Progress of the 2000 Addenda of the RSE-M Code in Analytical Evaluation and Acceptance Criteria of Flaws

Bruno Barthelet [1), Pierre Cambefort [2), Patrick Le Delliou [3), Bernard Drubay [4), Philippe Gilles [5)

1) EDF Industry, Nuclear Power Operations, 1 Place Pleyel 93282 Saint-denis cedex, France
2) EDF Industry, SEPTEN, 12-14 avenue Dutriévoz 69628 Villeurbanne cedex, France
3) EDF Industry, R&D, Mechanics & Technology Department, Ecuelles 77818 Moret sur Loing cedex, France,
4) CEA DRN/DMT/SEMT/Labatory of Structural Integrity, Saclay Nuclear Center 91191 Gif sur Yvette cedex, France,
5) Framatome ANP, Tour Framatome, 92084 Paris La Défense cedex, France.

ABSTRACT

The RSE-M Code provides rules and requirements for in-service inspection of Pressurized Water Reactor power plant components.

This paper presents the main features of the Code in the field of flaw assessment procedures, comprising fracture mechanics analyses based on engineering methods, flaw acceptance criteria and codification of material characteristics.

The Code gives non mandatory guidance for analytical evaluation of flaws. Influence coefficients used to calculate the stress intensity factors in pipes and shells containing semi-elliptical surface defects are given for a wide range of geometrical parameters. Simplified methods to calculate the J integral in a pipe containing a circumferentially oriented surface crack are available for mechanical loads (in-plane bending and torsional moments, pressure, tension), thermal loads as well as for the combination of these loads.

The rules that are used to verify the acceptability of flaws in components generally rely on deterministic criteria supposed to ensure the safe operation of plants. Based on a probabilistic calibration methodology, partial safety factors on the main random variables involved in flaw assessments (loading, crack size, yield strength and material toughness) are given for each category of operating conditions (A, C or D) and for the possible failure modes (plastic collapse, ductile tearing or brittle fracture).

The Code gives data on the mechanical properties of main base and weld materials used in primary and secondary systems of the NSSS.

INTRODUCTION

The RSE-M Code [1] provides rules and requirements for in-service inspection of Pressurized Water Reactor power plant components. Its scope is close to the scope of Division 1 in Section XI of ASME [2], except that concrete components and metallic liners are not included.

The first edition of the Code was established by EDF and published in 1990 by AFCEN. The second edition [3], established and published in 1997 by AFCEN, contains major complements and improvements. Four technical working groups were created to produce this second edition, respectively in charge of :

❶ inspection programs and general rules,
❷ in-service monitoring methods and non-destructive examinations,
❸ mechanical analysis methods for flaw assessment and material properties,
❹ repair and maintenance procedures.

This paper presents the current state of the Code (2000 Addenda) in the field of flaw assessment procedures, comprising fracture mechanics analyses based on simplified methods, flaw acceptance criteria and codification of material characteristics.

CALCULATION OF THE STRESS INTENSITY FACTOR

The Code gives non mandatory guidance for analytical evaluation of flaws. These methods are gathered in Appendix 5.4.

An extensive work was conducted by the CEA (French Atomic Energy Commission) to provide influence coefficients used to calculate the stress intensity factors in pipes and shells containing semi-elliptical surface defects [4], [5]. The influence coefficients i_0 to i_3 and the shape factor F_b (for circumferential cracks only) were calculated for both circumferential and longitudinal surface cracks placed either on the outer or the inner surface of a pipe, for a wide range of geometrical parameters :

- $a/t \in [0 ; 0.1 ; 0.2 ; 0.4 ; 0.6 ; 0.8]$
- $a/c \in [1 ; 1/2 ; 1/4 ; 1/8 ; 1/16 ; 0]$
- $t/r_i \in [1 ; 1/2 ; 1/5 ; 1/10 ; 1/20 ; 1/40 ; 1/80 ; 0]$

The cases $a/c = 0$ and $t/r_i = 0$ are limiting cases corresponding respectively to a continuous crack (axisymmetric or strip-shaped) and to a plate. The values were validated by a comparison with Bergman data [6] for circumferential cracks (t/r_i = 1/5 and 1/10) and with Raju data [7] for longitudinal cracks (t/r_i = 1/4 and 1/10). A good agreement was generally observed, the differences being larger for elongated cracks, influence coefficients i_2 and i_3, and the crack surface point.

ANALYTICAL EVALUATION OF THE J-INTEGRAL

EDF, FRAMATOME and CEA have developed simplified methods to calculate the J integral in a pipe containing a circumferentially oriented surface crack. Figure 1 shows a semi-elliptical crack on the outside surface of a pipe. The crack angle β is defined by : $\beta = \frac{c}{r_e}$ ($\beta = \frac{c}{r_i}$ if the crack is on the inside surface).

These methods are currently available for mechanical loads (in-plane bending and torsional moments, pressure, tension), thermal loads as well as for the combination of these loads. They are gathered in Appendix 5.4.

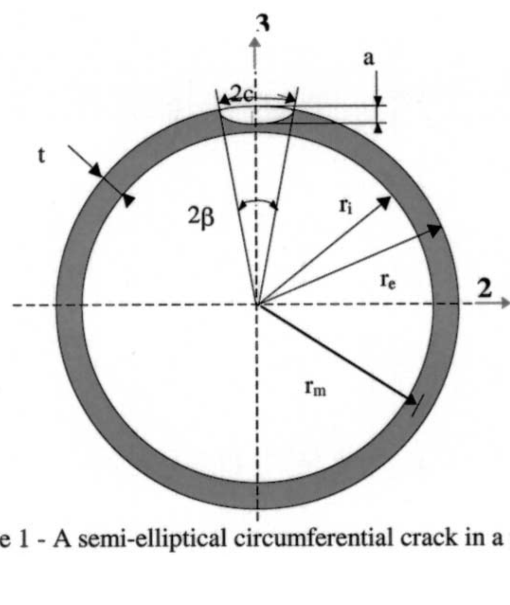

Figure 1 - A semi-elliptical circumferential crack in a pipe

ESTIMATION OF THE J-INTEGRAL UNDER MECHANICAL LOADING

Two methods - named CLC and CEP - and derived from the R6 rule [8], are available for mechanical loads. Both methods are fully developed in the 2000 Addenda of the Code (appendix 5.4).

CLC method

The CLC method, based on a corrected limit load, will be shortly presented here (for the CEP method see [9].. The equation used to calculate L_r for a pressure combined with an in-plane bending moment is :

$$L_r = \sqrt{\left[\frac{m_2}{q_m \mu_{em} \mu_t}\right]^2 + \left[(1-\mu_{ti})\frac{p}{\mu_{ep}}\right]^2} + \mu_{ti}\frac{p}{\mu_{ep}} \qquad (1)$$

where m_2 and p are adimensional loading : $m_2 = \frac{M_2}{4 r_m^2 t S_y}$ $\qquad p = \frac{\sqrt{3}}{2}\frac{P r_m}{t S_y}$ (2), (3)

and q_m, μ_{em}, μ_t, μ_{ep} and μ_{ti} are coefficients given in Table 1, depending only on geometrical parameters.

Table 1 - Coefficients for the CLC method

Coefficients	q_m	μ_{em}	μ_{em}	μ_t	μ_{ti}
$\beta < 2\pi\frac{a}{t}$	$\cos\left(\frac{\beta}{2}\frac{a}{t}\right) - \frac{1}{2}\frac{a}{t}\sin(\beta)$	$1-0.16\sqrt{\frac{a}{t}}$	1 for inner surface crack	$1+\frac{1}{2}\frac{a}{t}\frac{\beta}{\pi}$	$\mu_{ti} = \frac{\sqrt{\mu_t^2 - 1}}{\mu_t}$
$\beta \geq 2\pi\frac{a}{t}$	$1-\frac{a}{t}$	1	0.9 for outer surface crack	$1+\frac{1}{2}\frac{a}{t}$	

Then K_r is calculated from L_r by :

$$K_r = \left[\frac{E\,\varepsilon_{ref}}{L_r\,S_y} + \frac{1}{2}\frac{L_r^2}{L_r^2+1}\right]^{-\frac{1}{2}} \qquad (4)$$

where ε_{ref} is the strain corresponding to the stress $\sigma_{ref} = L_r S_y$ on the true stress - true strain curve of the material (same approach as Option 2 of the R6 rule).

Finally, an estimation of the elastic-plastic J-integral is obtained by :

$$J = \frac{J_e}{K_r^2} \qquad (5)$$

where J_e is the elastic value of J

CEP method

The CEP method [9] combines the elastic and fully plastic behavior through two equivalent stresses sig_{eqel} and sig_{eqpl},

$$[sig_{eqel}]^2 = \left(\sigma_{1m} + \frac{1}{f}\cdot\sigma_{gb}\right)^2 + \sigma_{2m}^2 - \left(\sigma_{1m} + \frac{1}{f}\cdot\sigma_{gb}\right)\cdot\sigma_{2m} \qquad (6)$$

$$[sig_{eqpl}]^2 = \left(\sigma_{1m} + \frac{g}{f}\cdot\sigma_{gb}\right)^2 + \sigma_{2m}^2 - \left(\sigma_{1m} + \frac{g}{f}\cdot\sigma_{gb}\right)\cdot\sigma_{2m} \qquad (7)$$

The value of the stresses (σ_{1m} : axial membrane stress, σ_{2m} : circumferential membrane stress, σ_{gb} : global bending stress due to M_2), g and f are given in Table 2.

Table 2 – Values of stresses and coefficients for the CEP method

σ_{1m}	σ_{2m}	σ_{gb}	f	g
$\frac{P\left(r_i^2+\frac{ac}{2}\right)}{\left(r_e^2-r_i^2\right)-\frac{ac}{2}}$	$P\frac{r_m}{t}$	$\approx\frac{M_2}{\pi\cdot r_m^2\cdot t}$	$\cos\left(\frac{\beta}{2}\frac{a}{t}\frac{\pi}{4}\right)-\frac{a}{2t}\sin\left(\frac{\pi}{4}\beta\right)$	$0.535\leq g\leq 1$

The strains related to these two equivalent stresses are combined on the true stress-strain curve to determine the reference strain ε_{ref} and the reference stress σ_{ref} (Figure 2).

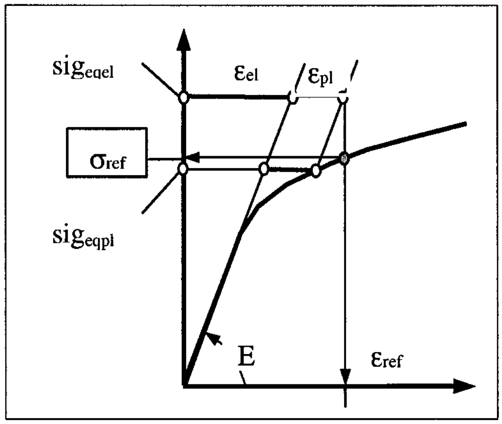

Figure 2 – Reference stress evaluation

Finally, an estimation of the elastic-plastic J-integral is obtained by :

$$J = J_e \cdot \frac{E\varepsilon_{ref}}{\sigma_{ref}} \tag{8}$$

CLC and CEP methods

The CLC and CEP methods were validated thanks to a large database of finite element results, comprising about 70 2D cases (axisymmetric cracks) and 70 3D cases (semi-elliptical cracks), see for example [10]. The following parameters were investigated :

- relative pipe wall thickness (t/r_m = 1/5 or 1/10),
- crack location (inside or outside),
- relative crack depth (a/t = 1/8 ; 1/4 ; 1/2),
- crack aspect ratio (a/c = 1/3 for most cases),
- marerial stress-strain curve (Ramberg-Osgood fit with n = 5 or 8, 316 stainless steel, carbon steel with a plateau),
- type of loading.

Two cases of validation are presented here. Their characteristics are given in Table 3.

Table 3 - Characteristics of the cases presented

Parameter	Value
r_m (mm)	300
t (mm)	60
crack location	outside
a (mm)	15
c (mm)	45
E (MPa)	177000

Parameter	Value
ν	0.3
Ramberg-Osgood n	5
Ramberg-Osgood α	3
Ramberg-Osgood σ_0 (MPa)	120
Case 1 - Loading : M_2	0 to 5000 kN.m
Case 2 - Loading : P + M_2	0 to 21.2 Mpa, 0 to 5000 kN.m

Figures 3 and 5 show the evolution of J at the deepest point of the crack as a function of L_r, whereas Fig. 4 and 6 show the evolution of the relative difference on J :

$$\Delta J / J \ (\%) = 100 \frac{J_{RSE-M} - J_{EF}}{J_{EF}} \qquad (9)$$

This type of analysis was conducted on the whole database, in order to determine an overall trend on the accuracy of the simplified methods. On most of the cases, the differences stay under 20 %.

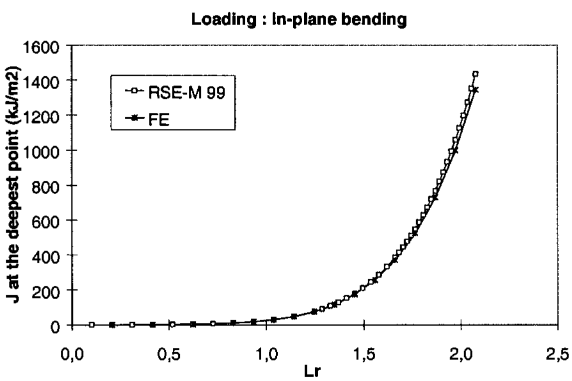

Figure 3 - Case 1 : Evolution of J as a function of Lr

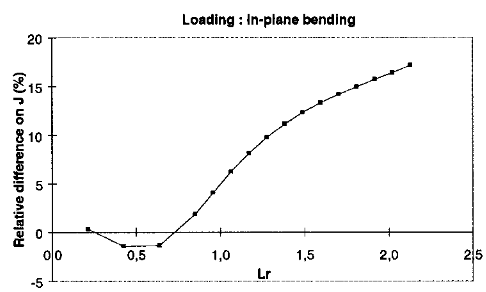

Figure 4 - Case 1 : Evolution of the relative difference on J

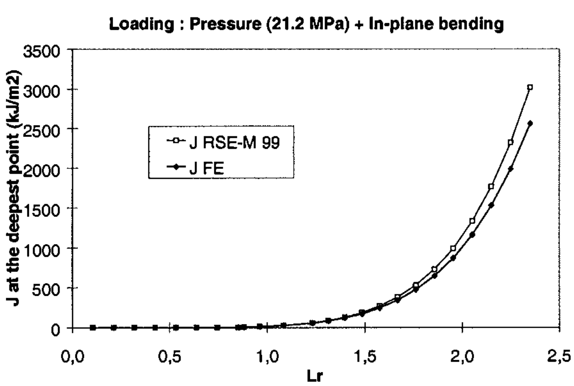

Figure 5 - Case 2 : Evolution of J as a function of Lr

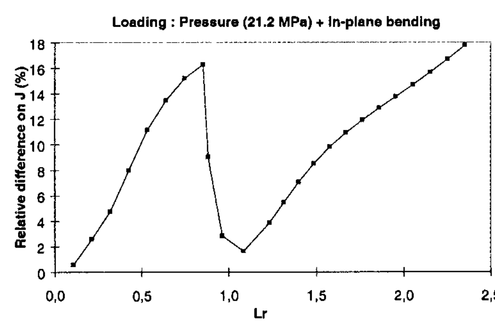

Figure 6 - Case 2 : Evolution of the relative difference on J.

ESTIMATION OF THE J-INTEGRAL UNDER THERMAL LOADING

A method is proposed to calculate J for an inside circumferential surface crack subjected to a cold thermal transient. It is assumed that the temperature distribution through the pipe wall and the elastic value of J - denoted J_e^{th} - are known. J_e^{th} can be obtained by an elastic analysis of the uncracked body and the use of influence coefficients.

First, a thermal strain ε_{th} is calculated :

$$\varepsilon_{th} = 0.85 \frac{\alpha\left(\frac{\Delta T_1}{2} + \Delta T_2\right)}{\frac{4}{3}(1-\nu)} f\left(\frac{a}{t}\right) \quad (10)$$

- where ΔT_1 and ΔT_2 are the values of $\Delta T_1(t)$ and $\Delta T_2(t)$ at the time of the transient when J_e^{th} is maximum,
- and f a parameter given in Table 4.

Table 4 - Values of the parameter f

a/t	<1/30	1/16	1/8	1/4	1/3	1/2.5	1/2
f(a/t) deepest point	1	1.06	1.10	0.86	0.63	0.54	0.54
f(a/t) surface point	1.6	1.6	1.6	1.6	1.6	1.6	1.6

Figure 7 shows the definition of ΔT_1 and ΔT_2. They are respectively the linear thermal gradient and the non-linear thermal gradient defined in ASME Section III NB-3600 [11]. Their absolute value should be used in the above equation.

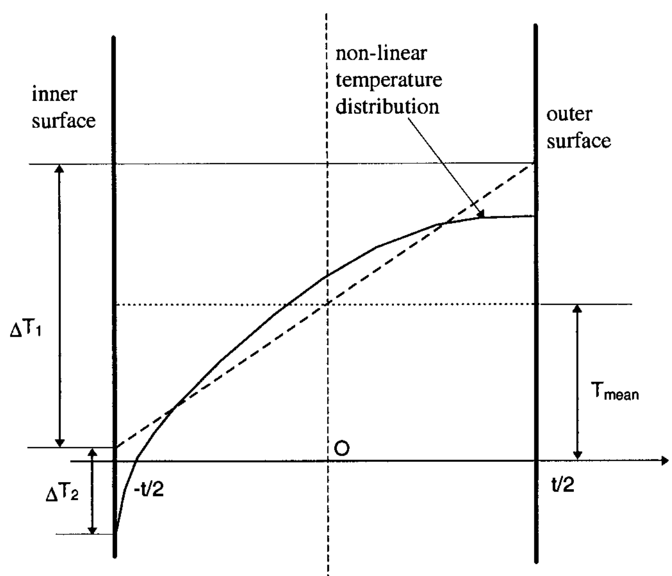

Figure 7 - Through wall temperature distribution in a pipe

Then an elastic-plastic corrective coefficient k_{th} is determined by :

$$k_{th} = \mathrm{Max}\left[\begin{array}{l}\sqrt{1.28\dfrac{\sigma_{th}}{E\,\varepsilon_{th}} - 0.28\left(\dfrac{\sigma_{th}}{E\,\varepsilon_{th}}\right)^2} \\ 0.5\end{array}\right] \quad (11)$$

where σ_{th} is the stress corresponding to the strain ε_{th} on the true stress - true strain curve of the material. Finally, an estimation of the elastic-plastic J-integral is obtained by :

$$J_{th} = k_{th}^2\, J_e^{th} \quad (12)$$

This method was also validated thanks to a large finite element results database, comprising mainly 2D cases (axisymmetric cracks).

ESTIMATION OF THE J-INTEGRAL UNDER COMBINED LOADING

A very simple method consists to add the elastic-plastic stress intensity factors (denoted K_J), respectively due to the mechanical loading and to the thermal loading :

$$K_J = K_J^m + K_J^{th} = K_J^m + k_{th} K_I^{th} \quad (13)$$

However, this method is sometimes not conservative, as the stress systems interact. To take into account this interaction, a parameter k_{th}^* is introduced to calculate J :

$$J = \left[\sqrt{J^m} + k_{th}^* \sqrt{J_{el}^{th}}\right]^2 \quad (14)$$

This parameter k_{th}^* is defined as follows :

1) $k^*_{th} = k_{th}$ (no interaction) if at least one of the following conditions is verified :

a) $L_r \leq 0.5$

b) $L_r(P=0) \leq 2p$

where - $L_r(P=0)$ is calculated by the formula given for the mechanical loads with P = 0,

- and p is the adimensional pressure previously defined ($p = \dfrac{\sqrt{3}}{2}\dfrac{Pr_m}{tS_y}$).

2) $k_{th}^* = 1 - \dfrac{2p}{L_r(P=0)}\left(1 - k_{th}\right)$ if neither of the above conditions a) and b) is verified.

FLAW ASSESSMENT CRITERIA

The rules that are used to verify the acceptability of flaws in components habitually rely on deterministic criteria supposed to ensure the safe operation of plants. In order to have a reliable method of evaluating the safety margins, EDF conducted a study to link safety factors with safety levels [12], [13].

Based on a probabilistic calibration methodology, partial safety factors on the main random variables involved in flaw assessments (loading, crack size, yield strength and material toughness) are given in Appendix 5.5 of the Code for each category of operating conditions (A, C or D) and for the possible failure modes (plastic collapse, ductile tearing or brittle fracture). These partial safety factors should be used with the material characteristics specified in Appendix 5.6 of the Code, to insure the coherence of the methodology.

A similar approach was developed by Bergman [14]. A specific Annex on reliability and partial safety factors is under preparation for the new British Standard Guide BS7910 [15]. A reflection to move towards such an approach is underway within ASME Section XI.

MATERIAL PROPERTIES

Appendix 5.6 of the Code gives data on the mechanical properties of main base-metals and welds used in primary and secondary systems of the NSSS. These data were developed by statistical analyses of both laboratory results and manufacturing data. A detailed presentation of this work is available in [16]. The components presently covered by the Appendix are as follows :

- reactor pressure vessel forged parts,
- pressurizer forged parts and plates,
- steam generators parts (forgings and plates),
- main reactor coolant forged piping,
- secondary circuit piping (main steam lines and feedwater lines),
- the welds corresponding to each type of components.

Three families of steel are used in these components :

- manganese-nickel-molybdenum low alloy steel (16 MND5 or 20 MND5, French standards similar to SA508 cl. 3 or SA533 gr. B),
- carbon-manganese steel (A42 or A48, French standards similar to SA106),
- austenitic stainless steel (Z3 CND 17-12 or Z2 CN 18-10, French standards similar to AISI 316L or 304L).

The material characteristics included in the Appendix 5.6 of the Code are as follows :

- tensile properties comprising yield strength, ultimate tensile strength and adimensional reference true stress - true strain curves,
- fracture toughness K_{Ic} and K_{Jc} in the transition regime (low alloy steel),
- value of the J-integral in the ductile regime at the onset of crack extension ($J_{0.2}$ after 0.2 mm of crack extension),
- J-Δa curves in the ductile regime,
- Fatigue crack growth rates.

CONCLUSIONS

The RSE-M Code provides rules and requirements for in-service inspection of French Pressurized Water Reactor power plant components. Its scope is close to the scope of Division 1 in Section XI of ASME.

The current state of the Code (2000 Addenda) in the field of flaw assessment procedures was presented in this paper. It is focused on fracture mechanics analyses based on simplified methods, flaw acceptance criteria and codification of material characteristics.

First, influence coefficients used to calculate the stress intensity factors in pipes and shells containing semi-elliptical surface defects are given for a wide range of the pertinent geometric parameters.

Secondly, simplified methods are proposed to calculate the J integral in a pipe containing a circumferentially oriented surface crack, submitted to mechanical or thermal loading.

Partial safety factors on the main random variables involved in flaw assessments (loading, crack size, yield strength and material toughness) are given for each category of operating conditions (A, C or D) and for the possible failure modes (plastic collapse, ductile tearing or brittle fracture).

Finally, mechanical properties of main base and weld materials used in primary and secondary systems of the NSSS are provided. These specified properties should be used for determining the acceptability of flaws that have been detected during in-service inspections.

Work is on-going on several topics : enlarge the scope of the J-estimation methods to various geometries (longitudinal flaws, elbows, tapered transitions...) and to embedded flaws, extend the codification range of material properties, validate new tables of acceptable flaws.

NOMENCLATURE

r_i	Inside radius of pipe	α	Coefficient of thermal expansion
r_e	Outside radius	E	Young's modulus
r_m	Mean radius	ν	Poisson's ratio
t	Pipe wall thickness	S_y	Yield stress
a	Crack depth	M_2	In-plane bending moment
c	Half-crack	P	Pressure
β	Half-crack angle	i_j	Influence coefficient ($0 \leq j \leq 3$)
		F_b	Shape factor for in-plane bending

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