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# HTR-M Vessel Materials – Evaluation of the Weld Factor

Sophie Dubiez-Le Goff

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**Nom et Visa du Chef d'Affaire**

B. RIOU

10, rue Juliette Recamier 69456 LYON CEDEX 06 – Telephone : 04.72.74.82.21 – Telecopie : 04.72.74.84.90

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# Summary

The aim of this document is to determine the weldment strength reduction factor Jr of the modified 9Cr1Mo grade of steel, candidate for the HTR pressure vessel.

Jr assessment is here proposed from creep tests results performed at 550°C on welded joint produced by narrow gap TIG on a 150 mm thick plate. These data have been acquired in the frame of the HTR-M program. The two laboratories involved for testing are NRG and JRC in Petten and CEA in Cadarache; Framatome-ANP supplied one welded joint per laboratory.

The influence of the irradiation on creep behaviour is also commented, supported by tensile and impact tests, performed on un-irradiated and post-irradiated specimens, submitted to an equivalent end-of-life dose.

The study of these data highlights the following points:

- The low dose encountered by HTR vessel has no influence on mechanical behaviour, according to tensile, creep and impact results.
- PWHT temperature appears to be a key parameter toward creep strength of mod. 9Cr1Mo steel.
  750°C seems better than 760°C, but when decreasing the PWHT temperature, toughness also decreases, and a suitable compromise has to be found before reviewing creep design data.
- A value of 0.9 is proposed for Jr. It covers the whole weld data, excepted for very short term range (one test of 25 h life time), but longer term data seem to indicate that the value of 0.9 is sufficient to cover the loss of creep strength of the weldment compared to base metal. To be convenient for the whole creep range, Jr could be re-assessed as a time dependent factor, but before, the PWHT has to be fixed.

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# 1. Introduction

In the frame of the HTR-M project, the aim of this document is to determine the weldment strength reduction factor Jr of the modified 9Cr1Mo grade of steel, candidate for the HTR pressure vessel. Used in design concept, Jr is the time dependent weldment factor to be applied to Sr, the minimum stress to rupture value.

Jr assessment is here proposed from creep tests results performed at 550°C on welded joint produced by narrow gap TIG on a 150 mm thick plate. The two laboratories involved for testing in this program are NRG and JRC in Petten and CEA in Cadarache; Framatome-ANP supplied one welded joint at each laboratory.

The influence of the irradiation on creep behaviour is also commented, supported by tensile, and impact tests performed on un-irradiated and post-irradiated specimens, submitted to an equivalent end-of-life dose.

# 2. Synthesis of the different tests results

## 2.1 Results from NRG and JRC (Ref. 1 and 2)

### 2.1.1 Material supply

Testing has been performed on a welded joint supply by Framatome-ANP. The material history and specification are reported in table 1. The welded joint was heat treated in industrial conditions before delivery at Petten

### 2.1.2 Irradiation conditions

The irradiation conditions have been assessed from estimation of the end-of-life (EOL) dose of the vessel. The targeted EOL dose deduced corresponds to the following parameters:

- minimum neutron fluence : $8.10^{18}$ n/m² (E>0.1 MeV)
- nominal irradiation temperature : 375°C ± 10°C

Irradiation took place in the Pool Side Facility (PSF) of the High Flux Reactor (HFR). The individual dose encountered by the specimens, interpolated from 12 activation monitors sets, is characterized by following parameters:

- average fluence: $9.44 \cdot 10^{18}$ $m^{-2}$ (E>0.1MeV), 5.84 mdpa
- maximum fluence: $11.41 \cdot 10^{18}$ $m^{-2}$ (E>0.1MeV), 7.07 mdpa
- minimum fluence: $7.97 \cdot 10^{18}$ $m^{-2}$ (E>0.1MeV), 4.93 mdpa

It can be noted that the variation of fluence between the different specimens reachs about 30% around the mean value of 9.44 $10^{18}$ $m^{-2}$ (E>0.1MeV).

### 2.1.3 Tests performed

Base metal and weldment behaviours have been characterized in both reference and irradiated states, with tensile, creep, impact tests. Specimens have been sampled in different zones:

- base metal (BM) in parallel (L) and in perpendicular (T) direction with respect to the rolling direction
- heat affected zone (HAZ)
- weld metal (WM), tested parallel to the weld direction, and the cross-weld specimen, tested perpendicular to the weld direction

## 2.2 Results from CEA-Cadarache (Ref. 3 and 4)

### 2.2.1 Material supply

Testing has been performed on a welded joint also supplied by Framatome-ANP. The base metal and the filler metal used for welding are identical, but the weldment has been delivered in Cadarache in the as-welded conditions. The post weld heat treatment (PWHT) was performed in the laboratory conditions.

The material history and specification are reported in table 1.

### 2.2.2 Tests performed

Creep tests have been performed at 550°C in the frame of the PhD of Vincent Gaffard. Only one test is allowable on the weld metal at this temperature.

# 3. Creep results and consequence on the design

## 3.1 Analyses of the allowable creep data at 550°C on non irradiated specimen

### 3.1.1 Base metal results

The figure 1 presents the stress to rupture as a function of the time of both base metal and weld, in un-irradiated state. Minimum stress to rupture, Sr, given by the RCC-MR (ref. 5), is added on the graph for comparison with the base metal results. This representation highlights that:

- the creep strength of modified 9Cr1Mo grade investigated by CEA is higher than the creep strength of the modified 9Cr1Mo grade investigated by NRG/JRC.
- below 1000 hrs, the data obtained by NRG/JRC are below the lower bound curve corresponding to RCC-MR values.

### 3.1.2 Welded zone

Concerning tests performed on cross weld and the weld metal, all results are located above or just on the border of a curve corresponding to 0.9xSr (Figure 1), excepted one point of short life time (23 hrs), corresponding to cross weld specimen sampled from NRG/JRC plate, located slightly above the curve.

### 3.1.3 Discussion

The two welded joints investigated present one difference, the PWHT temperature: 750°C for CEA welded joint and 760°C for NRG/JRC's one. It appears that this temperature highly influences the creep strength of mod. 9Cr1Mo steel. It seems that 750°C is more suitable for creep strength than 760°C. Before reviewing the creep data curve, it is needed to fix the post weld heat treatment temperature.

The Jr value of 0.9 had already been proposed for welded components in mod. 9Cr1Mo steel in the frame of the EFR project (Ref. 6). This study was based on Japanese, US, UK and German data, for a design temperature limited to 525°C. Short term data (only one point today), corresponding to cross weld specimen, may not be covered by the Jr value of 0.9, but as for base metal, the PWHT temperature has to be fixed before re-assessment of Jr value. It can be yet noted that cross weld specimen sampled from CEA plate, i.e. with a PWHT of 750°C, is above the 0.9xSr curve.

## 3.2 Analyses of the allowable creep data at 550°C on un-irradiated and post-irradiated specimen

### 3.2.1 Irradiation influence on creep data

The figure 1 presents the stress to rupture as a function of the time of both base metal and weld, in un-irradiated and post-irradiated states. All post-irradiated results fall within the scatter band drawn by un-irradiated creep results. The difference between the un-irradiated reference tests and the irradiated tests is almost negligible toward creep to rupture results.

It can be noted that one result is located just below the lower bound defined by the 0.9xSr curve. It corresponds to a weld metal specimen, sampled from NRG/JRC plate, which is also below the 0.9xSr curve at the un-irradiated state.

### 3.2.2 Irradiation influence on other mechanical properties

As for creep, a negligible effect of irradiation exposure is also observed on tensile results at room temperature and at 550°C.

Impact tests have also been performed on two kinds of Charpy specimen:

- sub-size Charpy in un-irradiated and post-irradiated states (full size Charpy are too big to be stacked inside the irradiation ring).
- full size Charpy, un-irradiated, to study the specimen size effect in comparison with un-irradiated sub-size Charpy

Tests performed on sub-size Charpy confirm the trend observed in creep and in tensile. The shift of ductile to brittle temperature (DBTT) observed from un-irradiated to post-irradiated specimens is small compared to the scattering: The maximum value of the difference between pre- and post-irradiation observed is limited at +10°C.

The DBTT issued from sub-size Charpy can only be used for relative analyses. To assess the DBTT values, the full size Charpy data are needed. For the base metal, DBTT calculated at half the upper shelf energy is -27°C. This result is in accordance with the transition temperature ($RT_{NDT}$) obtained on a 200 mm thick forged plate made of modified 9Cr1Mo grade, found at -25°C. If it is considered that the size effect is the same with irradiated and un-irradiated specimen, the $RT_{NDT}$ after irradiation can be deduced, it is of the order of -15°C.

For comparison, the transition temperature encountered in the Pressurized Water Reactor, which is similar before irradiation to the values of the HTR pressure vessel grade, is shifted of the order of +40°C at the EOL. Compared with the case of PWR, in the case of the VHTR, there is an important margin for the minimum temperature for pressurisation during service. The table 2 summarizes the situation.

It can be noticed that the DBTT of the weld metal, measured on un-irradiated full size Charpy specimen, is lower than for the base metal; it is of the order of -80°C. This property is linked to the TIG process, which permit to obtain very few inclusions in the weld metal.

## 4. Conclusion

The low dose encountered by HTR vessel has no influence on mechanical behaviour, according to tensile, creep and impact results performed in the frame of the HTR-M project.

Creep test performed at 550°C on two welded joints differing from PWHT temperature highlight that PWHT temperature is a key parameter toward creep strength of mod. 9Cr1Mo steel. 750°C seems better than 760°C, but when decreasing the PWHT temperature, toughness also decrease, and a suitable compromise has to be found before reviewing creep design data.

A value of 0.9 is proposed for Jr, which covers the whole weld data, excepted for very short term range (one test of 25 h life time). Longer term data seems to indicate that the value of 0.9 is sufficient to cover the loss of creep strength of the weldment compared to bas metal. To be convenient for the whole creep range, Jr could be re-assessed as a time dependent factor, but before, the PWHT has to be fixed.

## Table 1

## Material specification

| | NRC/JRC | CEA |
|---|---|---|
| **Base metal** | | |
| *Identification* | Heat Number 88295 - plate Number 88295-1<br>MARREL (INDUSTEEL) | |
| *Thickness* | 150 mm | |
| *Heat treatment* | 1070°C, then water quenching.<br>Tempering 765°C-6h45 | |
| **Weld** | | |
| *Filler metal* | KOBE wire – product name TGS-9CB – diameter of wire 1,2mm.<br>Lot EZ00773 | KOBE wire – product name TGS-9CB – diameter of wire 1,2mm. |
| *Heat treatment* | Holding time : **760**±5°C – 10 h 30<br>Cooling rate : ≤ 25°C / h (down to 300°C) | Holding time : **750°C**-15h18 water quench down to 400°C, then air quench below |

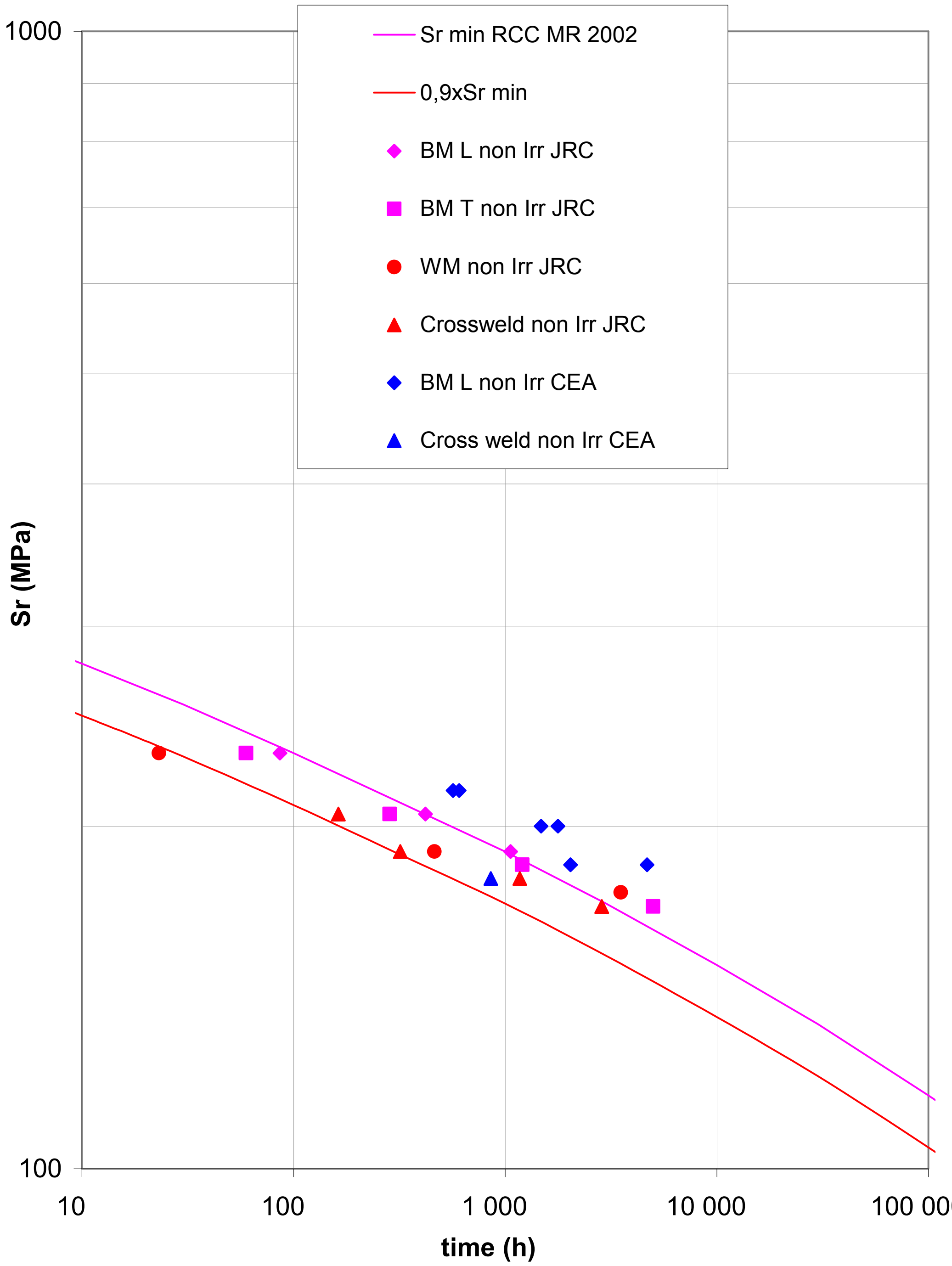
## Table 2

## Shift in $RT_{NDT}$ due to irradiation of vessel steel in PWR and HTR

| | | PWR | | HTR | |
|---|---|---|---|---|---|
| | | Un-irradiated | $5.10^{19}$ n / cm² | Un-irradiated | $8.10^{18}$ n / cm² |
| $RT_{NDT}$ | Max | -5°C | +35°C | | |
| | Mean | -25°C | +15°C | -25°C | -15°C |

# Figure 1

## Creep results at 550°C on un-irradiated specimen-Base metal and weldments



## Figure 2

## Creep results at 550°C on un-irradiated and post-irradadiated specimens - Base metal and weldments