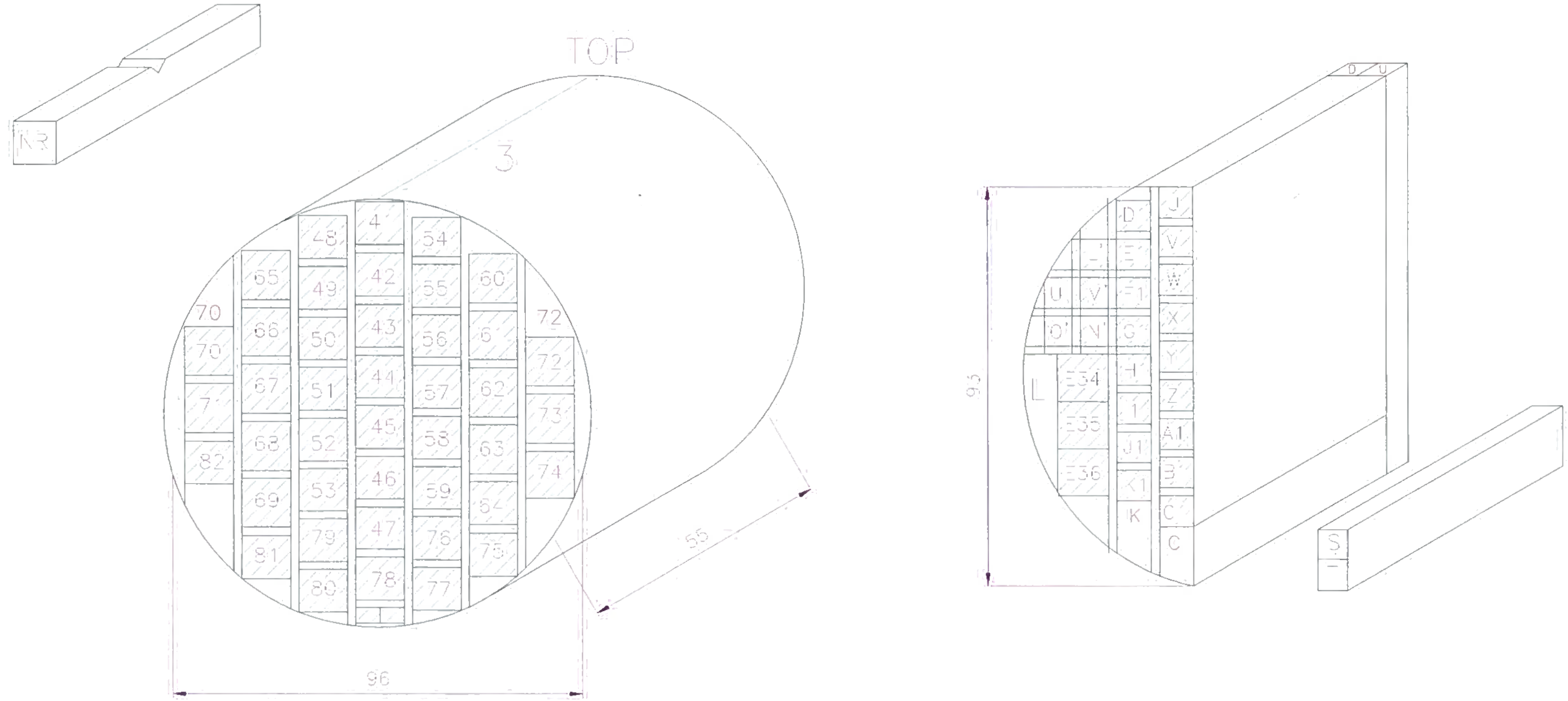
# ANNEX 1

# Cutting plan for IRFUMA-II specimens



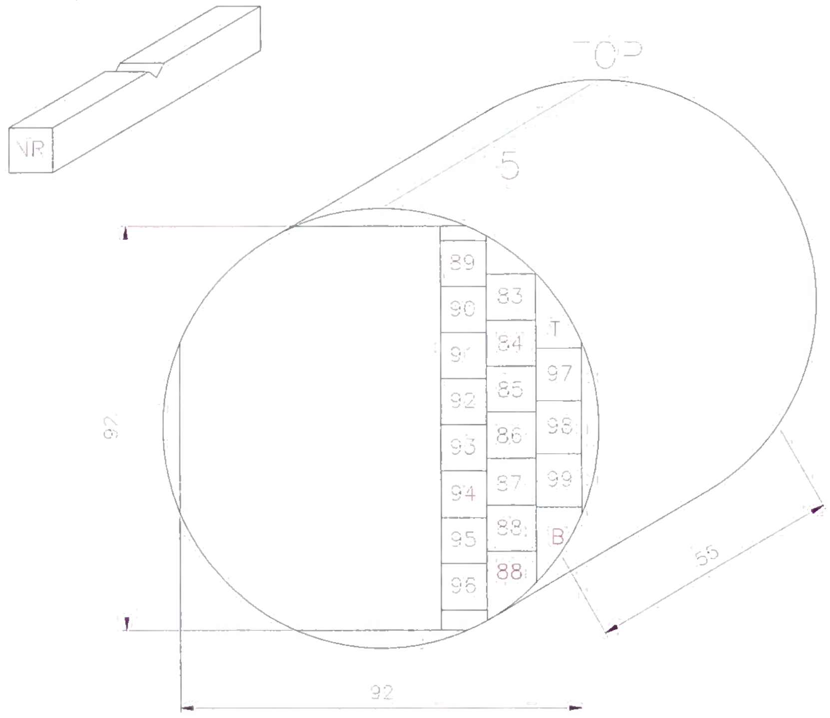

Nummering:
- E97-41 tot E97-58 = CV
- E97-59 tot E97-73 = PCCV
- S tot Z & A1 tot K' = Tensile
- L'-M'-N'-O' = trekproefstukken L. Eysermans
- E97-74 tot E97-82 = CV (E. Lucon)
- E97-E34 tot E97-E36 = CV (E. Lucon)

| Ind. | Dat. | Wijziging - Modification - Up dating | Par. | App. |
|---|---|---|---|---|
| B | 2003.01.28 | 12 CV's E97-74 tot E97-82 + E34 tot E36 | | |
| A | 2001.04.04 | Aanpassing nummering E97-59 tot E97-73 | | |

| | |
|---|---|
| Tek. Dess. Draw. | Mertens R. |
| Verificat. | |
| Approbat. | |
| L.H.M.A. | Vrijmaat tol. / Tol. libre / Free tol.: TOL |
| Afwerking / Et. de surface / Finishing grade | AFW |
| Schaal / Echelle / Scale | 1/1 |
| File | Eurofer 97-2 |
| Datum-Date-Date | 2001-02-07 |
| Nr. | RMO-165B |

SCK•CEN

# Cutting scheme Eurofer 97 - Irfuma 2




Rood=restant

Nummering:
- E97-83 to: E97-88 = CV
- E97-89 to: E97-93 = CV (M.M.)
- E97-94 to: E97-96 = PCCV (V.M.)
- E97-97 to: E97-99 = PCCV (R.C)

| | | | | | |
|---|---|---|---|---|---|
| Tek. Dess. Draw. **Mertens R.** | | | | | |
| | B | 2003.04.22 | 3 PCCV's (R. Chaouadi) | | |
| Verificat. | A | 2003.03.20 | 5 CV's + 3 PCCV's (Milena Matijasevic) | | |
| Approbat. | Ind. | Dat. | Wijziging → Modification → Up dating | Par. | App. |

| | | | |
|---|---|---|---|
| L.H.M.A. | Vrijmaat tol.<br>Tol. libre TOL<br>Free tol. | Afwerking<br>Et. de surface AFW<br>Finishing grade | Schaal<br>Echelle 1/1<br>Scale |
| SCK•CEN | File<br>**Eurofer 97-3** | Datum-Date-Date<br>2003-02-26 | Nr. RMO-239B |

**Cutting scheme Eurofer 97 blok 5**