

RSE-M NUCLEAR IN-SERVICE INSPECTION CODE A SET OF MODERN FLAW EVALUATION RULES

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ABSTRACT

After a quick overview of RSEM scope now used for more than 100 Nuclear Power Plants in the World, this paper will present the flaw evaluation rules of RSE-M Appendix 5.

These Appendix consider cracks, volumetric defects and thinning areas. Periodically updated on a yearly bases, the rules cover cracks in different components, for different material, in different location. It consider defects interaction, clad components, mismatch effects, mechanical and thermal loads, warm pre-stressed ...

Crack in brittle and ductile regimes are considered using K and J parameters for different crack shape (surface and sub-surface, inner or outer surface, elliptical or infinitely long cracks) in different location: base metal, weld, underclad, dissimilar welds....

The RSEM Appendix 5 covers: flaw geometry definition, acceptance standards, fatigue and plastic-instability, K-J parameter evaluation, planar defect acceptance criteria, material properties, volumetric defect evaluation, partial safety factors

This paper will be focused on different J estimation scheme presented in detailed in RSEM 2015 edition and last modifications of 2016.

INTRODUCTION

General

The evaluation of the fitness for service of structural components is a key aspect for developing safety justifications for continued operation in many industries concerned with pressurised piping and vessels, and in particular for safety in nuclear power plants. Over the years different countries have developed their own rules in connection with their particular needs and in accordance with their national regulation. With the internationalisation of the nuclear industry and the markets there is now an on-going effort in harmonizing such rules to ensure best practice across the world.

The presentation is focused on light water reactor (LWR) at low temperature (no creep consideration) and based on 2015 edition of RSE-M and RCC-MRx Codes edition 2015 that are totally consistent. Both Codes are developed under AFCEN organization: French Association for Design, Construction and Surveillance Rules of Nuclear Power Plant Components of Nuclear Power Plants. AFCEN is to-day an open international non-profit organization to establish, publish, revise and update detailed and practical rules for the design, manufacture, installation, commissioning and in-service inspection, deconstruction of nuclear components from PWR, Experimental, High Temperature and Fusion reactors.

The flaw evaluation procedures in these 2 Codes have been developed in a very close format with many common experts in Fracture Mechanic from EDF, AREVA and CEA. The rules are in non-mandatory appendices:

- Appendix 5 for RSE-M
- Appendix A16 for RCC-MRx.

RSE-M: "Rules for In-service Inspection of Nuclear Power Plant Components"

The first RSE-M version was published in 1990, and last one in 2016 as the result of more than 20 years of many PWRs in France and outside France. The flaw evaluation based on fracture mechanic analysis of cracked components has been continuously improved from 1990 to 2016 editions. The last Edition 2016 is available in French and in English. The 2002 Edition has been translated and largely used in Chinese

RCC-MRx: Design and Construction Rules for Mechanical Components

It's the result of merge of RCC-MR developed for Fast Breeder Reactor (LMFBR) in the 1980 and the RCCM_x developed by CEA for Research Reactors (RR) in the same period. The first draft compiled version was issued in 2010 based on RCCM_x 2007 and RCCMR 2008, last Edition was published in 2015, in English. It's a complete set of rules for design, material selection, fabrication and welding, examination of safety class mechanical components. To-day, no dedicated In-service Code is available in AFCEN for these type of reactors. Nevertheless, a very detailed fracture mechanic appendix (A16) has been developed for flaw evaluation and leak before break justification at design level.

This paper will consider mainly the Appendix 5 of RSE-M.

RSE-M content

The French RSE-M is the Code for Operation and In-Service Inspection of PWR Mechanical Components that include:

- the 10-year requalification of pressure systems and components
- the periodic In-service Inspection (ISI) and associated qualification of procedure and personnel for performance demonstration
- surveillance and monitoring activities
- deviation and indications treatment including flaw evaluation (local thinning areas and cracks)
- the maintenance requirements including modifications, repair, replacement

All these tasks are under Utility responsibility in French regulation, except requalification which is under Safety Authority responsibility, in any case sub-contracts are acceptable through certified independent bodies or recognized Utility Inspection Service.

A set of appendices covers general information on PWR to use the Code, inspection plan development, ISI qualification, corrective maintenance procedure, tables of visit content and associated figures, and to analyse inspection results by flaw evaluation procedure (Appendix 5)

The major concern of this paper is the non-mandatory RSE-M appendix 5, supplemented by a Code Case (RPP-02) on "flaw evaluation of cracks close to the cladding with Warm Pre-Stress consideration".

Elastic and elastic-plastic fracture mechanic are used in the different procedures proposed in Appendix 5 to evaluate the key parameters: K and J. In any case, for few particular cases, a direct elastic-plastic Finite Element Method (FEM) on cracked component can be used to evaluate these fracture mechanic parameters, some recommendations are done in RSE-M appendix 5 in order to perform these analyses.

Table 1: RSE-M Appendix 5 content

Appendix 5.1	Defect geometry for analysis
Appendix 5.2	Acceptable standards
Appendix 5.3	Fatigue and Plastic instability analysis
Appendix 5.4	Analytical Methods for K and J evaluation
Appendix 5.5	Allowable plan defect- Mechanical acceptability criteria
Appendix 5.6	Material Properties
Appendix 5.7	Specific analysis of volumetric defect
Appendix 5.8	General principles to develop partial safety factors

BASIC APPROACH FOR FLAW EVALUATION

General

The step by step flaw evaluation procedure is based on:

- Elastic stress evaluation of the component (based on an un-cracked model) to determine stress on the cracked section,
- Elastic stress intensity K_I , K_{II} and K_{III} evaluation through superposition principle (influence functions), associated to a combination rule for mode I, II and III
- J evaluation scheme based on reference stress method, considering in particular different approaches for mechanical and thermal loads
- Comparison with allowable maximum load for the cracked body to analyze margins in front of collapse load with consistent margins as the design rules
- Comparison of J evaluation with the material J-resistance curve proposed in RSE-M appendices 5.6

Different improvements are done in a case by case basis:

- clad components
- J-estimation scheme by reference stress method, with specific considerations:
 - o Mechanical and thermal loads
 - o Ferritic steels with "plateau" on stress-strain curve
 - o Weld mismatch
- Steam Generator tube

This paper will be focused on different J_{pl} estimation scheme, considering plasticity and elastic stress classification.

Elastic stress intensity factors

- Basic principle of the stress intensity factor evaluation:
 - o Polynomial stress distribution in the cracked section:

$$\sigma = \sigma_0 + \sigma_1 x/t + \sigma_2 (x/t)^2 + \sigma_3 (x/t)^3 + \sigma_4 (x/t)^4$$
 - o Use of a large data bank of influence function i to derive K value:

$$K = \sqrt{\pi a} \left[\sigma_0 i_0 + \sigma_1 i_1 \frac{x}{t} + \sigma_2 i_2 \left(\frac{x}{t} \right)^2 + \sigma_3 i_3 \left(\frac{x}{t} \right)^3 + \sigma_4 i_4 \left(\frac{x}{t} \right)^4 \right]$$

The RSE-M K handbook of influence functions

Content of the K handbook of power 4 influence functions:

- for cylinder (and plate), for:
 - o $a/t = 0 ; 0.1 ; 0.2 ; 0.4 ; 0.6 ; 0.8$
 - o $a/c = 1 ; 1/2 ; 1/4 ; 1/8 ; 1/16 ; 0$ ($a/c = 0$ infinitely long crack)
 - o $t/r_i = 1 ; 1/2 ; 1/5 ; 1/10 ; 1/20 ; 1/40 ; 1/80 ; 0$ ($t/r_i = 0$ plate of infinite radius)
 - o surface point and deepest point, inner surface and outer surface crack
- plate, cylinder, elbow, thickness variation
- around 80 tables to cover all these geometries:
 - o plate, cylinder, thickness variation, elbow
 - o with different cracks: elliptical and infinite crack, surface and sub-surface, inner and outer surface.

J evaluation scheme based on reference stress method

Basic principle of the reference stress method:

- $J_s = J_{pl}$
- $J_{pl} / J_{el} = \varepsilon_{ref} / (\sigma_{ref}/E) = 1/K_R$
- $\sigma_{ref} = L_R \cdot \sigma_y = C / C_{L,\sigma_y} \cdot \sigma_y$
- ε_{ref} correspond to σ_{ref} on the stress strain curve

- $J_s = J_{pl} = J_{el} [\epsilon_{ref} / (\sigma_{ref}/E) + \psi]$ with $\psi = 0.5 [\sigma_{ref}^2 / (\sigma_{ref}^2 + \sigma_y^2)]$ Two ways for application:
- Failure assessment Diagram: one by stress-strain curve
- Numerical approach of J_{pl}

Data collection for J estimation

- Geometry and sizes
- Crack size and location: $2a - 2l$
- Applied Loads: C
- Material properties: base metal and weld
 - o Stress-strain curve
 - o Young modulus
 - o Toughness
- Limit load formulae and K influence functions for the geometry and the crack to consider

Step by Step numerical J estimation scheme

- **Step 1:** Elastic K and J evaluation
 - o Elastic stress evaluation of un-cracked component
 - o Stress in the crack section polynomial smoothing of order 4

$$\sigma = \sigma_0 + \sigma_1 x/t + \sigma_2 (x/t)^2 + \sigma_3 (x/t)^3 + \sigma_4 (x/t)^4$$
 - o Using RSE-M K Handbook for given geometry and crack
 - o $J_{el} = K^2 / E$
- **Step 2:** C_L evaluation
 - o Limit load of cracked component for typical load for σ_y flow stress
 - o Using Compendium
- **Step 3:** $L_R = C / C_L$
- **Step 4:** $\sigma_{ref} = L_R R_{p0.2}$
- **Step 5:** ϵ_{ref} on stress-strain curve for σ_{ref}
- **Step 6:** K_R estimation

$$K_R = [\epsilon_{ref} / (\sigma_{ref}/E) + \psi] \quad \text{with:} \quad \psi = 0.5 [\sigma_{ref}^2 / (\sigma_{ref}^2 + R_{p0.2}^2)]$$
- **Step 7:** $J_s = J_{pl} = J_{el} / K_R^2$

Graphical presentation of Failure Assessment Diagram

- **Step 1:** σ_{ref} evaluation
 - o for $L_R = 0$ to $(R_{p0.2} + R_m)/R_{p0.2}$, evaluate $\sigma_{ref} = L_R R_{p0.2}$
- **Step 2:** ϵ_{ref} on stress-strain curve for σ_{ref}
- **Step 3:** K_R estimation
 - o $K_R = [\epsilon_{ref} / (\sigma_{ref}/E) + \psi]$ with: $\psi = 0.5 [\sigma_{ref}^2 / (\sigma_{ref}^2 + R_{p0.2}^2)]$
- **Step 4:** Plot K_r - L_r diagram

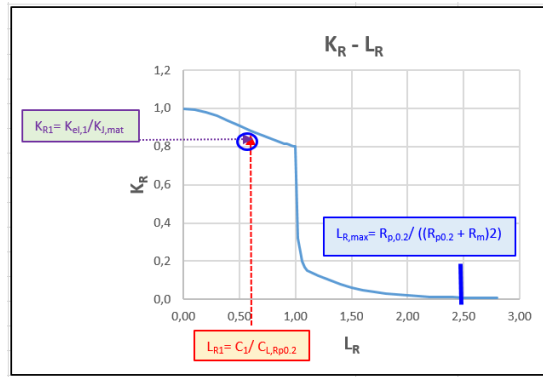


Figure 1: Kr – Lr Failure Assessment Diagram

- **Step 5:** Use of Failure Assessment Diagram (FAD)
 - o Evaluate L_{R1} for a load C_1 : $L_{R1} = C_1 / C_{L,RP0.2}$
 - o Evaluate elastic $K_{el,1}$ for load C_1 with influence function
 - o Evaluate K_{R1} for load C_1 and material toughness K_J : $K_{R1} = K_{el,1} / K_J$
- **Step 6:** Evaluation of intersection point:
 - o Under the FAD : no crack initiation for C1
 - o Over the FAD: crack initiation and ductile crack growth has to be evaluated

J EVALUATION SCHEME IMPROVEMENTS

“Mismatch Effect” on J evaluation for Mechanical Loads in a weld

Scope of validity

The proposed method is valid for:

- a straight pipe,
- a V-shaped, circumferential weld joint, which involves two materials and is "overmatched" (i.e. where the weld deposited metal has a higher yield stress than the base metal),
- identical elastic properties for the base metal and the crack weld deposited metal,
- a mechanical load such as internal pressure, axial load and/or bending moment / torsional moment,
- an axisymmetric or semi-elliptical emerging defect with a relative depth of $a/t < 0.25$
- a circumferential defect on the internal surface at the centre of the joint (see Figure 2 - position 1),
- a circumferential defect on the internal surface at the base of the weld bead (see Fig. 2 position 2),
- a circumferential defect on the external surface at the base of the weld bead (see Fig. 2 position 3), with the crack tip on the base metal side,
- a defect on the internal surface at the interface between the base metal and the weld deposited metal (see Fig.2 position 4)

Definition of Equivalent Material

The definition of equivalent material is based on a law governing mixtures which covers the stress-strain curves for the base metal and the weld deposited metal (Figure 3). For a given plastic strain, the corresponding stress for the stress-strain-curve for the equivalent metal is:

$$\sigma_e(\varepsilon^p) = \frac{(\alpha(M) - 1) \sigma_w(\varepsilon^p) + (M - \alpha(M)) \sigma_b(\varepsilon^p)}{M - 1}$$

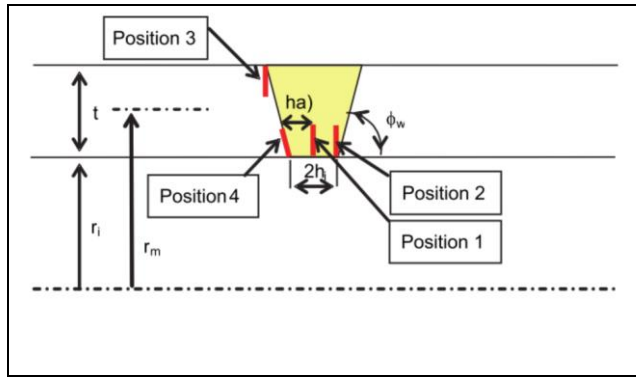


Figure 2: Crack location in the weld

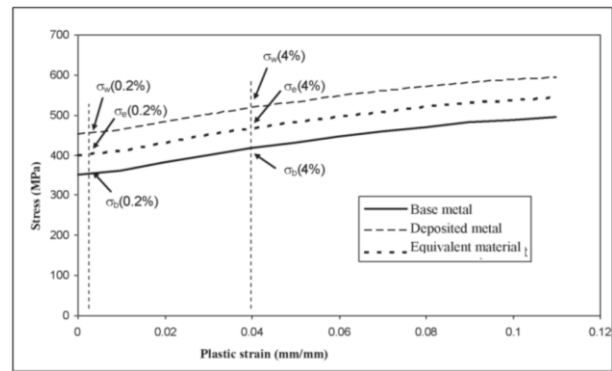


Figure 3: Equivalent material

Where:

- σ_b is the stress corresponding to plastic strain ϵ_p on the stress-strain curve for the base metal,
- σ_w is the stress corresponding to plastic strain ϵ_p on the stress-strain curve for the weld deposited metal,
- M is the “local” mismatch associated with plastic strain ϵ_p , corresponding to the ratio σ_w / σ_b ,
- $\alpha(M)$ is the weight function which depends on the geometric data for the problem (defect and component part) and the mechanical load to consider

With low levels of plastic strain (less than 0.006 mm/mm), this curve must be corrected to allow for a gradual progression between the stress-strain curve for the base metal and that of the equivalent material. This correction is carried out on the basis of the following relation which is applied to parameter α when creating the stress-strain curve for the equivalent material:

$$\alpha_{\text{corr}}(\epsilon^p) = 1 + [\alpha(M(0.006)) - 1] \cdot \left(\frac{\epsilon^p}{0.006} \right)^{0.25}$$

Similar formulae are proposed in RSE-M Appendix 5.4 for thickness transition and elbow with circumferential and longitudinal surface crack

Mechanical Imposed Displacement load

J evaluation for imposed displacements using simplified methods is complex because of the relationship between the global imposed load and the actual stresses imposed at a potential crack: unlike with imposed force type loadings, evaluating the stresses, and in particular the reference stress, is no longer merely a geometric relation linked to the structure and the defect but also has to take account of the material stress-strain curve. The detailed are presented in RSEM-Appendix 5.4 Article IV.6 (not presented in this paper)

Thermal loads (without mechanical load)

Scope and validity limits

The scope of validity for the J_{th} method is as follows:

- straight pipe or shell such as $r_m/t \geq 3$ only subject to a thermal cooling transient applied to an internal surface;
- any RCC-M material or similar;
- circumferential or longitudinal defect located on a straight cylindrical section well away from any major discontinuity:
 - o more than or equal to $1.5\sqrt{r_m t}$ from a thickness transition, from an elbow.
 - o and located more than or equal to $1.5\sqrt{\frac{r_m^3}{t}}$ from an elbow.
- circumferential defect on the internal surface, semi-elliptical (CDSI) or axisymmetric (CDAI), longitudinal defect on the internal surface, semi-elliptical (LDSI) or continuous (LDII), such as:

circumferential defect	$\frac{a}{t} \leq \frac{1}{4}$	$\frac{1}{4} < \frac{a}{t} \leq \frac{1}{2}$
$\frac{1}{3} < \frac{a}{c} \leq 1$	Bottom Surface	- Surface
$\frac{a}{c} \leq \frac{1}{3}$	Bottom Surface	Bottom Surface

Table 2: Validity limits for circumferential defect

longitudinal defect	$\frac{a}{t} \leq \frac{1}{8}$	$\frac{1}{8} < \frac{a}{t} \leq \frac{1}{3}$
$\frac{1}{3} \leq \frac{a}{c} \leq 1$	Bottom Surface	Bottom Surface
$\frac{a}{c} < \frac{1}{3}$	Bottom Surface	

Table 3: Validity limits for longitudinal defect

The validity limits of J_{th} for Thickness transition and elbows is defined in RSE-M Appendix 5.4 article V.1.

J_{th} General Expression

Radial temperature variations in the wall due to thermal transients lead to imposed strains, consequently, J_{el} shall be corrected to allow for attenuation due to plasticity effects.

$$J_{th} = k_{th}^2 \cdot J_{el}^{th}$$

where:

- J_{el}^{th} : maximum value of J elastic during the transient
- k_{th} : elastic-plastic adjustment coefficient
- J_{el} : elastic J obtained by $J = K_I^2 / E^*$ with K_I the elastic stress intensity factor

K_{th} evaluation: Option 1 without stress-strain curve

$$k_{th} = \text{Min} \left[1, 0.5 + 0.5 \cdot \exp[-0.46(L_{th} - 1)] \right]$$

with adimensional parameter L_{th} :

$$L_{th} = \frac{E\alpha \left(\frac{\Delta T_1}{2} + \Delta T_2 \right)}{\frac{4}{3}(1-\nu)S_0} f\left(\frac{a}{t}\right)$$

- ΔT_1 and ΔT_2 are values for ΔT_1 (tps) and ΔT_2 (tps) recorded at the time during the thermal transient when J_{el}^{th} is maximum
- S_0 is the stress obtained over the material's stress-strain curve for which elastic strain is equal to plastic strain (S_0 may be determined by considering the intersection between the stress-strain curve and the straight line for equation $\sigma = 0.5 \cdot E \cdot \epsilon$)
- α : linear expansion coefficient for the material;
- f : coefficient obtained by linear interpolation as a/t from Table 2 for a circumferential defect and from Table 3 for a longitudinal defect;
- the characteristics of material S_0 et α are taken at the final fluid temperature T_f

$\frac{a}{t}$	$\leq \frac{1}{30}$	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{2.5}$	$\frac{1}{2}$
f at the tip	1	1.06	1.10	0.86	0.63	0.54	0.54
f on the surface	1.6	1.6	1.6	1.6	1.6	1.6	1.6

Table 4: f values for a circumferential defect

$\frac{a}{t}$	$\leq \frac{1}{30}$	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{3}$
f at the tip	1	1.06	1.10	0.75	0.54
f on the surface	1.1	1.1	1.1	1.1	1.1

Table 5: f values for a longitudinal defect

K_{th} evaluation: Option 2 using stress-strain curve

The elastic-plastic correction factor k_{th} is defined by:

$$k_{th} = \text{Max} \left[0.5; \sqrt{1.28 \frac{\sigma_{th}}{E \varepsilon_{th}} - 0.28 \left(\frac{\sigma_{th}}{E \varepsilon_{th}} \right)^2} \right]$$

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

with strain ε_{th} :

- ΔT_1 and ΔT_2 are values for ΔT_1 (tps) and ΔT_2 (tps) taken at the time during the thermal transient when J_{el}^{th} is at its maximum
- σ_{th} is the stress corresponding to strain ε_{th} for the material's true stress-strain curve
- α is the linear expansion coefficient for the material
- f is calculated as in option 1 (Tables 2 and 3)
- the characteristics of the material α and $\sigma_{th} = f(\varepsilon_{th})$ are taken at the final fluid temperature T_f

J under combined mechanical and thermal load

General evaluation

The effect of radial temperature variations in the wall thickness due to thermal transients referred to as "th" is processed separately before being combined, multiplied by coefficient k_{th}^{*}, with that due to other mechanical and thermal loads referred to as "mt".

According to the chosen method, K_{cp} or J_s, in order to calculate an estimate of J under mechanical and thermal loads other than a thermal transient, the value of J under a combined load is given by the following formulae:

$$J = \left[\sqrt{J_{cp}^{mt}} + k_{th}^* \cdot \sqrt{J_{el}^{th}} \right]^2 \quad \text{or} \quad J = \left[\sqrt{J_s^{mt}} + k_{th}^* \cdot \sqrt{J_{el}^{th}} \right]^2$$

Thermo-elastic-plastic properties, dependent of temperature, used to calculate J_{mt} , J_{el}^{th} and k_{th}^* are given in the RSE-M Appendix 5.6 or RCC-M Appendix ZI.

J – Calculation of k_{th}^* for Straight Pipe

- for circumferential surface crack

$$L_r(P=0) = \sqrt{\left[\frac{3}{5} \frac{m_2}{q_m \mu_{em} \mu_t} + \sqrt{\left(\frac{n_1}{q_n \mu_{en} \mu_t} \right)^2 + \left(\frac{2}{5} \frac{m_2}{q_m \mu_{em} \mu_t} \right)^2} \right]^2 + \left[\frac{m_1}{q_n \mu_{en}} \right]^2}$$

k_{th}^* is evaluated as:

- o If at least one of the following two conditions a) and b) is verified:

a) $L_r \leq 0.5$

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

where p relates to reduced pressure (RSE-M Appendix 5.4 Article IV.4.1.1.1)

then: $k_{th}^* = k_{th}$

- o Otherwise:

$$k_{th}^* = 1 - \frac{2p}{L_r(P=0)} (1 - k_{th})$$

- For longitudinal surface crack

- o $K_{th}^* = k_{th}$

J- Calculation of k_{th}^* for Thickness Transition and Elbow

- Similar formulae are proposed in RSE-M Appendix 5.4 for thickness transition and elbow with circumferential and longitudinal surface crack

CONCLUSION

Since 1990 the RSE-M In-service Code is regularly updated, in particular for flaw evaluation rules. The last Edition published is 2016 and will be used by a lot of PWR plants in the world (around 100 in a near future). This RSE-M appendix 5 on "flaw evaluation" is developed in total consistency with RCC-MRx Appendix A16.

The key innovative approach of RSE-M flaw evaluation are:

- an innovative new approach for defect/defect interaction and defect/surface interaction
- an extensive Handbook (around 80 tables) of order 4 influence function for straight pipe, thickness transition and elbow in order to evaluate elastic K
- associated to elastic K evaluation, multi-modal loads and equivalent K_{eq} formulae is provided
- plastic zone size correction for limited plasticity, slightly more than small scale yielding with dedicated α and β coefficients
- cracks close and in the cladding
- a J estimation scheme based on reference stress
- a large set of limit loads formulae's for cracked straight pipe, thickness transition and elbow
- different J estimation scheme improvements: weld mismatch, mechanical displacement control load, thermal loads, mixed thermal and mechanical loads
- fatigue crack growth analyses with conservative $da/dN-\Delta K$ laws, mixed mode condition, plasticity correction and transient combination rules
- plastic collapse loads of cracked components
- all the material properties needed for analyses
- partial safety factors on loads and toughness, considering also uncertainties in crack size and location
- regulatory margins coefficients

- recently, "Warm Pre-Stress" considerations for cladded Reactor Pressure Vessel was added in a non-mandatory Code Case.
- recommendation to add a detailed finite element analyses of cracked components for the more limited case

A large validation program has been developed with a large number of comparisons of J estimation through RSE-M engineering methods and direct finite element analysis of cracked body. All the quality assessment associated to these rule development is a key issue to assure safety and availability of French and International Nuclear PWRs.

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