Three dimensional Fracture Analysis of the Reactor Pressure Vessel inlet nozzle under Pressurized Thermal Shock

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ABSTRACT

This paper presents a 3D FE mechanical analysis of the brittle fracture risk of a Reactor Pressure Vessel (RPV) inlet nozzle corner submitted to a Pressurized Thermal Shock (PTS). The input transient loading comes from a 3D thermo-hydraulic analysis of a Loss of Coolant Accident resulting from a 2" small break LOCA in one of the hot legs of the primary system. The present study investigates the margins against brittle fracture along the crack front. The aim is to show that a full 3D study of the PTS captures all the physical phenomena, namely the cold tongue and its effect on a defect postulated in the most severe location.

The transient has been computed using a 3D thermal-hydraulic model with STAR-CD software. The selected transient is one of the most severe in 3rd category and a 20 mm deep crack has been postulated in the inlet nozzle corner area where the cold tongue effect is maximum. The mechanical analysis has been performed with SYSTUS Finite Element software which contains fracture mechanics modules for refined meshing of 3D flaws and fracture analyses.

The margin against brittle fracture is evaluated at the tip of an open defect in the inner RPV inlet nozzle corner, according to the codified approach. The approach is based on Linear Elastic Fracture Mechanics and compares the Stress Intensity Factor along the crack front during the transient with the End of Life fracture toughness.

Under such complex loading, the 3D analysis gives a fully representative picture of the defect behavior under real conditions. The using and the mastering of complex numerical tools allow quantifying accurately the margin to brittle fracture, in order to improve the demonstration of the AREVA reactors safety.

INTRODUCTION

Mechanical behavior RPV components evaluation is performed under safety injection induced by a small LOCA. Indeed, in the case of a PTS, a sensible (high stressed) area is the RPV inlet nozzle corner. So, a brittle fracture analysis in presence of a defect has to be performed in this area. As a consequence of the safety injection, the RPV wall is unevenly cooled in the circumferential direction. Because of the physical complex phenomena to take into account, 3D thermal-hydraulic and thermo-mechanical calculations are needed in order to evaluate the effect of such a transient and to quantify accurately the margins against brittle fracture. These margins are estimated at the tip of an open defect in the inner RPV inlet nozzle corner, according to the methodology referenced [1]. The defect is a conventional one (20 mm) and is located in the area where the cold tongue effect is maximum. This analysis is realized for a transient of the 3rd category (2" LOCA) which appears to be one of the most penalizing for the present study.

The present paper underlines the difficulties of the mechanical problem, explains the retained methodology, the input data used for the thermo-mechanical analysis, the calculation hypothesis and the brittle fracture results.

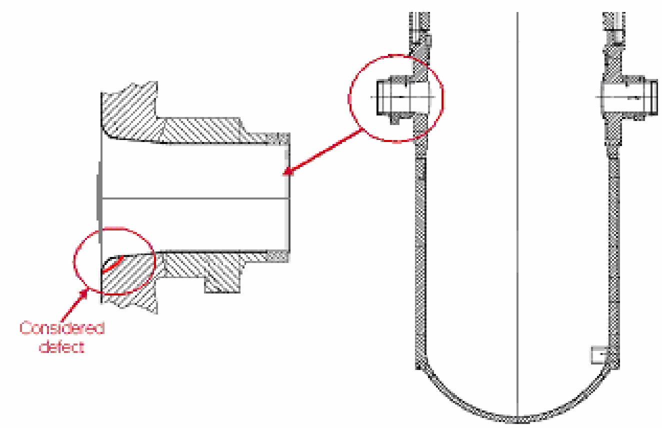

Fig. 1 Location of the studied defect

METHODOLOGY

In order to enable a realistic computation, the methodology consists in performing thermo-mechanical and mechanical calculations with SYSTUS [2] on a 3D FE model using input data from the two following steps:

- Overall thermal-hydraulic calculation: use of the thermal-hydraulic simulation code CATHARE [3] to compute the evolution of the main overall thermal-hydraulic parameters: flow rates inside RCS loops and RPV, average temperatures in the RCS. This provides initial and boundary conditions for the local calculation as well as averaged data for mechanical computations.
- Local thermal-hydraulic calculation: use of a 3D hydraulic simulation code STAR-CD [4] to compute the mixing at RPV inlet and inside RPV downcomer after the start of safety injection.

For each concerned instant of the transient, the value of the stress intensity factor K is determined. K is then compared with the toughness K_{IC} of the material at the tip of the defect (location where the margin is minimum). The toughness K_{IC} depends on the temperature and the transition temperature given by the RT_{NDT} temperature. The margin in the brittle domain and the nil ductility transition domain is appreciated in terms of the ratio:

$$C_S = \frac{K_{IC} \quad \text{(Toughness)}}{K \quad \text{(Stress intensity factor)}} \tag{1}$$

<u>Note:</u> The brittle fracture concerns structure areas where temperature is lower than RT_{NDT}+50°C.

MAIN DATA

Geometry

The figure 2 provides the main dimensions of the analyzed RPV:

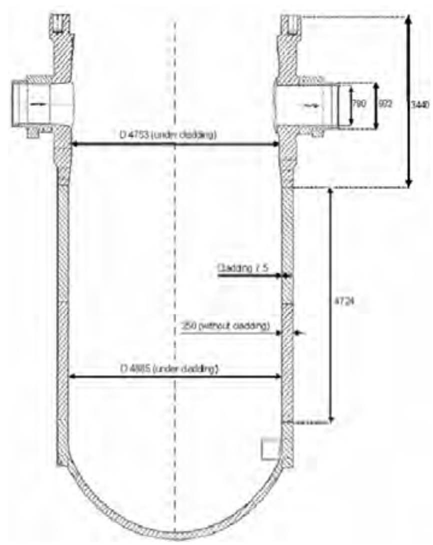

Fig. 2 Reactor Pressure Vessel

The safe ends and the cladding are represented. The reactor vessel head, the reactor vessel bottom head and the radial keys are not modeled.

Studied defect

The studied defect situated under cladding is a conventional reference defect of the semi-elliptical type and is considered as an open defect (The cladding in the present study is used only to perform the thermal analysis). This defect has the following dimensions (***2a*** is the small ellipse axis and ***2c*** is the big axis):

- A depth ***a*** equal to 20 mm,
- An aspect ratio ***a/2c***=1/6.

Material characteristics

The RPV is made of ferritic metal 16MND5. The cladding is made of austenitic deposited metal 309L and 308L. The safe ends are made of austenitic metal Z2 CND 18 12 with nitrogen controlled.

For the calculations of the present analysis, an end of life RT_{NDT} of -20°C is used for the tip of the defect. Moreover, the brittle domain is defined by:

$$T - RT_{NDT} \leq 50°C \tag{2}$$

T is the temperature of the structure analyzed point. Consequently, the brittle fracture domain corresponds to a structure temperature ≤ 30°C.

The critical stress intensity factor K_{IC} is given by the following picture:

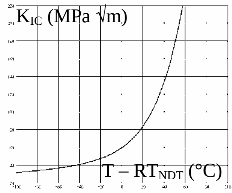

Fig. 3 K_{IC} variation

Analyzed transient

The transient considered consists in the opening of a small break of 2" (2" LOCA) in one of the hot legs (HL 1) of the primary system, the plant being initially operating at 100% nominal power. This accident implies the loss of the integrity of the second barrier and leads to a depressurization of the primary system (until 26.5 MPa), inducing some automatic safety actions (15°C cold water safety injection temperature). This transient belongs to the 3rd category transients.

CALCULATION HYPOTHESIS

Mesh models

Two meshes have been used: a first one with cladding, composed of linear elements and about 1700000 nodes, for thermal analysis and a second one without cladding and core shell but with defect, composed of quadratic elements and about 620000 nodes, for thermo-mechanical analysis. The first FE model is presented below:

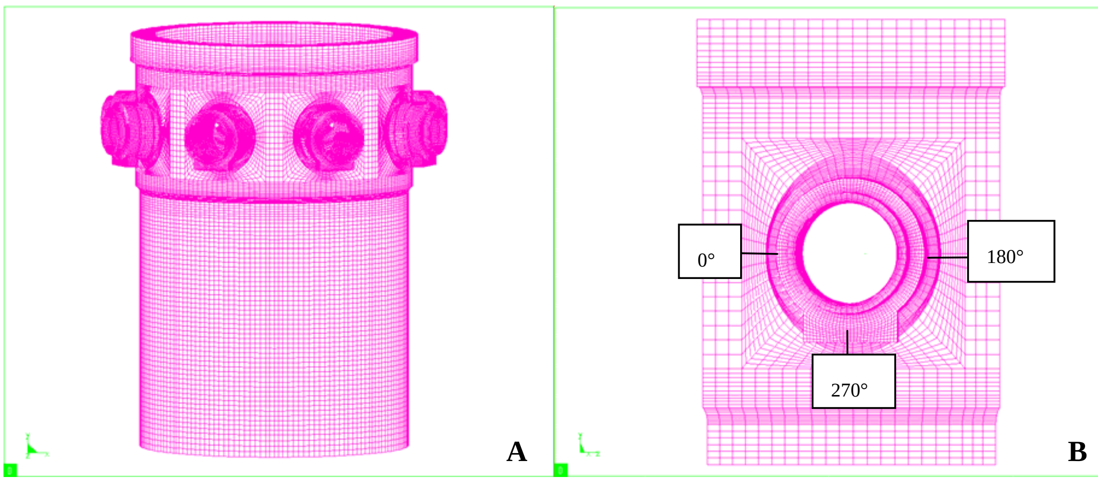

Fig. 4 3D linear FE model (A) and orientation of each inlet nozzle of the cold legs (B)

To position the defect in the most penalizing case, it has been necessary to analyze the fluid temperature obtained by the STAR-CD calculation, in the different cold legs. For each cold leg, the calculation with STAR-CD provides the variation of the fluid temperature obtained as function of time, for each azimuth in the associated radius:

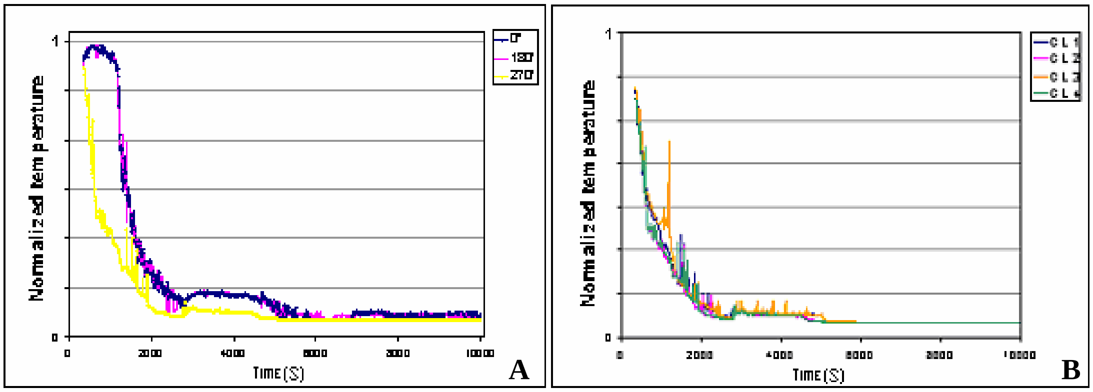

Fig. 5 Variation of the fluid temperature in the radius of the CL4 (A) and in the radius of the azimuth 270° for each cold leg (B)

The variation of fluid temperature presenting the same characteristics in the different cold legs, the azimuth 270° of the cold leg 4 appears to be the most subjected to the cold tongue effect. So, by using the Crack Block [6], the defect has been modeled in the inlet nozzle of the cold leg 4 to the azimuth 270°.

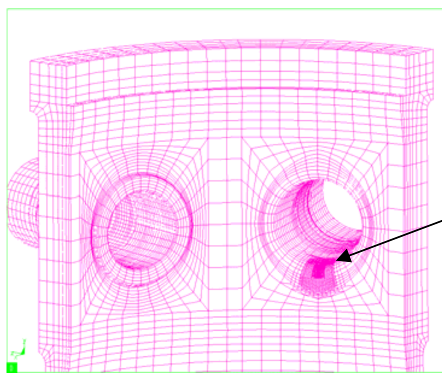

Fig. 6 Positioning of the defect in the inlet nozzle of the cold leg 4

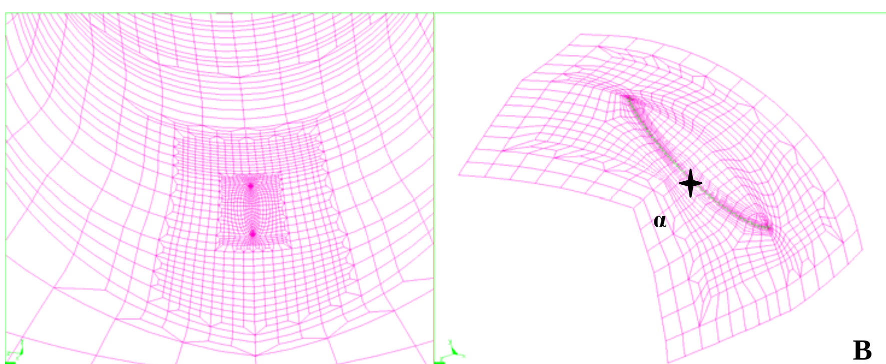

Fig. 7 Overall mesh (A) and cross section (B) of the defect

The line of nodes shows the bottom of the defect. The point α represents the tip of the defect.

Loading and boundary conditions

Thermal analysis: the variation of the inner wall temperature obtained from CATHARE and STAR-CD analyses, is directly applied on the inner skin of the model, following 2 steps:

- From 0 to 360s, the input data come from CATHARE calculation;
- From 360 to 10 000s, the input data come from CATHARE calculation and STAR-CD calculation.

CATHARE supplies the temperatures in 4 principal zones:

- The 4 cold legs with a distinction between the CL 1, CL 2 and CL 3&4 (up to 360s);
- The 4 hot legs with a distinction between the HL 1, HL 2 and HL 3&4 (up to 10000s);
- The downcomer which is the part of the vessel 2.4 m below the generating line of the legs (up to 360s);
- The voldown (complement of the vessel) with a distinction between the liquid and the steam phases (up to 10000s).

From 360s, STAR CD supplies the temperatures in 2 principal zones:

- The 4 cold legs with a distinction between the CL 1, CL 2, CL 3 and CL 4;
- The downcomer until the level of the upper generating line of the legs.

So, the description of the first step (0-360s) of the thermal calculation is summed up below:

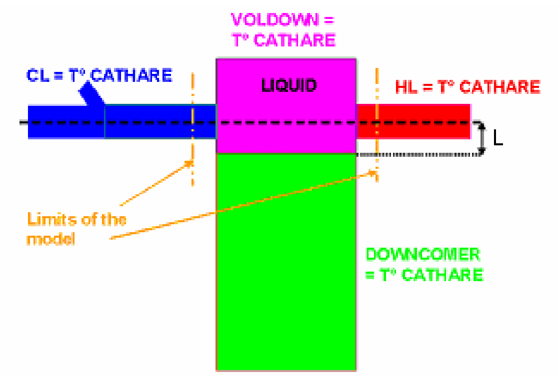

Fig. 8 Input data for the first step of the thermal calculation

From 0 to 360s, the level of liquid is constant (located above the generating line of the legs).

From 360 to 10 000s, the level of steam is variable and the temperature of the steam is not equal to the temperature of the liquid. The variation of the level of the steam and its approximation for calculation are presented on the following figure:

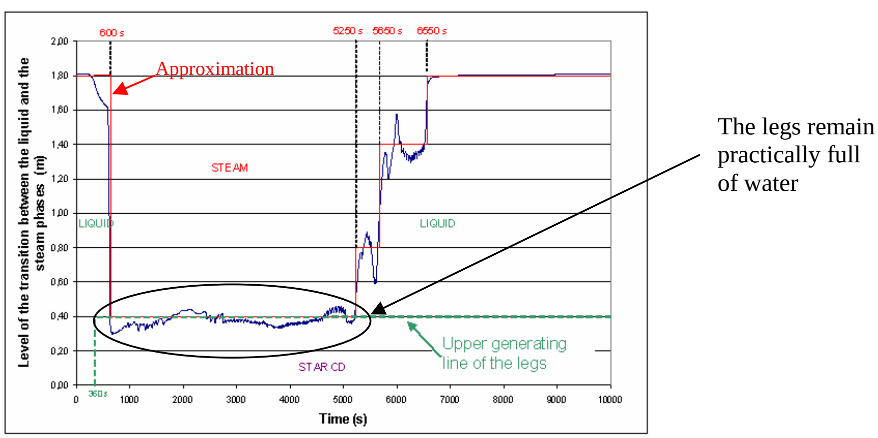

Fig. 9 Variation and approximation of the level of transition between the liquid and the steam phases

So, the description of the second step (360-1000s) of the thermal calculation is summed up below:

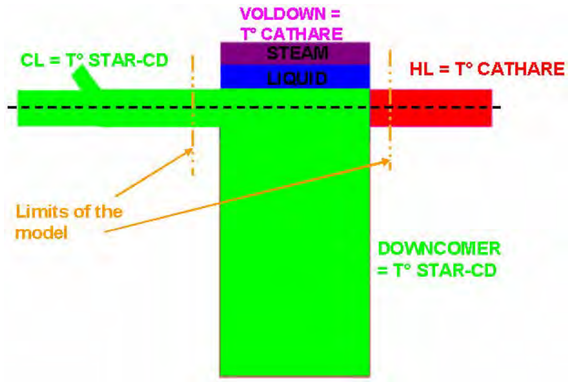

Fig. 10 Input data for the second step of the thermal calculation

The following pictures present some examples of thermal results:

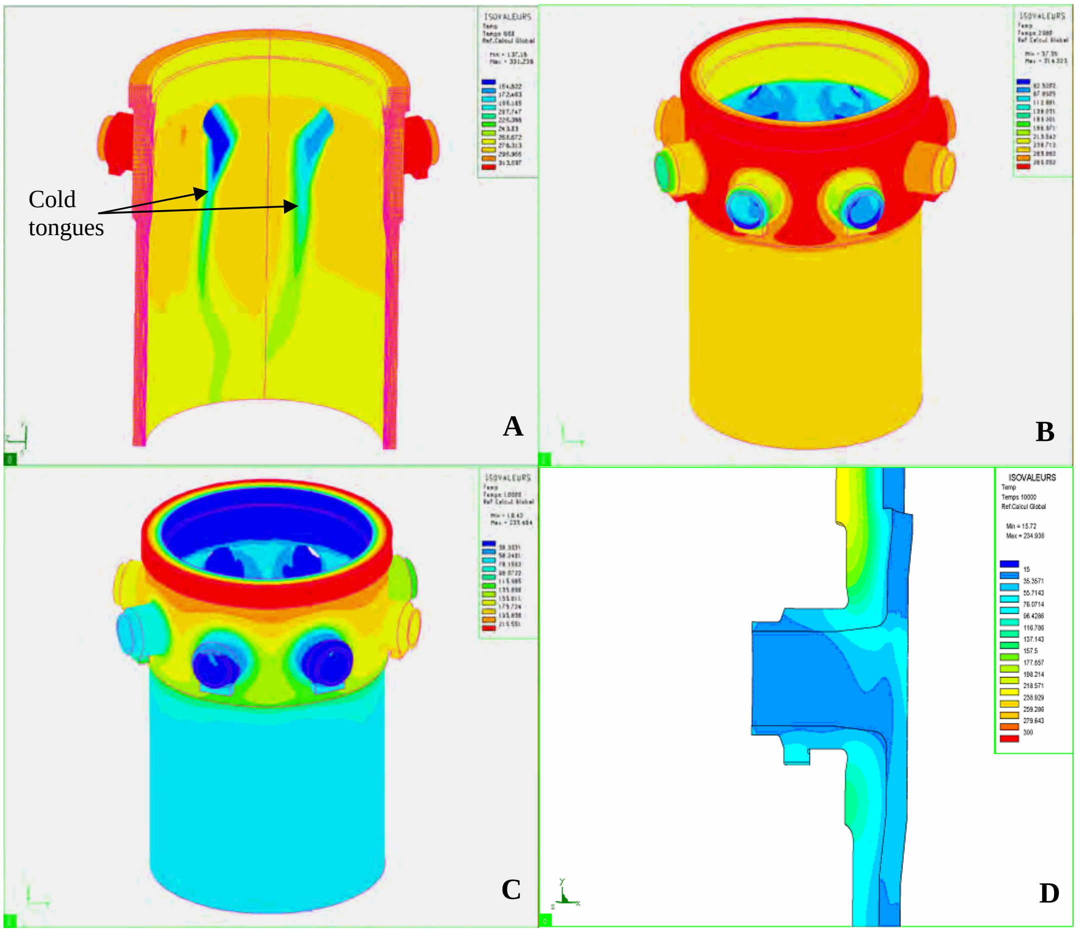

Fig. 11 Examples of temperature field obtained in the RPV at 660s (A), 2980s (B), 10000s (C) and in the cross section of the RPV inlet nozzle of the CL4 at 10000s (D)

<u>Note:</u> The thermal analysis is performed with thermal properties varying with the temperature.

Thermo-mechanical analysis: The mechanical boundary conditions allow the RPV to expand freely under pressure, and more precisely allow representing correctly the displacements of the free ends of the model under the effect of the pressure and the thermal field, without generating local overstresses:

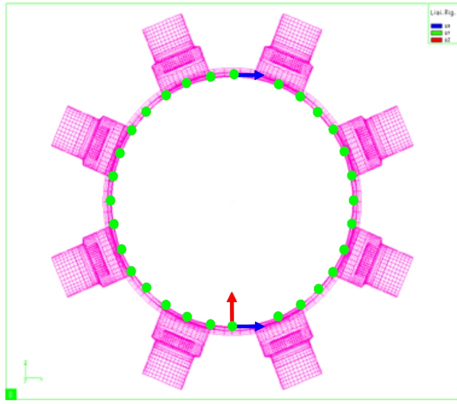

Fig. 12 Mechanical boundary conditions

The pressure is applied on the inner skin of the model and on the upper part of the safe ends (to take into account pressure end effects).

The temperature field resulting of the thermal calculation is directly applied to all the nodes of the model.

The following pictures present some examples of thermo-mechanical results:

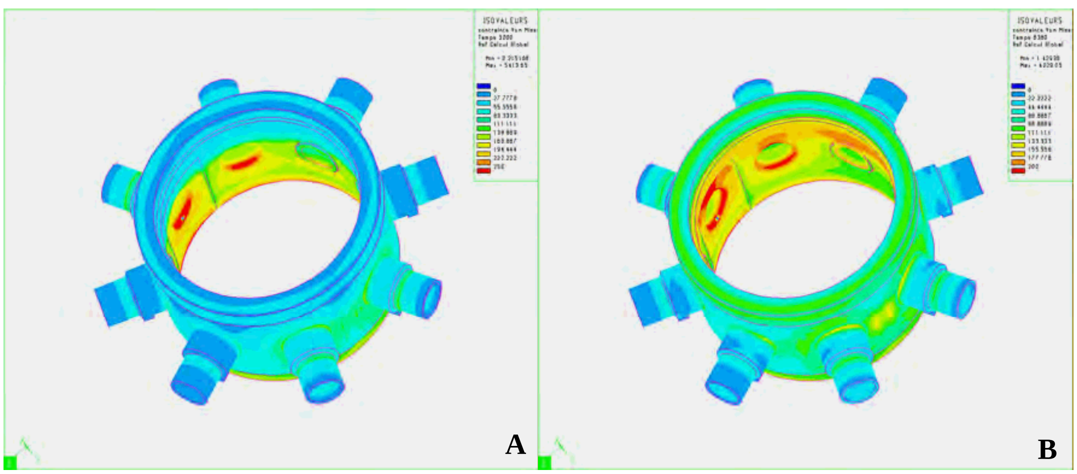

Fig. 13 Examples of stress field obtained in the RPV at 3000s (A) and 6380s (B)

Fast fracture calculation

K is calculated from the value of the Rice Integral J, using the SYSFISSURE tool [7]. For the defect tip,

$$K = \sqrt{\frac{E * J}{1 - \nu^2}} \qquad \text{(Plane stress state)} \qquad (3)$$

<u>Note:</u> The calculation is performed in the elastic range.

BRITTLE FRACTURE RESULTS

The K, K_{IC}, $K_{pressure}$, $K_{thermal}$ variation and the temperature at the defect tip as function of the time are presented below:

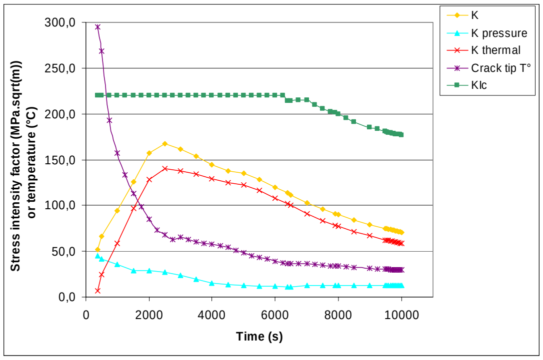

Fig. 14 Results at the tip of the defect

$C_{S\text{-}min}$ is obtained for a temperature T=30°C and an instant t=9750s.

SUMMARY AND CONCLUSION

During safety injection, the RPV wall is unevenly cooled in the circumferential direction, because of the presence of a cold tongue in the RPV nozzle and wall. The margin against brittle fracture is evaluated at the tip of an open defect in the inner RPV inlet nozzle corner. Under such complex loading, a 3D brittle fracture analysis gives a fully representative picture of the defect behavior under real conditions. The using and the mastering of complex numerical tools allow quantifying accurately the margin to brittle fracture, in order to improve the demonstration of the AREVA reactors safety.

NOMENCLATURE

CL, HL = Cold Leg, Hot Leg
C_S = Security Coefficient
E = Young's modulus
FE = Finite Element
K = Stress Intensity Factor
K_{IC} = Critical Stress Intensity Factor for the Brittle Domain
LOCA = Loss of Coolant Accident
PTS = Pressurized Thermal Shock
RCCM = Règle de conception et de Construction des Matériels Mécaniques des îlots nucléaires REP (Design and construction rules for mechanical components of PWR nuclear islands)
RCS = Reactor Coolant System
RPV = Reactor Pressure Vessel
RT_{NDT} = Transition Temperature
ν = Poisson coefficient

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