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CAST STAINLESS STEEL ELBOWS IN MAIN COOLANT LINES

Technical and regulatory history

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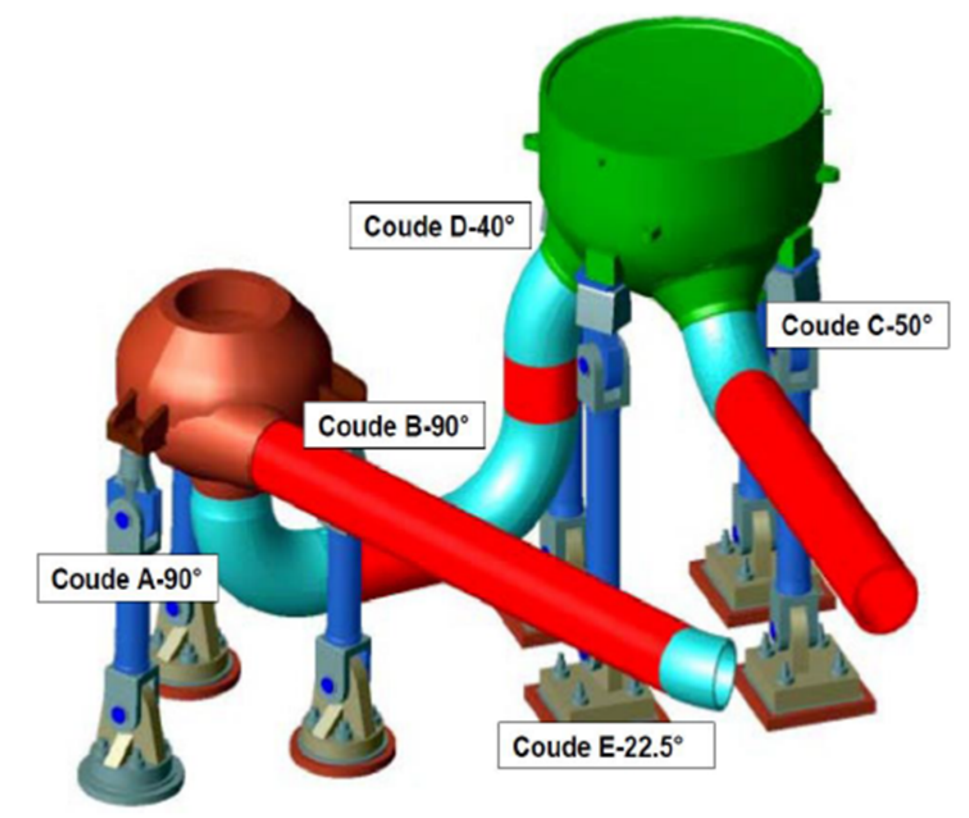
SOMMAIRE

1980'S AND 1990'S BACKGROUND

1.1. CASS ELBOWS ON FRENCH REACTORS

- Around 450 cast stainless steel elbows are installed on 900 MW French PWRs.
- CASS elbows manufactured in the 1970s and 1980s in CF8-M steel (Z3 CND 19-10 M).
- Composition of the steel (according to RCC-M code) :

	Z3 CND 19-10 M **(CF8-M)**	Z3 CN 20-09 M (CF8)
C	**< 0,04 %**	< 0,04 %
Si	**< 1,5 %**	< 1,5 %
Mn	**< 1,5 %**	< 1,5 %
S	**< 0,015 %**	< 0,015 %
P	**< 0,030 %**	< 0,030 %
Cr	**18 – 21 %**	19 – 21 %
Ni	**9 – 12 %**	8 – 11 %
Mo	**2,25 - 2,75 %**	(*)
Cu	**< 1 %**	< 1
Co	contract dependant	



Location of CASS elbows (in blue)

(*) Mo not expected, but concentration to be measured for documentary purposes

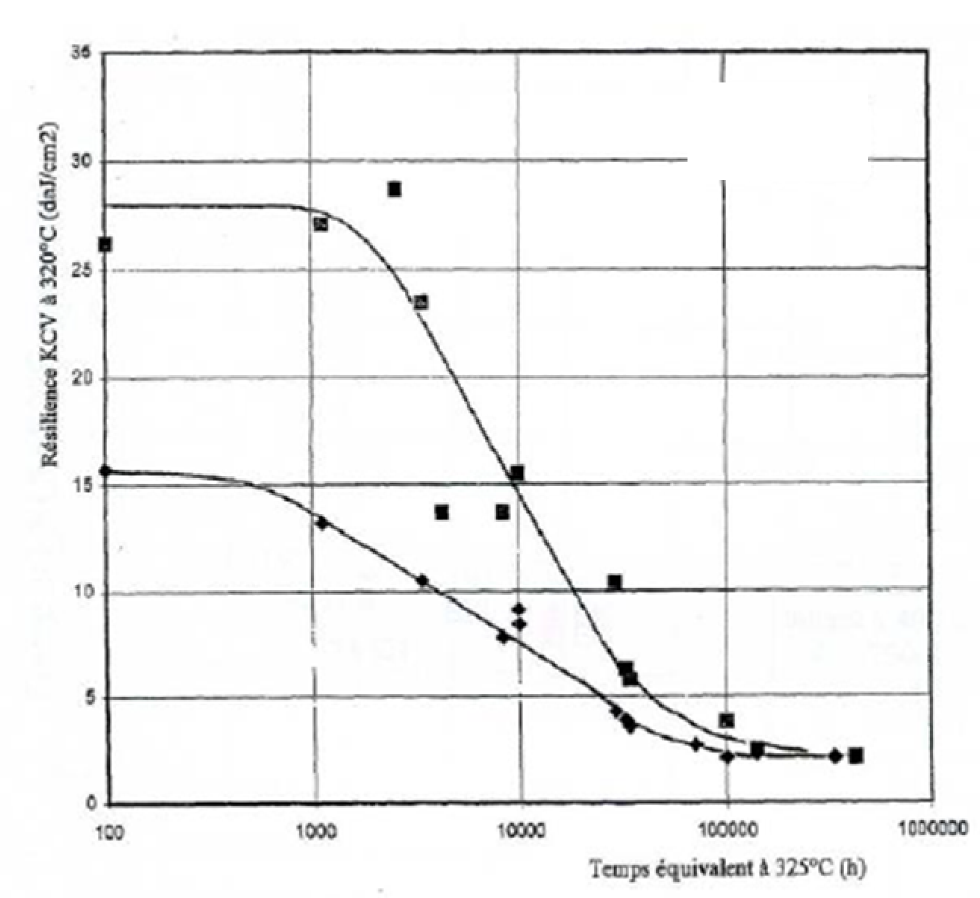
1.2. THERMAL EMBRITTLEMENT OF CF8-M STEEL

- Thermal embrittlement of CF8-M steel at the time of manufacturing was a known phenomenon, but probably largely underestimated at that time.
- CF8-M steel contains two phases :
  - a **Ferritic phase (α)**, ferrite content being between 15 and 30 % on French CASS elbows (exceeding 30 % in some cases) ;
  - an **austenitic phase (γ)**
- Embrittlement is caused by the **spinodal decomposition** of the α phase in two separate phases :
  - One rich in Fe (α) ;
  - One rich in Cr (α') ;
  - In addition, some precipitation can appear in the α/α' interface, in the form of small particles ;
  - Tests conducted on the austenitic phase show that it is not sensible to this decomposition.

1.2. THERMAL EMBRITTLEMENT OF CF8-M STEEL

- The spinodal decomposition is increased by the temperature, and the concentration of some elements like Cr, Mo and Si.
- Its effect on the material is increased when the ferrite content is high.
- The main effect of embrittlement on CASS mechanical behavior is a recuction of fracture toughness. Testing shows that toughness decreases over time upon reaching a plateau at the end of the decomposition process

Some tests perfomed in the 1980's on aged material showed J0,2 values as low as 23 to 35 kJ/m2 at 320 °C for the materials with the highest ferrite content (30 %), after ageing.

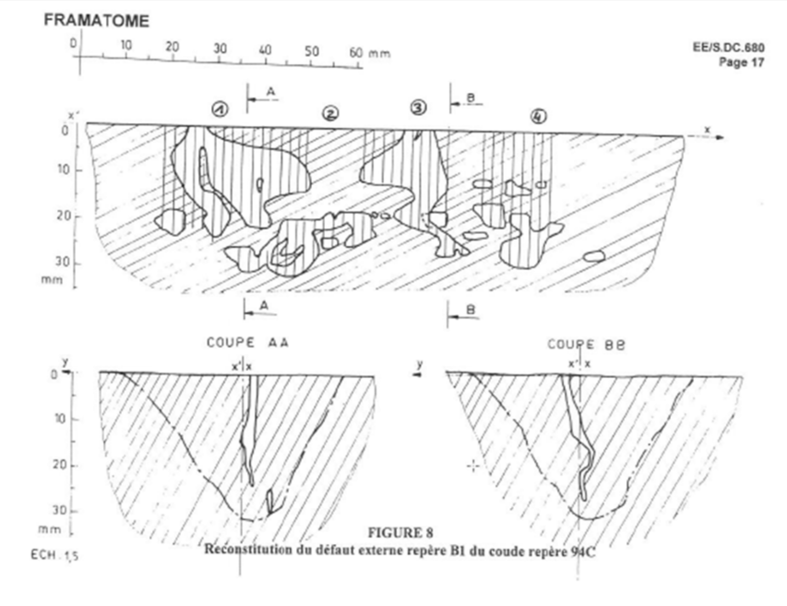


Effects of embrittlement on impact strength (KCV) at 320 °C, for two CF8-M products from different CASS elbows manufacturers

1.2. CASTING FLAWS ON CASS ELBOWS

- CASS elbows were machined on the inside and outside ;
- RT inspections (using either 60Co or 192Ir sources) were conducted on the whole volume at the end of manufacturing.
  - Radio indications were categorized using ASTM E186 tables.
  - For example, there are 5 categories of type C flaws (« retarssures »), cat 2 to 5 were considered unacceptable.
- PT inspections were also performed ;
- In 1980, during a final cleanup of the main primary lines of Saint-Laurent B2 reactor, before the first on-site hydraulic proof test, a flaw was detected on the inside surface. It had been classified C1 during RT inspection, however the overall dimensions of the cluster of cavities was around 32x90 mm.

This raised a concern about the possibility that some large surface flaws (or underlying flaws very close to the surface) had been missed by the manufacturers inspections. RT tests were conducted by the plant operators in the 80s on accessible elbows, showing a few other large flaws.



Reconstitution by Framatome of the SLB2 flaw.

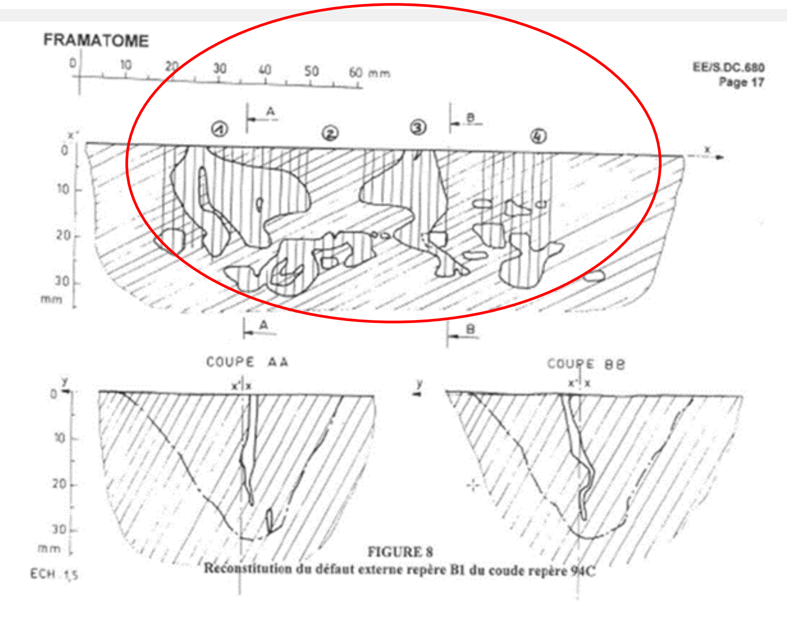
1.3. REGULATORY ACTIONS IN THE 1980’S AND 1990’S

The combination of the effects of thermal embrittlement and the finding of some large flaws on some already installed elbows lead the regulator to require some fracture mechanics analysis to be performed.

In 1988, some the following mechanical analysis were performed :

- **Study of two « reference » surface flaws : one semi-circular, 32mm deep ; one semi-elliptical, 15 mm deep.** There dimensions were determined following the results of the 1980’s surface inspections, considering the largest flaw that was detected at that time
  - The approach was largely conservative : « bridges » between cavities were note considered, the flaw considered in the mechanical anaylisis being plane and its dimensioned determined by the size of the cluster of cavities.
  - Considering the toughness values available at that time from the ageing tests, the conclusion of the 1988 report from ASN was that a operating time of 10 years was justified.

15x90mm semi-elliptical



Size of the 1988 reference flaw

1.3. REGULATORY ACTIONS IN THE 1980'S AND 1990'S

The regulatory approach was revised in 1993 and 1997 :

- **1993 :** mechanical analysis based on a conservative reference flaw were still required, using a 20x40 mm semi elliptical flaw considered to cover any flaw that could remain in service ;
- **1997 :** the ASN accepted that the nature of casting defects made them less severe as the plane semi-elliptical flaws considered in the mechanical analysis. Fatigue tests on some real casting defects also showed a good fatigue behaviour. The size of the reference defect was therefore lowered to that of a 10x40mm semi-elliptical flaw.
  - **Fracture analysis had to be performed using safety coefficients** on the loads, considering incidental and accidental transients (according to the 1999 operating order from ASN that was already being disussed) ;

	initiation	instability
Normal + upset (2nd)	1,3	2
Emergency (3th)	1,1	1,6
Faulted (4th)	./.	1,2

Safety factors to be applied on loads in fracture mechanics computation

$$J(\alpha \times \sigma, \text{flaw size}) < J_{0,2}$$

1.3. REGULATORY ACTIONS IN THE 1980’S AND 1990’S

- **1997 regulatory appraoch (continued) : <u>prediction of material toughness</u>**
  - Material toughness values were predicted using chemical composition of each elbow using formulas taking into account : Cr, Si and Mo concentration ;
  - Formulas were derived from test material, obtained after ageing at 400 °C for 2,500, 10,000 and 30,000 hours. Predictions were obtained for impact strength at 20°C (KCV) and 320 °C (KCU) :

Example : KCV at 320 °C after 30,000 of ageing at 400 °C :

$$\mathrm{KCV} = \frac{1}{10^{2\times 0.1303}} \times 10^{6{,}520-0{,}3546\times Si-0{,}2491Cr-0{,}1546Mo} \text{ in daJ/cm2}$$

For ageing times between 2,500, 10,000 and 30,000 hours, results were interpolated, and ageing at operating temperature (around 320 °C for elbows in the hot leg) was derived using the following time equivalent formula :

$$\frac{t_1}{t_2} = e^{\frac{Q}{R}\left(\frac{1}{T1}-\frac{1}{T2}\right)}$$

(Q being an activiting energy that was determined empirically).

Fracture toughness values ($J_{0,2}, J_{\Delta a}$) were finaly derived from KCV and KCU using empirical correlations.

CURRENT REGULATORY APPROACH

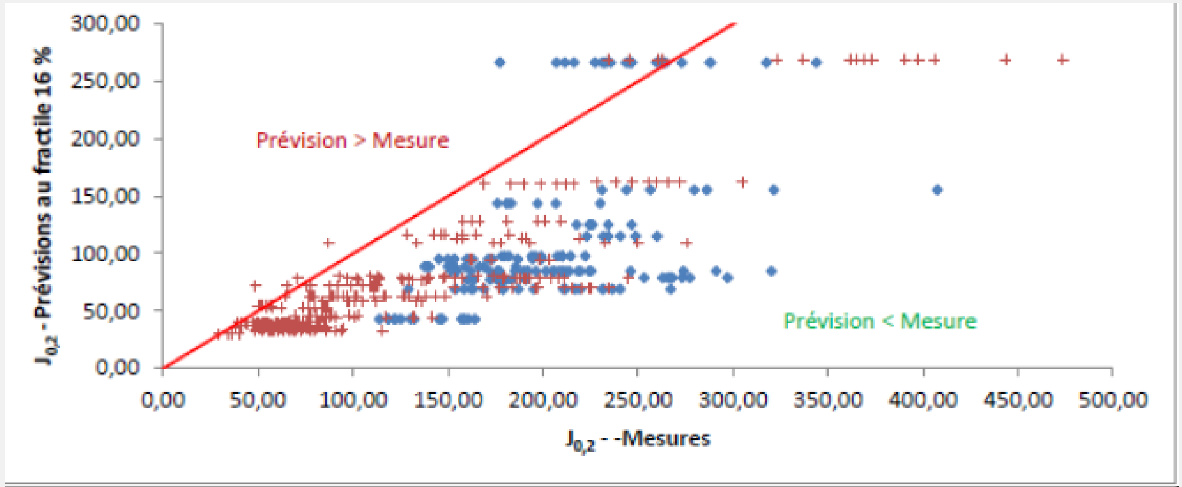
2. CURRENT REGULATORY APPROACH

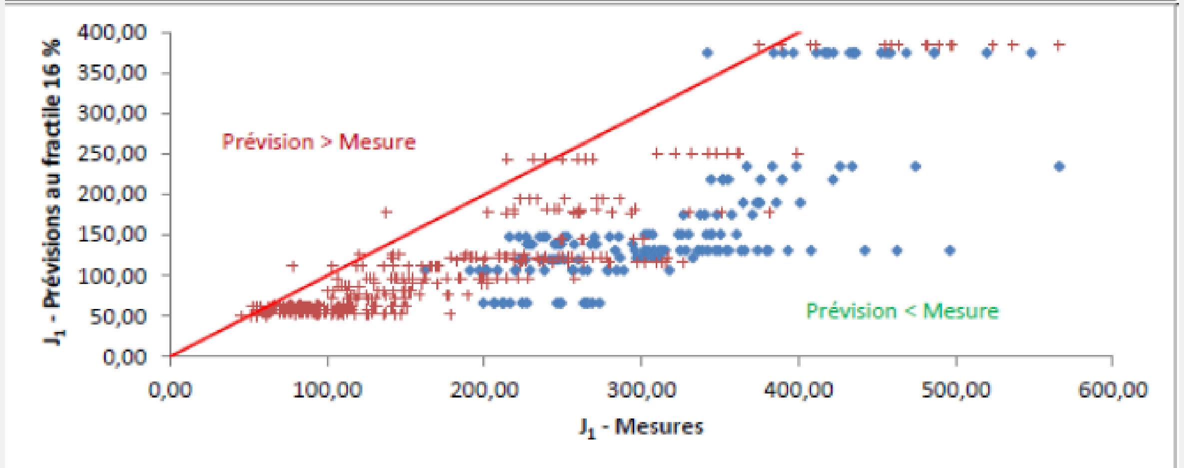
The current ASN position is based on the same principles as the 1990's regulatory approach :

- Each CASS elbow operation shall be justified by a fracture mechanics analysis considering all possible transients ; safety factors on loadings and the presence of a « reference » flaw 10x40 mm (semi-elleptical surface flaw) ;
- **Toughness prevision formulas have been <u>updated in the 2010's</u>.** Current formulas were designed by EDF.
  - **Same approach as 1990's formulas :** prevision of KCV and KCU impact strength, using time-temperature equivalence formulas, and toughness derived from impact strength prevision using statistical correlations ;
  - **Formulas now take into account :** ferrite content, concentration of Cr, Mo, Si, Ni, Mn, C, S, N, initial impact strength measured at manufacturing.
  - Impact strength formulas have been fitted from a database containing 600 KCV/KCU test results ; and toughness correlations were fitted from 1400 test results comparing toughness and impact strength.
  - Formulas were then validated using other databases called "validation databases".
- **ASN requires the licensee to perform regular checks of the prevision formulas, using aged material, including material harvested in service from the exterior of elbows.**
- **<u>Formulas must cover at least 84 % of test results.</u>**

2. CURRENT REGULATORY APPROACH

Exemple of checks performed by the ASN in 2019 (toughness prevision vs. Measurement) :





2. CURRENT REGULATORY APPROACH

Last computations performed by EDF using these formulas (alongside improvement in mechanical computations, such as the use of elactic-plastic finite element analysis, refinements of the simulation of transients…) show that :

- **Most « hot elbows » (those on the hot leg) can be justified up to 60 years of operation. Elbows that are not justified (the ones showing the lowest toughness previsions) are being replaced during ten-yearly maintenance operations ;**
- **The same applies to « cold eblows », however the lower operating temperature on cold legs make them less prone to ageing.**
    - **A few « E elbows » (connected to the RPV) are not justified after 40 to 60 years of operation, which is the highest current concern as they are not easiliy replacable.**

PERSPECTIVES

2. CURRENT REGULATORY APPROACH

As stated above, the main concern is caused by the few E elbows that are note easily replaceable because of their proximity to the RPV. ASN asked the Licensee to study the possibility of replacement or of producing additional justifications.

The following is currently discussed :

1. **Replacement :**

According to EDF, these operations would be highly difficult. Radiological exposure would aslo be very high. Therefore, ASN agreed to consider that this approach shall be applied only if other acceptable justifications cannot be performed. ASN however recommend the Licensee to study it to provide assurance in case other justifications are not possible.

2. **Additional in service inspections : developpement of an ET-UT inspection procedure**

ASN considers that manufacturing inspections were not qualified enough to provide the guaranty that no manufacturing flaw remains, so facture mechanics analysis shall be done considering a 10x40 mm reference flaw. The Licensee is currently developping an ET/UT testing procedure to cover all the internal surface of a E-elbow, that would be able to guarantee the detection of a flaw smaller thant 10x40 mm.

This developpement is more difficult than expected, because of the small size of the flaws to be detected and the challendes caused by austenitic-ferritic stainless steel microstructure.

2. CURRENT REGULATORY APPROACH

3. New fracture mechanics hypothesis

EDF considers that the nature of casting defects, which are less harmful than plan cracks, has still not be taken into account in a complete extent. EDF is currently undertaking some studies that would lead to the definition of a « corrected J0,2 » toughness value to be used for the study of CASS flaws.

Indeed, the current J0,2 values are based on CT testing on fatigue cracked notched specimens, fatigure cracks being more severe than casting flaws.

The ASN considers that these studies are relevant, but their conclusions shall be backed by solid empirical data to be taken into account in the safety demonstrations.

4. GFR method

Current mechanical analysis consider that a flaw is unstable if the crack does not consolidate after 3mm of ductile propagation (instability computations are performed using J3 toughness values).

EDF is developping an energetic approach of ductile fracture propagation, based on a criteria called GFR (developped in Stephane Marie PhD in the 1990s) :

$$R = \frac{dU_{diss}}{dA} = \frac{d(U_{tot} - U_{el})}{dA} = \frac{dU_{pl}}{dA} + G_{fr}$$

The use of this approach could allow to demonstrate the stability of bigger flaws in E elbows.

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